Experimental Study of a Si/CdTe Semiconductor Compton Camera for the Next Generation of Gamma-ray Astronomy

次世代ガンマ線天文学のためのSi/CdTe 半導体コンプトンカメラの実証的研究

平成20年12月博士（理学）申請
東京大学大学院理学系研究科
物理学専攻
武田 伸一郎
Abstract

A Compton camera is the most promising detector for gamma-ray astronomy in the energy band from a few tens of keV to MeV. Its detection method, based on Compton scattering kinematics, allows us to determine the direction of incident gamma-rays and significantly reduce background events caused by cosmic charged particle or detector activation in orbit. In this thesis, we describe a new Compton camera, named the Si/CdTe semiconductor Compton camera, which consists of many layers of position-sensitive Silicon and CdTe detectors. In order to verify the performance and to understand the detector response, we construct prototype Si/CdTe Compton cameras. The spectral response is studied by taking charge sharing, charge collection efficiency and thermal diffusion inside the Si and CdTe semiconductor devices used in the detectors. The imaging capability with various kinds of gamma-ray targets, such as a point source, arranged point sources and extended sources, is examined. Utilizing the maximum-likelihood iteration algorithm, the extended source and adjacent sources were successfully deconvolved with its internal structure. The ability of polarization measurements, which is one of key features of the Compton camera, are demonstrated through the experiment at synchrotron beam facility. The direction of the polarization vector is determined to within an accuracy of 1°. For the 92.5 % polarized 170 keV gamma-rays, the modulation factor of 0.82 is obtained. Based on the Monte Carlo simulator verified by the results from various experiments in this thesis, in-orbit performances for all-sky survey is studied. We confirmed that the Si/CdTe Compton camera can achieve one order of magnitude higher sensitivity in comparison with the COMPTEL onboard CGRO in the energy band from 500 keV to a few MeV.
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Chapter 1

Introduction

The hard X-ray and gamma-ray bands have long been recognized as important windows for exploring the energetic universe. It is in these energy bands that non-thermal emission, primarily due to accelerated high-energy particles, becomes dominant. The Compton Gamma-ray Observatory (CGRO) satellite, which operated from 1991 to 2000, revealed that there are a variety of γ-ray sources. With its four onboard instruments, CGRO covered a wide energy range, from 20 keV to 30 GeV. This wide energy coverage, six decades in photon energy, played an important role in studying the realm of non-thermal astrophysics.

We can expect a further revolution brought by the INTEGRAL [1], Suzaku [2], Fermi [3] and other near-future missions. However, when compared with X-ray astronomy, hard X-ray and γ-ray astronomy are still immature. As clearly shown in Fig. 1.1, the sensitivity of instruments is far from the level achieved by the current X-ray missions employing focusing telescopes in the energy band below 10 keV. The situation is particularly unsatisfactory in the region between ~10 keV and ~100 MeV. In this “sensitivity gap”, the jump at the low energy end comes from the fact that current X-ray mirrors cannot focus hard X-rays. At energies above ~100 MeV, sensitivity is recovered by utilizing pair-production telescopes.

The universe in the sub-MeV to MeV energy band, from several hundred keV to a few MeV, is characterized by violent high energy phenomenon from most powerful and dynamic sources and also by nuclear transitions. The scientific objectives are spanning from compact objects as broad class annihilators, over long lived galactic radioisotopes. The non-thermal emission from these objects are the clue to study how the energy is concentrated to particle acceleration or extremely high temperature plasma. In order to study the non-thermal emission at these energy regions and to draw a more complete picture of the non-thermal universe, highly sensitive observations are important. In particular, sub-MeV and MeV γ-ray observations to match observations at other wave-lengths are indispensable, because the wide band emission is what we could expect from non-thermal emission. To this end, future high-energy instruments should provide much improved angular and spectral resolutions over the instruments in use today. A γ-ray telescope with one to two orders of magnitude better sensitivity than the current instruments, once realized, the observation will open up a new window of astrophysics with the application of elementary particle physics, general relativity, relativistic plasma-physics and electrodynamics, quantum theory and even cosmology.

While the total cross section has its minimum at a few MeV, the energy range between
several hundred keV and about 30 MeV is dominated by the Compton effect. At these energies, the detection method based on Compton effect is the most promising technique to achieve high sensitivity by suppressing background as demonstrated by COMPTTEL [4, 5, 6, 7, 8] on board CGRO (Compton Gamma-Ray Observatory) satellite.

In this thesis, the development, building, and various experimental studies of the Si/CdTe Compton camera are presented together with the results of simulation as the new instrument for the next generation of $\gamma$-ray astronomy. Chapter 2 reviews the importance of sub-MeV/MeV gamma-ray astronomy. In Chapter 3, interaction of $\gamma$-ray and principles of a Compton Camera are summarized with some histories of application of Compton camera to astrophysics. In Chapter 4, we introduce our Si/CdTe semiconductor Compton camera as a promising candidate for future $\gamma$-ray detector featuring both high imaging quality and good spectroscopic capability, and thus high sensitivities. Chapter 5 describes the developments of the Si/CdTe Compton camera. In Chapter 6, we investigated the response of the Compton camera. New simulation code which includes the effects of charge sharing and diffusion in the device has been developed. Chapter 7 describes the imaging capability of the Compton camera based on experiments with both point and diffuse sources. Polarization measurements are expected to provide a powerful prove into high-energy emission mechanisms as well as the distribution of magnetic fields, radiation fields and interstellar matter. Chapter 8 demonstrated the ability as a polarimeter through the tests at accelerators of SPring-8. Finally, in Chapter 9, we study the optimum design of Si/CdTe Compton Camera for the use in the next generation of $\gamma$-ray astronomy.

Figure 1.1: Continuum sensitivity. There are “sensitivity” gap between 10 keV and 100 MeV.
Chapter 2

Sub-MeV/MeV Gamma-ray Astronomy

2.1 Study of the non-thermal universe

The sub-MeV/MeV gamma-ray sky is mainly characterized by non-thermal emission from “cosmic accelerators”, where a part of thermally distributed particles is picked up to relativistic energies by some acceleration mechanisms. Such cosmic particle accelerators are believed to be common in the universe. These particles are observed nearby solar flares, pulsars, X-ray binaries (XRBs), super nova remnants (SNR), and at cosmological distances, active galactic nuclei (AGN) or gamma-ray bursts (GRB). Even clusters of galaxies give some hints of such particle acceleration. The main energy source powering these particle accelerators varies among source classes, that is, release of gravitational energy, magnetic rotational energy, electromagnetism energy and nuclear energy. However, more detailed emission scenarios are still unknown: how the particle energy is converted to radiation, what are the emitting geometries and the spatial distribution of matter/plasma, and what are the relevant physical parameters and their values.

Super Nova Remnants

Shocks in Super Nova Remnants (SNR) were long thought to be the major sites of particle accelerations in our Galaxy. Several hard X-ray observations of young SNRs, such as SN1006 [9] and RXJ 1713.7–3946 [10], reveal that the non-thermal X-ray emission is produced via the synchrotron mechanism from the non-thermally distributed electrons reaching tens of TeV. On the other hand, GeV and TeV emission is produced by either inverse Compton from the same electron population or by secondary photons decayed from π⁰ produced by photon interactions. Therefore, observing the sub-MeV/MeV range will distinguish these scenarios and shed new light on whole-picture SNRs.

Active Galactic Nuclei

The Compton Gamma-Ray Observatory (CGRO) showed that nuclear activity in galaxies produces extraordinarily powerful and rapidly variable fluxes of gamma rays. The only compelling explanation is that a supermassive black-hole engine at the center of a galaxy
generates this emission. The active galactic nuclei (AGN) that have been detected at gamma-ray energies fall into two distinct classes. The first class includes radio galaxies and Seyfert AGNs with redshifts \( z < 0.1 \) and \( > 50 \) keV luminosities between \( 10^{40} \)–\( 10^{45} \) ergs/s. The OSSE [11] and COMPTEL [4, 5, 6, 7, 8] onboard CGRO provides strong evidence for spectral softening or cutoffs above 100 keV for these AGNs. Blazars comprise the second class of gamma-ray emitting AGNs. These include BL Lac objects, core-dominated flat spectrum radio quasars, and highly polarized and optically violently variable quasars. Blazars emit strong fluxes at 0.1–10 MeV, and the bulk of their power output is often concentrated on these energies or higher.

**Galactic Black Hole**

Results from CGRO show that galactic black hole candidate sources are bright at MeV gamma-ray energies, and display a wide range of spectral states both individually and among classes. Black hole X-ray binaries such as GX 339–4 and Cygnus X–1 undergo a series of transitions from the bright, soft X-ray state to the dimmer, hard gamma-ray state where the photon energy of peak power output is at hundreds of keV.

**Neutron Stars & Pulsars**

Neutron stars, both accreting neutron stars and radio pulsars, are known to be strong continuum sources above 100 keV. However, the phase resolved continuum spectra from radio pulsars are indicators of the emission mechanism, as most of the emitted power is in gamma-ray photons. Particle acceleration and photon production mechanisms in pulsar magnetospheres are still mysterious. The information about the polarization gives a clue to the problem, since such spectral features can be strongly dependent on the photon polarization; observation of polarized signals in the 100 keV–10 MeV band may discern whether or not the exotic QED process of photon splitting occurs.

**2.2 Nucleosynthesis**

At the endpoint of stellar evolution, gravity ultimately dominates over energy releases through nuclear fusion, in the case of a massive star leading to a violent explosion. Observing gamma-ray line signatures from radioactive isotopes synthesized during such explosions is a powerful means to prove the physical conditions and mechanisms that drive these events.

The topic related to Type Ia supernovae is important and challenging in gamma-ray astronomy. It is widely accepted that Type Ia supernovae are the outcome of the thermonuclear explosion of a white dwarf in a binary system. They are regarded as standard candles due to their uniform progenitors and are consequently used for cosmological distance determination. Their optical light curve and spectra are studied in great detail; however, the nature of these events is still unknown. Although the evidence for the existence of dark energy is essentially based on the distance measurement by Type Ia supernovae, nobody knows how the white dwarf approaches the Chandrasekhar limit and ignites or how the spark propagates through the star. Therefore, the understanding of the physics of Type Ia supernovae is the critical problem concerning our understanding...
of Universe. Radioactive nuclei and the decay products during this event are the most direct tracers of the physical condition of the explosion.

The main radioactive nuclei synthesized in novae, that are relevant for the gamma-ray emission, are presented in Table 2.1. Note that these are the sources whose existence has already recognized. The sub-MeV/MeV energy band is very attractive to study the nucleosynthesis in the universe. But, the line flux from celestial objects is usually very weak compared to the dominant non-thermal emissions, as low as $10^{-6} - 10^{-5}$ photons cm$^{-2}$ s$^{-1}$ level, and only a handful of objects have been observed at present. In order to overcome this situation and open new doors in gamma-ray line astronomy, a new instrument should achieve an order of $10^{-7}$ photons cm$^{-2}$ s$^{-1}$ for line sensitivity. Both the high energy resolution ($\Delta E/E \sim 1\%$) of the instrument and high background rejection capability are essential.

### $^{26}$Al Decay

The proton rich isotope $^{26}$Al decays to the first excited state of $^{26}$Mg at 1.809 MeV with a mean lifetime of 1.04×$10^6$ yr. This is the most apparent radioactivity in the sky. Radioactive $^{26}$Al is presumably produced by explosive nucleosynthesis in core collapse Type II supernovae, in novae or by hydrostatic nuclear burning in the interior of massive stars (Wolf-Rayet stars etc). Due to its long decay time, $^{26}$Al decay traces galactic nucleosynthesis processes over the past million years.

The HEAO–C discovered the 1.809 MeV gamma-ray line from radioactive $^{26}$Al in the Galaxy [12]. The COMPTEL has achieved a major breakthrough by generating the first all-sky map [13, 14] of the 1.8 MeV (Fig. 2.1). We see a line flux of $\sim3\times10^{-4}$ photons cm$^{-2}$ s$^{-1}$ from the central Galaxy. The flux distribution along the Galactic plane is not smooth, but clumpy with hot spots. The observed flux of $2\times10^{-5}$ photons cm$^{-2}$ s$^{-1}$ from the Vela SNR is within the range of predicted 15 to 20 $M_\odot$ core collapse supernovae yields, if the Vela distance is less than 400 pc [15]. Other localized source regions are the Carina and the Cygnus region, and spiral arm regions.

### $^{60}$Fe Decay

The neutron rich isotope, $^{60}$Fe (1.5×$10^6$ yr ), whose decay results in 1.173 and 1.333 MeV, is exclusively ejected from core-collapse supernovae, not by any other potential $^{26}$Al
source. RHESSI \cite{16} and INTEGRAL may have detected line emission from $^{60}$Co, the short-lived daughter of $^{60}$Fe. The total flux is an order of magnitude smaller than $^{26}$Al. The total galactic production as well as individual source yields of $^{60}$Fe and $^{26}$Al will provide unprecedented constraints on core collapse supernova nucleosynthesis calculations. If the nuclear flame proceeds slowly in the initial burning in thermonuclear supernovae, a significant older stellar population could also be represented in the $^{60}$Fe emission. The spatial differences between these two million year radionuclides will teach us about the nucleosynthesis of both within several classes of sources.

$^{56}$Ni Decay

Lines at 0.847 MeV and 1.238 MeV from the decay chain $^{56}$Ni$\rightarrow^{56}$Co$\rightarrow^{56}$Fe with their characteristic 111-day decay time were first detected from the core-collapse supernova SN1987A \cite{17} in the nearby Large Magellanic Cloud, and measurements of a thermonuclear supernova SN1991T \cite{18} in the far more distant Virgo cluster showed suggestive line features from this even more significant source type (0.5 M$_\odot$ of $^{56}$Ni are expected from typical thermonuclear SNe, while only 0.075 M$_\odot$ were ejected in SN1987A). Surprisingly only upper limits were obtained from the thermonuclear supernova SN1998bu at a distance of 9 Mpc. The predicted 0.847 MeV line flux from thermonuclear supernovae, which is expected to peak at 70 days after the explosion, is \((6\pm3)\times d$ (Mpc)$^{-2}$ photons cm$^{-2}$ s$^{-1}$. Note that large expansion velocities of the ejected material broaden these lines significantly (>5-50 keV line widths are expected for supernovae).

$^{44}$Ti Decay

The 1.157 MeV line from the decay-chain of $^{44}$Ti$\rightarrow^{44}$Sc$\rightarrow^{44}$Ca with its characteristic 89 year decay time is another direct probe of supernova nucleosynthesis, and a unique
2.3. POSITRON ASTROPHYSICS

511 keV line from electron/positron annihilation has been one of the important features of high energy astrophysics. For the past 30 years more than a dozen balloon and satellite observations have been reporting 511 keV annihilation line radiation from the general direction of our Galactic Center (GC) [20, 21, 22]. Recent observation with the SPI onboard INTEGRAL [23] have revealed that a significant amount of the positron annihilation radiation comes from the galactic bulge region (Fig. 2.2). They have determined a 511 keV flux of $(8.7 \pm 0.6) \times 10^{-4}$ photons cm$^{-2}$ s$^{-1}$ and a positronium fraction $f = 0.98 \pm 0.05$. The spatial distribution of the 511 keV line emission is essentially concentrated within the central region of the Galaxy. However, the origin of the positrons is still unknown. The Compact objects, – Type Ia supernovae, novae, or low mass X-ray binaries (LMXB) – are believed to be the sites of positron production leading to the 511 keV emission in the inevitable process of annihilation. The observation of the characteristic 511 keV annihilation line signature and the accompanying three-photon continuum provides a powerful tool to prove plasma composition, temperature, density and ionization degree.

![Figure 2.2: (Left) INTEGRAL mapped the glow of 511 keV gamma rays from electron-positron annihilation. The map shows the whole sky, with the galactic center in the middle. The emission extends to the right. (Right) Spectrum of the Galactic Center region. The 511 keV annihilation lines are clearly observed.](24)

Pulsars are potentially regarded as an important contributor [25] to the galactic positron budget because they require the formation of electron-positron plasma in their pulsar magnetospheres. The nova and supernova are also believed to be important contributors [26]. An escape fraction of $\sim 1\%$ for the $^{56}$Co positrons produced in galactic Type 1a supernovae could account for much of the observed distribution.
The detection of 511 keV annihilation line radiation from AGNs would markedly change our understanding of the condition in the innermost region near a black hole. The most likely origin of the electron-positron pair in AGNs is through pair production from $\gamma - \gamma$ attenuation, which requires energetic electrons and photons in a compact environment. Although the detection of a broad pair annihilation line from Seyfert galaxies is the most feasible if a non-thermal electron spectrum is present, OSSE [11] and INTEGRAL [1] observations indicate that the Seyfert X-ray and $\gamma$-ray emission is mainly due to thermal electrons scattering soft photons. Accordingly, a broadened annihilation line is not expected, though a narrow annihilation line from Seyfert galaxies could be formed if pairs escape from the center nucleus. For blazers, the composition of the jet plasma is not known, and the detection of transient pair annihilation lines would conclusively measure the amount of antimatter present in the jet.

The deep observation of the annihilation line with excellent angular resolution could reveal the numerous problems surrounding the nature of positron. The discovery of the annihilation line from any one of the point sources would shed light on the mystery because it provides the evidence of the positron production site. The DUAL mission (see Section 4.4.2) which features focusing of a gamma-ray will enable a point source search with $\sim 1$ arcmin angular resolution. The high energy resolution of the Compton camera ($\Delta E/E \sim 1\%$) placed on a focal plane allows the detailed line-shape analysis probing of the production sites and their physical condition. In addition, the Compton camera also works an all-sky monitor with an angular resolution of $\sim 1^\circ$. Its line sensitivity of several $10^{-7}$ photons cm$^{-2}$ s$^{-1}$ would address the variability of the diffuse 511 keV emission from GC.

### 2.4 Polarization

For the most part, the analysis of celestial X-ray and gamma-ray sources has been confined to spectral characteristics and time variability. However, this analysis often allows two or more different models to successfully explain the observation. For example, there are two general categories of theoretical models to explain the production of gamma-rays by isolated pulsars, polar cap models [27] and outer gap models [28]. Polarization measurement has the diagnostic potential to discriminate between the different compact source models and can provide a unique insight into the geometrical nature of the emission zone. However, polarization measurement has never been performed at photon energy greater than $\sim 10$ keV, due to the difficulties in making polarimetric instruments for such high-energy regions.

Any observation of polarized soft gamma-rays from X-ray binaries can prove the orientation of the accretion disk; since Compton scattering models [29] predict that the achromatic polarization is a function of observer orientation to the direction normal to the disk. This can be a particularly potent geometrical diagnostic if transient annihilation reflection features are also present, for which the kinematic coupling between energy and direction in Compton scattering can be used to distinct advantage.

Polarimetric information will probe the GRB geometry and emission mechanism. Detections of highly polarized gamma-rays ($>40\%$) would strongly argue for the synchrotron mechanism [30], and suggest that field tangling can only arise on scales larger than the synchrotron coherence length. Polarization evolution through the burst can provide diagnostic probes of the character of the underlying electron distribution, such as the relative
thermal and non-thermal content, and also weigh in on whether or not self-absorption is present.

Recently, the SPI onboard INTEGRAL reported the gamma-ray polarization from the Crab pulsar for the first time [31]. The degree of polarization is $46 \pm 10\%$ and the direction of the polarization vector shows a remarkable alignment with the inner jet structure. The alignment of the polarization vector along the jet axis implies an orthogonal magnetic field configuration if the synchrotron process operates. They state that there is high-energy acceleration of electrons up to at least $10^{14}$ to $10^{15}$ eV, which are then capable of producing TeV emission via inverse Compton scattering on the cosmic microwave background or some other locally produced photons.

The Compton polarimeter [32] based on the detection method utilizing the directional information of scattered gamma-ray in the detector is the most promising approach in the sub-MeV/MeV energy band, where the physical process is dominated by the Compton scattering. In recent years, several kinds of newly designed Compton polarimeters have been proposed [33, 34, 35]. Their basic configurations surrounding the scattering detector by the absorption detectors would provide high detection efficiency and high analyzing power. But, the instruments possessing gamma-ray imaging capability are very rare. As demonstrated by COMPTEL onboard CGRO, the capacity allows a significantly reduction in background events induced by cosmic particles such as protons, neutrons and gamma-ray in orbit.

The Si/CdTe Compton camera is the best detector for polarization measurements. The Compton scattering process in the detector is precisely tracked by a high position and energy resolution semiconductor imaging device, leading to accurate measurement of gamma-ray linear polarization. The significant background reduction is realized by the Compton reconstruction approach such as energy window selection and/or incident gamma-ray direction. The demonstration through the test at accelerator is reported in Chapter 8.
Chapter 3
Principle of Compton Camera

3.1 The interaction of photons

In sub-MeV to MeV energy region, the interaction of a material and a gamma-ray is described by three type of mechanism: photoelectric absorption, Compton scattering, and pair production. The photoelectric absorption involves the absorption of a photon by an atomic electron with the subsequent ejection of the electron from the atom. The Compton scattering plays dominant role typically in the energy band from a few hundred to 10 MeV (Fig. 3.1). It is an elastic scattering between the incident photons and electrons in the scatter medium. In matter, the electrons are bound; however, if the photon energy is high with respect to the binding energy, this latter energy can be ignored and the electrons can be considered as essentially free. Above 10 MeV, the pair production becomes dominant process, involving the transformation of a photon into an electron-positron pair.

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Figure 3.1: The significant interaction of gamma-rays and matter [36]

---

1At low energies, the momentum of bound electrons can not be neglected and affect the performance of Compton Camera. We will discuss this effect in 3.4.3
3.2 Compton Scattering

As illustrated in Fig.3.2, the incident gamma-ray transfers part of its energy to an electron and is scattered at an angle $\theta$ with respect to its initial direction. All the energy lost in scattering will be given up to secondary electrons as kinetic energy.

Assuming the initial electron is free and at rest, according to the conservation laws of energy and momentum, the energy of the incident gamma-ray is

$$E_0 = E'_e + E'_\gamma$$  \hspace{1cm} (3.1)

and the relationship between the scattering angle $\theta$ and the energy of the scattered photon is described as

$$\cos \theta = 1 - m_e c^2 \left( \frac{1}{E'_\gamma} - \frac{1}{E_0} \right)$$  \hspace{1cm} (3.2)

where $E_0$ is the energy of the incident gamma-ray, $E'_\gamma$ is the energy of the scattered photon, $E'_e$ is the energy of the recoil electron, and $m_e c^2$ is the rest mass of an electron. Therefore, if the system detects the energy of the recoil electron and the scattered photon, the scattering angle of the incident gamma-ray is determined by Eq. 3.2.

The energy of scattered $\gamma$-ray is calculated to be

$$E'_\gamma = \frac{E_0}{1 + \frac{E_0(1-\cos \theta)}{m_e c^2}}$$  \hspace{1cm} (3.3)

The kinetic energy of electron, $K = E'_e - m_e c^2$ becomes,

$$K = E_0(1 - \frac{m_e c^2}{mc^2 + E_0(1-\cos \theta)})$$  \hspace{1cm} (3.4)

The cross section for Compton scattering is know as "Klein-Nishina" formula:

$$\frac{d\sigma^{KN}}{d\Omega} = \frac{r_0^2}{2} \left( \frac{E'_\gamma}{E_0} \right)^2 \left( \frac{E'_e}{E_0} + \frac{E_0}{E'_\gamma} - \sin^2 \theta \right)$$  \hspace{1cm} (3.5)

where $r_0$ is the classical electron radius. Integration of this formula over $d\Omega$, then, given the total probability per electron for a Compton scattering to occur

$$\sigma^{KN} = \sigma_T \frac{3}{4} \left[ \ln(1 + 2u) - \frac{1 + 3u}{(1 + 2u)^2} \right]$$  \hspace{1cm} (3.6)

where $u = E_0/m_e c^2$. If $\gamma$-ray energy is much smaller than electron mass, the total cross section is expressed as Thomson cross section ($\sigma_T$).
3.3 The Compton Camera

The Compton camera reconstructs the information of the incident gamma-ray with information of Compton scattering recorded in the detector.

Figure 3.3 shows the schematic of the gamma-ray measurement by Compton scattering. In conventional Compton Cameras, the incident gamma-ray is identified by successive interactions in the two detector layers \( D_1 \) and \( D_2 \). Once the locations and energies of the two interactions are measured, the Compton kinematics allows us to calculate the energy and direction (as a cone in the sky) of the incident \( \gamma \)-ray following the Compton equation. We assume that the incident gamma-ray deposits energy \( E_1 \) in Compton scattering, and deposits its full energy \( E_2 \) in the second detector. Equation 3.1 and 3.2 become:

\[
E_{in} = E_1 + E_2 \tag{3.7}
\]

\[
\cos \theta = 1 - m_e c^2 \left( \frac{1}{E_2} - \frac{1}{E_1 + E_2} \right) \tag{3.8}
\]

where \( \theta \) is the scattering angle. As shown in the equations, The incident direction of a \( \gamma \)-ray is calculated from the position and the energy information of the interactions. Therefore, fine position and energy resolution is the key requirement for the semiconductor Compton telescope to retain a low background level with Compton kinematics.

It should be noted that, a \( \gamma \)-ray telescope based on a Compton Camera has an extremely low background, because the coincidence condition between \( D_1 \) and \( D_2 \) discriminate against most of the internal \( n/\beta \) background.
CHAPTER 3. PRINCIPLE OF COMPTON CAMERA

\[ \cos \theta = 1 - m_e c^2 \left( \frac{1}{E_2} - \frac{1}{E_1 + E_2} \right) \]

Figure 3.3: Gamma-ray measurement by Compton scattering

3.4 Uncertainties in angular determination

The angular resolution is one of the most important parameter to evaluate the Compton camera performance. There are several factors that cause uncertainty in angular determination. These include the imperfection of the detection system and the natures of Compton scattering. The former corresponds the position and energy resolution of detector, and the later corresponds to the Doppler broadening effect. This section discusses about those factors in detail.

3.4.1 Angular Resolution Measure (ARM)

The angular resolution of a Compton camera is usually described in terms of Angular Resolution Measure (ARM). ARM is defined as the angle between the reconstructed Compton cone and the actual source direction. As shown in Fig.3.4, the incident gamma-ray deposits its energy \( E_1 \) at \( r_1 \), and deposits rest of the energy \( E_2 \) at \( r_2 \). Because of the finite resolution of the energy and the position, measurement gives \( E_{1m} \) at \( r_{1m} \) and \( E_{2m} \) at \( r_{2m} \), respectively. ARM is defined as the difference between \( \theta_g \) and \( \theta_e \). Here, \( \theta_g \) is calculated from measured interaction positions and the real direction of the source and \( \theta_e \) is calculated from the measured energy deposits;

\[
\cos \theta_g = \frac{(r_{1m} - r_0) \cdot (r_{2m} - r_{1m})}{|r_{1m} - r_0| \cdot |r_{2m} - r_{1m}|} \quad (3.9)
\]

\[
\cos \theta_e = 1 - m_e c^2 \left( \frac{1}{E_{2m}} - \frac{1}{E_{1m} + E_{2m}} \right) \quad (3.10)
\]

\[ ARM = \theta_e - \theta_g \quad (3.11) \]

The position uncertainty brings about the error of \( \theta_g \) and the energy uncertainty brings about the error of \( \theta_e \). The angular resolution of a Compton camera is estimated by the distribution of ARM value with sufficient amount of the events.
3.4. UNCERTAINTIES IN ANGULAR DETERMINATION

3.4.2 Effects of Incomplete measurements

Contribution due to Finite Position Resolution

Because the gamma-ray interaction position determines the axis of the Compton cone, the position uncertainty introduces an uncertainty in the cone axis direction. The contribution from the position uncertainty is strongly due to the detector's geometry, for example, the position resolution of detectors and the arrangement of them. It is very important to estimate the effect of the detector’s geometry to the angular resolution in order to design the Compton camera.

For simplicity, we introduce the condition as shown in Fig.3.5. The gamma-ray comes from the z-direction, and is scattered in \((x_1, y_1, z_1)\) then absorbed in \((x_2, y_2, z_2)\). The angle \(\theta\) is the scattering angle and the value \(\sigma_\theta\) gives the contribution of the position uncertainty to the angular resolution. The angle \(\theta\) is

\[
\theta = \arctan \frac{z_2 - z_1}{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}}
\]  

(3.12)

By means of error propagation, the uncertainty of angle \(\theta\) can be calculated as

\[
\sigma_\theta^2 = \frac{2\{(x_2 - x_1)^2 + (y_2 - y_1)^2\}(\Delta Z)^2}{d^4} + \frac{(z_2 - z_1)^2(p_1^2 + p_2^2)}{12d^4}
\]  

(3.13)

where, \(d\) is the distance between interaction position, \(d^2 = (x_2-x_1)^2 + (y_2-y_1)^2 + (z_2-z_1)^2\); \(\Delta Z\) is the detector thickness, \(p_1\) and \(p_2\) are the pixel size of the each detector.

Figure 3.6(a) and 3.6(b) show the calculated results of the contribution of the position uncertainties to the angular resolution with respect to the scattering angle. The distance between the detector varies from 2 mm to 50 mm. The thickness of the detector is
0.5 mm in both detector. The pixel size $p_1$ and $p_2$ are 1.4 mm and 1.4 mm in Fig. 3.6(a), and 0.4 mm and 0.4 mm in Fig. 3.6(b), respectively. As the distance between each detector become larger or the pixel size become smaller, the higher angular resolution can be achieved. The contribution of the position uncertainty can be reduced to less than 1 deg with the 0.4 mm pixel size detectors apart from 50 mm. However, the detection efficiency decreases as the distance become larger, because the number of the scattered photon which escape from the detector increase. There is a trade-off between the detection efficiency and the angular resolution.

Figure 3.5: Simplified condition to estimate the angular uncertainty from detector’s position resolution

Figure 3.6: The contribution of position resolution of the detector to angular resolution. (a) pixel size $p_1$ and $p_2$ are 1.4 mm and 1.4 mm, (b) pixel size $p_1$ and $p_2$ are 0.4 mm and 0.4 mm, The thickness of detector is 0.5 mm for both case.
3.4. UNCERTAINTIES IN ANGULAR DETERMINATION

Contribution due to Finite Energy Resolution

Another factor from the incomplete measurements is the energy uncertainty. Applying error propagation to Eq. 3.8, the energy uncertainty contribution to the angular resolution is given by

\[
(\Delta \theta_{\text{energy}})^2 = \left[ \frac{m_e c^2}{\sin \theta (E_1 + E_2)^2} \right]^2 (\Delta E_1)^2 + \left[ \frac{m_e c^2}{\sin \theta (E_1 + E_2)^2} - \frac{1}{E_2^2} \right]^2 (\Delta E_2)^2
\]  

(3.14)

The energy resolution \( \Delta E \) can be normally modeled by the quadrature sum of the electronics noise and the statistical fluctuation. The statistical noise is usually modeled as [37]

\[
\Delta E_{\text{static}} = 2.35 \sqrt{F \cdot E \cdot W} \tag{3.15}
\]

in which, \( F \) is the Fano factor, \( E \) is the gamma-ray energy, and \( W \) is the average ionization energy. In semiconductor materials, the Fano factor is usually less than one, and the measured value is around 0.1. The average ionization energy is typically 3.6 eV in Si and 4.5 eV in CdTe. Here, we use the average value of 4.0 eV for the estimation as

\[
\Delta E = \sqrt{\Delta E_{\text{electronics}}^2 + 2.35^2 \cdot 0.1 \cdot 4.0 \times 10^{-3} \cdot E(\text{keV})} \text{ [ keV ]}
\]

The estimation is performed in two cases of the electronics noise, \( \Delta E_{\text{electronics}} = 0.5 \text{ keV (FWHM)} \) and \( 2.0 \text{ keV (FWHM)} \).

Figure 3.7 shows the result of the estimation for the various incident gamma-ray energy with respect to the scattering angle. As the incident energy becomes larger, the contribution of the energy uncertainty become smaller. This is because, from Eq. 3.14, the angular uncertainty from the energy uncertainty roughly inversely proportional to the incident gamma-ray energy. The contribution can be reduced to less than 1 degree for the gamma-ray above \( \sim 300 \text{ keV} \). The deterioration due to increase of the electronics noise is severe as the gamma-ray energy becomes lower. The value for a 80 keV photon becomes greater than 10° in the case of \( \Delta E_{\text{electronics}} = 2.0 \text{ keV} \). In order to obtain good angular resolution for such low energy photon, special care must be required for read-out electronics to reduce noise level.

Figure 3.7: The contribution of energy resolution of the detector to angular resolution
3.4.3 Doppler broadening effect

The Compton equation 3.2 is based on the assumption that the electron is free and at rest before the scattering interaction. But in reality, the electron is bound to a nucleus, and has finite momentum. Although this effect is negligible as the gamma-ray energy becomes higher, it gives a considerable deterioration to the angular resolution in sub-MeV band. To describe this effect which commonly called Doppler broadening, a more precise Compton cross section than Klein-Nishina equation is required.

The Compton differential cross section is represented by a double differential differential cross section (DDCS) obtained from the relativistic impulse approximation (IA) by Ribberfors [38]. Brusa simplified the equation by some first order approximation [39] and proposed a simple parameterization of the Compton profile from which the sampling algorithm can be formulated in a closed analytical form. Here, we use this method to estimate the contribution of the Doppler broadening.

The simplified Compton atomic DDCS obtained from the IA is given by [39],

\[
\frac{d^2\sigma}{dE'd\Omega} = \left(\frac{d\sigma^{KN}}{d\Omega}\right) F(p_z) J(p_z) \frac{dp_z}{dE'} \tag{3.16}
\]

here,

\[
\frac{d\sigma^{KN}}{d\Omega} = \frac{r_e^2 e^2}{2} \left(\frac{E_c}{E}\right)^2 \left(\frac{E}{E_c} - \frac{E}{E_c} \sin^2 \theta\right) \tag{3.17}
\]

is the Klein-Nishina (KN) formula, where \(r_e\) is the classical electron radius, \(E_c\) is the scattered photon energy at scattering angle \(\theta\) if the initial electron is at rest. The quantity \(F(p_z)\) is defined as

\[
F(p_z) = 1 + \frac{q_c}{E} \left(1 + \frac{E_c(E_c - E \cos \theta)}{(cq_c)^2}\right) \frac{p_z}{mc} \tag{3.18}
\]

where \(m\) is the electron mass, \(c\) is the velocity of light, and \(q_c\) is the momentum transfer,

\[
q_c = \frac{1}{c} \sqrt{E^2 + E_c^2 - 2EE_c \cos \theta} \tag{3.19}
\]

The \(p_z\) is the projection of the initial momentum \(p\) of the electron on the direction of the scattering vector \(q \equiv k - k'\), where \(k\) and \(k'\) are the momenta of the incident and scattered photon; it is given by

\[
p_z = -\frac{p \cdot q}{q} = \frac{EE'(1 - \cos \theta) - mc^2(E - E')}{c^2 q} \tag{3.20}
\]

with

\[
q = \frac{1}{c} \sqrt{E^2 + E'^2 - 2EE' \cos \theta} \tag{3.21}
\]

if \(p_z = 0\), Eq. 3.20 reduces to the Compton scattering formula of Eq. 3.2. In a real atom, \(p_z\) has a distribution defined by

\[
J_i(p_z) \equiv \int \int \rho_i(p) dp_x dp_y \tag{3.22}
\]
in which \( J_i(p_z) \) is the one-electron Compton profile in atomic shell \( i \). Therefore, the atomic Compton profile is given by the sum of all electrons,

\[
J(p_z) = \sum Z_i J_i(p_z)
\]

where \( Z_i \) is the number of electron in atomic shell \( i \).

The Compton profile can be obtained by numerical Hartree-Fock profiles tabulated by Biggs \cite{40}. But, the details of the Compton profile are not very important. Ribberfors and Berggren \cite{41} have shown that quite accurate incoherent scattering functions can be obtained by replacing the integrated Compton profile by a simple linear approximation.

In order to minimize the required numerical information and to simplify the random sampling, Brusa \cite{39} proposed analytical one-electron profile of the form

\[
J^A_i(p_z) = \sqrt{2} J_{i,0} \left( \frac{1}{\sqrt{2}} + \sqrt{2} J_{i,0} |p_z| \right) \exp \left[ \frac{1}{2} - \left( \frac{1}{\sqrt{2}} + \sqrt{2} J_{i,0} |p_z| \right)^2 \right]
\]

The quantity \( J_{i,0} \) is the value of the profile at \( p_z = 0 \) obtained from the Hartree-Fock orbital \cite{40}.

We calculated the Compton DDCS as a function of the scattering angle \( \theta \) and the scattered photon energy \( E' \). Figure 3.8 shows the result of the calculation of a Silicon atom in case of the 80 keV and 511 keV incident gamma-ray energy. The result shows the Compton DDCS for the particular scattering angle from 20° to 160°. Figure 3.9 and Fig. 3.10 are that of a Germanium and a CdTe. In the case of CdTe, we average a Tellurium and a Cadmium DDCS. The center energy for each scattering angle corresponds with the scattered photon energy derived from Klein-Nishina formula, but, the distribution is broaden due to the bound electron to a nucleus. This effect is emphasized for the large scattering angle and lower incident gamma-ray energy. Comparing a Silicon, a Germanium and a CdTe material, the effect is minimized in the case of a Silicon.

Finally, we summarized the angular uncertainty resulting from Doppler broadening effect in Fig. 3.11, for three semiconductor materials, Silicon, Germanium, and CdTe. Silicon provides the best angular resolution, roughly 2-3 times better than other materials. Assuming the ideal detector properties, Si can realize \( \sim 5^\circ \) (FWHM) resolution for a 80 keV incident gamma-ray and less than 1° (FWHM) resolution for a 511 keV incident gamma-ray. Actually, the angular resolution is deteriorated by the finite energy resolution of the detector and this effect is emphasized for low energy photon. For a 80 keV incident gamma-ray, as shown in Fig. 3.7, the angular resolution by energy uncertainty is roughly 5° (FWHM) even if 0.5 keV (FWHM) electronics noise is achieved. Special care to reduce noise level is required to obtain the angular resolution closing to Doppler limit for a low energy gamma-ray. While, for higher energy than \( \sim 300 \) keV, the contribution from the energy uncertainty becomes smaller, therefore, 1° angular resolution is feasible utilizing low Doppler broadening effect of Silicon material.
Figure 3.8: Compton DDCS for Silicon
Figure 3.9: Compton DDCS for Germanium
Figure 3.10: Compton DDCS for CdTe
3.5 Polarization Measurement

The radiation processes in high energy astrophysics, such as synchrotron radiation, bremsstrahlung or Compton scattering, generate polarized gamma-rays. However, all past and present gamma-ray detectors was not optimized to detect this polarization. The Compton camera suites to detect the polarized gamma-rays and will provide novel information for constraining emission geometries and magnetic field configuration.

For a linearly polarized gamma-ray, Klein-Nishina formula (Eq. 3.2) becomes:

$$\frac{d\sigma_{KN}}{d\Omega} = \frac{r_e^2}{2} \left( \frac{E'_\gamma}{E_0} \right)^2 \left( \frac{E'_\gamma}{E_0} + \frac{E_0}{E'_\gamma} - 2 \sin^2 \theta \cos^2 \eta \right)$$

where, $\eta$ is the angle between the electric vector of the incident gamma-ray and the azimuthal scatter angle. It can be seen that for any specific scattering angle $\theta$, the scattering provability is maximized when $\eta = \pi/2$, which means that the scattered photon prefers to be ejected at directions perpendicular to the polarization plane of the incident photon. To quantify the polarization information, the Q factor for an arbitrary angle $\phi$ and a given polarization vector angle $\phi_0$ is defined as

$$Q(\phi, \phi_0) = \frac{d\sigma(\phi - \phi_0)}{d\sigma(\phi + \pi/2 - \phi_0)}$$

$$= \frac{-\sin^2 \theta}{\frac{E_0}{E'_\gamma} + \frac{E'_\gamma}{E_0} - \sin^2 \theta} \cos(2(\phi - \phi_0))$$

The amplitude of the Q factor versus the scattering angle at different the incident gamma-ray energies is shown in Fig. 3.12. For a fixed incident gamma-ray energy, the amplitude of the Q factor is maximized when the scattering angle is slightly less than 90°. The maximum value is enhanced for lower gamma-ray energy. For the azimuthal direction,
the Q factor is maximized when $\phi$ is perpendicular to the polarization plane of the incident photon, and is minimized when $\phi$ is along the polarization plane. Therefore, the polarization direction and degree can be deduced from the measured phases and amplitude of the modulation ratio, respectively.

The larger amplitude of the Q factor has an advantage of polarization measurements because the polarization information can be derived even from low statistics data. But, in practice, the amplitude of the Q factor determined by a detector will be dependent upon several factors which will generally decrease its value from that calculated in the idealized case. These factors are, for example; (i) the physical configuration of the detectors; (ii) the presence of passive material; (iii) the energy thresholds of the detectors; (iv) background levels. Therefore, it is important to extract the proper events from data recorded in the detectors and to distinguish them with the background events. The Compton camera will suit with polarization measurements thanks to the significant background reduction with the Compton kinematics.

![Figure 3.12: The amplitude of the Q factor versus the scattering angle](image)
3.6 History of Compton camera

After the first concept for the Compton Camera proposed by Schönfelder et al (1975), a number of Compton telescope designs have been proposed, tested, and flown [42, 43, 7]. The success of these missions and the improvement in the technology over following twenty years lead to the launch of COMPTEL [4, 5, 6, 7, 8] onboard NASA's Compton Gamma Ray Observatory (CGRO) in 1991.

COMPTEL

A most successful application of utilizing Compton Scattering was the imaging Compton Telescope (COMPTEL). COMPTEL detects gamma rays by the occurrence of two successive interactions in the telescope: first a Compton scattering collision occurs in a detector of low-Z material (liquid scintillator NE213A) in the upper planar modules, then a second interaction takes place in a lower plane of detector module. High Z material, NaI(Tl), was used to absorb the scattered gamma-ray.

COMPTEL consists of an upper array of 7 liquid scintillation detectors and a lower array of 14 NaI scintillation detectors (Fig. 3.13). The two detector arrays are separated by a distance of 1.5 m. Each detector is entirely surrounded by a thin plastic scintillator which acts as an anticoincidence shield for charged particle rejection. In COMPTEL,
Time-of-flight methods are used to reduce the background events from high-energy neutrons. It covers the energy range from 0.7 to 30 MeV and has yielded significant breakthroughs in the field of the high energy astrophysics. With its large field-of-view of about 1 steradian different sources within this field can be resolved if they are separated by more than about 3 to 5 degrees. Its energy resolution of 5% to 10% FWHM is an important feature for gamma-ray line investigations. Within a 2-week observation period, it can detect sources that are about ten times weaker than the Crab.

Figure 3.14 shows All-sky map from COMPTEL in the 1–30 MeV range [13]. The concentration of the emission along the Galactic Plane was clearly resolved for the first time. It also generated the first all-sky map of the 1.8 MeV line from radioactive $^{26}$Al. In addition, COMPTEL succeeded in the first detection of the 1.156 MeV line from radioactive $^{44}$Ti from a supernova remnant Cas A.

From COMPTEL, we have learnt that the sky is rich in phenomena and objects that can be studied around 1 MeV. But, it is also true that with COMPTEL we could only see the tip of the iceberg. The achieved COMPTEL sensitivity was still modest. This becomes clearly evident, if the COMPTEL sensitivity is compared to the sensitivities so far achieved in the neighbouring X and high energy gamma-ray range. The SPI onboard INTEGRAL, which is latest coded mask instrument, also can not fill this sensitivity gap. It is now generally agreed that a next-generation sub-MeV/MeV instrument should have a sensitivity which is comparable to that achieved by GLAST sensitivity. There seems to be a world-wide agreement that such a step can only be obtained with and instrument, which is based on the Compton telescope principle.
Compton Cameras after COMPTEL

The Compton camera has been also developed in the field of medical imaging. Soon after the proposal by Schonfelder, Todd proposed that the Compton imaging device for medical application be used as an alternative to the mechanically collimated imaging system like an Anger camera [44, 45]. The first working prototype for medical imaging developed by Singh and Doria [46, 47] in early 1980s. The prototype replaced the conventional collimator with a High Purity Germanium (HPGe) detector in front of an Anger camera. With the development of semiconductor radiation detectors during 1980s and 1990, many Compton camera system followed the scheme proposed by Singh, which used semiconductor detector as the front-plane detector and scintillator detector as the back-plane detector. In 1993, Martin [48] proposed a ring Compton scatter camera which consists of a 4x4 array of HPGe detectors and a ring array of cylindrical NaI scintillators (Fig.3.15(a)). In 1998, LeBlanc et al. built a prototype Compton camera, C-SPRINT (Fig.3.15(b)), for nuclear medicine [49, 50, 51]. Instead of Germanium detector, C-SPRINT consists of 3x3x0.1 cm size Si pad detector that pixellated into 22x22 array. The performance study has been compared with mechanically collimated SPECT system. Although the noise equivalent sensitivity was limited at the low energy end such as the 140 keV gamma-rays from $^{99m}$Tc, it excels at higher energy band such as the 392 keV gamma-ray from $^{113m}$In.

The concept of multiple scattering Compton camera was proposed by Kamae [52] in 1988. It consists of many layer of thin Si strip detectors surrounded by a cylindrical CsI scintillator (Fig.3.15(c)). Two years later, Dogan et al. proposed to reconstruct the image using multiple scattering gamma-ray based on the Kamae’s design [53]. In 2004, Wulf et al. developed a Compton camera using three layer s of double-sided silicon strip detectors [54]. Reconstructed images and spectra from $^{137}$Cs and $^{57}$Co gamma-ray sources was obtained using multiple Compton technique proposed by Kroeger [55]. The energy spectrum for 662 keV gamma-rays that did not deposit their full energy in the instruments shows a peak at 662 keV with a FWHM of 27.6 keV. The reconstructed image of the source shows an angular resolution of 3.3° FWHM.

A Compton camera with a HPGe detector which features excellent energy resolution has been developed energetically. In 1994, McKisson et al [56] reported the result of a Compton camera that consists of eight HPGe coaxial detectors. It obtained $^{137}$Cs image at 1 meter from front plane and achieved fine energy resolution of 0.27 % at 662 keV and 0.30 % at 1333 keV. Tow years later, Phlips et al [57] built a Compton camera by using position sensitive HPGe double-sided strip detectors. By combining a 25x25 strip (2mm pitch) detector with a 5x5 strip detector (9mm pitch), they created a imaging system with 625x25 pixel combination. In 2001, Schmid et al [58] proposed original concept to develop a Compton camera with a single coaxial HPGe detector. The position information is obtained by way of a segmented outer contact and digital pulse-shape analysis. A significant improvement of detection efficiency can be achieved by employing a single large volume crystal (5x5 cm) and by detecting all full energy events that Compton scatter within detector. They demonstrated the ability to image the 662 keV gamma-ray from a $^{137}$Cs source with an angular resolution of 5° and a relative efficiency of 0.3 % [59] (Fig.3.15(d)). In 2007, Mihaiescu et al [60] developed the imaging system which consists of a single double-sided segmented planar HPGe detector with a depth measurement technic utilizing the pulse shape analysis. Combining this HPGe and a double-sided silicon strip detector, a Si/Ge Compton camera has been
CHAPTER 3. PRINCIPLE OF COMPTON CAMERA

developed \cite{61}. It achieved good angular resolution that are dominated by the intrinsic Doppler broadening, typically, less than 2° above 300 keV incident gamma-rays.

There are the Compton cameras which characterized by the capability of tracking recoil electrons in the field of MeV gamma-ray astronomy. Measuring the direction of the electron recoil in the first scatter can further restrict the initial photon direction to an arc segment on the Compton cone. The Advanced Compton Telescope (ACT) mission has been identified in the NASA roadmap as the next major step in gamma-ray astronomy \cite{62, 63}. The baseline of the detectors was chosen as a hybrid Si-Ge array, consisting of a 27 layer of 2 mm thick silicon detectors, situated immediately above a 4 layer array of 16 mm thick germanium detectors (Fig.3.15(e)). The ACT will probe the fires where chemical elements are formed by enabling high resolution spectroscopy and imaging of nuclear emission form supernova explosions.

Future missions

In recent year, the next mission with newly designed Compton Camera is planed in several groups beyond the COMPTEL. However, the only a handful missions are realizable within the next decade because of the difficulty of the developments of the new detector technologies for tracking the Compton scattering photon with high accuracy. One of the candidates is the Advanced Compton Telescope (ACT) mission \cite{62, 63}, also known as NACT \cite{64}, the Nuclear Astrophysics Compton Telescope, which investigates the nucleon synthesis with nuclear lines from a supernovae, as well. The other is the series of mission by our group, based on a Si/CdTe semiconductor Compton Camera which originally proposed and described in this thesis. The Si/CdTe semiconductor Compton camera adopted as the SGD (Soft Gamma-ray Detector) onboard ASTRO-H mission \cite{65, 66}, planed Japanese sixth x-ray astronomy satellite as a successor to the current Suzaku X-ray mission \cite{2}. In addition, the DUAL mission \cite{67}, combining the Compton camera with a Laue Lenses \cite{68} which is newly developed gamma-ray focussing lenses and allows high sensitive spectroscopy, is planning now. Not only operating as the focal plane detector of the Laue Lenses, the Compton camera act as detectors to serve all-sky survey in this mission.
3.6. HISTORY OF COMPTON CAMERA

(a) Martin [48]
(b) C-SPRINT [49, 50, 51]
(c) Multiple scattering Compton camera [52]
(d) Compton camera with a single coaxial HPGe detector [59]
(e) The Advanced Compton Telescope concept [63]

Figure 3.15: Traditional and future Compton camera
Chapter 4

Si/CdTe Semiconductor Compton Camera

4.1 Introduction

The energy band between 0.1 MeV and 10 MeV is poorly explored due to difficulties associated with the detection of such photons. Compton telescopes have the advantage of a large signal-to-noise ratio in an energy range where the backgrounds are intense on a space platform. The Compton telescope COMPTEL [4, 5, 6, 7, 8] on board CGRO demonstrated that a gamma-ray instrument based on the Compton scattering is useful for the detection of the gamma-rays in this energy band. In fact, the achieved sensitivity of COMPTEL above MeV is superior than that obtained by OSSE, a collimated phoswich detector, also onboard CGRO. Although COMPTEL performed very well as the first orbit-based Compton telescope for MeV gamma-ray astrophysics, it suffered from large background, poor angular resolution, and complicated image decoding. Also, the lower detection threshold is limited to ~750 keV due to the relatively high threshold of the scattering detectors (~50 keV). In order to fill the sensitivity gap (see Fig. 1.1) beyond COMPTEL, the innovative detector technology is definitely required.

In order to overcome this situation, our group proposed a new Compton telescope, in 2001 [69]. The telescope was based on an idea of Si/CdTe Compton Camera which uses our advanced technology of CdTe and Si imaging sensors, accumulated for last 10 years. In addition to the low background capability by utilizing the Compton kinematics, it features high spectral resolution (2 keV (FHWM) at 100 keV) and high angular resolution close to the theoretical limit defined by the Doppler broadening. Capability to measure gamma-ray polarization from the directional information of scattered gamma-rays is also attractive feature of a Compton camera.

Since then we have been working on the development of the Si/CdTe Compton Camera. Several key technologies had to be established before making the prototype.

4.2 Configuration of the Si/CdTe Compton Camera

The conceptual design of the Si/CdTe semiconductor Compton camera is shown in Fig. 4.1. The telescope is based on a hybrid semiconductor gamma-ray detector consisting of layers of thin Si and CdTe layers to detect photons in a wide energy band (0.05 - 1 MeV);
the Si layers are required to improve the performance at a lower energy band (< 0.3 MeV). In the stack of Si and CdTe layers, we require each event to interact twice, once by Compton scattering and then by photo-absorption. Once the locations and energies of the two interactions are measured, the Compton kinematics allows us to calculate the energy and direction (as a cone in the sky) of the incident $\gamma$-ray following the Compton equation.

The scattering part is very important in the Compton telescope. In order to cover a wide energy band and also to cover the wide scattering angle of the Compton interaction in the detector, the energy threshold of the detector must be low. Furthermore high Compton scattering probability is desirable to obtain a high efficiency as a Compton telescope. The properties of the semiconductors are summarized in Table 4.1. The combination of a low-Z material (Si) and a high-Z material (CdTe) is suitable to obtain the high detection efficiency. Since the cross section of Compton scattering of a Si becomes dominant above a 60 keV gamma-ray as shown in Fig. 4.2, the Compton camera works effectively even from the energy band below 100 keV. While, CdTe works very nicely as a absorption part thanks to the high photo-absorption cross section and high density. In order to surpass the performance of COMPTEL, we need to improve angular resolution as described in section 3.4.3, Si provides roughly 2–3 times higher angular resolution than Germanium or CdTe. The choice of Si would be best and required to obtain ultimate angular resolution closing to 1° above 500 keV gamma-ray.

Advantage of our Si/CdTe Compton Camera over other Compton Camera is that all components are made by semiconductor devices. For imaging devices, their good energy resolution and the ability to fabricate compact arrays or strips are very attractive features in comparison with inorganic scintillator couple to either photodiodes or photomultiplier tubes. In particular, the adoption of CdTe as absorbers is essential for the improvement of angular resolution by keeping detection efficiency.

The incident direction of a $\gamma$-ray is calculated from the position and the energy information of the interactions. Therefore, fine energy resolution is the key requirement for the semiconductor Compton telescope to retain a low background level with Compton kinematics. The energy resolution around 1 keV is required for both Si and CdTe detectors to approach the physical limit of the angular resolution due to Doppler broadening. In our stack configuration, the Compton scattering process in the detector can be precisely tracked with high accuracy for both position and energy measurements, leading the high angular resolution is realized.
4.2. CONFIGURATION OF THE SI/CdTe COMPTON CAMERA

The schematic view of the Compton events which detected in the Compton camera are illustrated in Fig. 4.3. Type A is a basic event. The incident gamma-ray is scattered in Si scatterer, then, absorbed its full energy in CdTe absorber. The direction of incident photon is reconstructed as a Compton cone. In the energy region above 1 MeV, the scattered electron tends to penetrate the thin Si detectors (Type B). In this case, Si works as a electron tracker. The direction of scattered electron can be measured and thus the direction of incident gamma-ray is restricted to an arc not to a cone. The more parameters of the incident gamma-ray can be obtained, the better the chances to reject background. In the case of Type C, the gamma-ray escapes from the detector after the second interaction. The measured energy of the scattered photon is always less than the correct energy, therefore, the Compton cone spreads than the correct one. Although this type of events can be eliminated if the energy of incident gamma-ray is known, it becomes a back-ground event (see below for another technique to handle these events). One idea to overcome this problem is to use the anti-coincidence measurements for the escape photon. If the incident photon is scattered at least three times in the detector (Type D), the Compton reconstruction is performed successfully regardless of whether the photon escapes or not, as

\[
E_0 = E_1 + \frac{E_2 + \sqrt{E_2^2 + 4E_2m_ec^2/(1 - \cos \theta_2)}}{2}
\]  

(4.1)

where, \(E_0\) is the energy of incident gamma-ray, \(E_1\) is energy deposit in first scattering, \(E_2\) is energy deposit in second scattering and \(\theta_2\) is the scattering angle determined from the interaction positions. This concept called the Multiple Compton Method, which was originally proposed by Kamae et al. (1987) [52], is very attractive. The idea of using silicon strip detectors stimulated new proposals for the next generation Compton telescope [62, 63, 70]. In this technique, a stack of many thin scatterers is used to record the Compton scatterings. The order of the interaction sequences, hence the correct energy and direction of the incident photon, can be reconstructed by examination of the energy-
Table 4.1: Properties of the semiconductors

<table>
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<th>semiconductor</th>
<th>density [g/cm$^3$]</th>
<th>$Z$</th>
<th>$E_{\text{gap}}$ [eV]</th>
<th>$\epsilon$ [eV]</th>
<th>$X_0$ [cm]</th>
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<td>1.6</td>
<td>4.6</td>
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<td>2.13</td>
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</tr>
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<td>31, 33</td>
<td>1.42</td>
<td>4.3</td>
<td>2.29</td>
</tr>
</tbody>
</table>

$E_{\text{gap}}$: band gap energy  
$\epsilon$: an ionization potential  
$X_0$: radiation length

momentum conservation for all possible sequences. This technique is very powerful to suppress background.

In the energy region above 10 MeV, pair production becomes the dominant process (see Fig.4.2). A stack of thin CdTe detectors has the potential to realize a new detector concept, an “active pair-production telescope” [71]. CdTe has a radiation length of 1.52 cm. A thickness of 0.5 mm of CdTe layer correspond to 0.03 r.l, which is almost same as the thickness of Tantal of Tungsten sheet used in the EGRET or LAT detectors. If we prepare 80 layers of CdTe with a thickness of 0.5 mm, we will have 2.6 r.l in total. Since each layer acts both as a converter and a tracker, the detector is very efficient at detecting pair-production events, especially for energies below 100 MeV, where energy information would be lost in passive material in the conventional pair-production telescopes which used the passive material as a converter.
Figure 4.2: The Attenuation Coefficient for Si and CdTe

Figure 4.3: Schematic view of the Compton events in Si/CdTe Compton camera. See the text for details.
4.3 Development of Key Technologies

The high energy resolution of the detectors is required in order to establish a Compton camera which works in sub-MeV energy band, from several tens keV to MeV. As shown in Fig. 3.7, at least 2 keV (FWHM) noise level is required to obtain $\sim 1^\circ$ angular resolution for the incident gamma-ray above 500 keV. We have originally developed both Si and CdTe detectors in order to derive ultimate performance from a Compton camera. The leading-edge technologies such as low noise Analog ASICs and high package density technique were applied.

As a scattering part, we have developed the double-sided silicon strip detector (DSSD) in collaboration with Hamamatsu Photonics, Japan. This device was historically created to track charged particles in particle physics. The basic geometry of the strip, which includes orthogonally implanted n and p strips on both sides of the detector, provides two-dimensional coordinate measurements of the position of the Compton scattering. An issue for applying to the sub-MeV Compton camera is noise performance. The signal generated by a recoil electron is much smaller than that made by a charged particle. For this reason, we wished to minimize electrical noise in the DSSD and read-out electronics. The geometry of the detector including a strip pitch, gap and detector thickness was carefully optimized because the input capacitance is the greatest contributor to this problem [72, 73]. Moreover, to realize low noise read-out from both P and N side, we utilized the DC coupling read-out for both side. To apply a reverse bias voltage, the N-side circuit as a whole is biased. We achieved 1.2 keV FWHM energy resolution of P-side and 2.8 keV of N-side with a 2.56 cm wide detector of 300 $\mu$m thickness [74].

CdTe has been regarded as a promising semiconductor material for hard X-ray and gamma-ray detection since the early 1970's. The high atomic number and density of the materials gives a high stopping power suitable for a detector operation typically in the 10-500 keV. However, a considerable amount of charge loss in these detectors produces a reduced energy resolution. This problem arises due to the low mobility and short lifetime of holes, typically $\mu_h\tau_h \simeq 1 \times 10^{-4}$ cm$^2$/V. We have succeeded to achieve high energy resolution CdTe diode detector. A high Schottky barrier formed on the In/p-CdTe interface lead us to the operation of the detector as a diode. As a result, the leakage current is suppressed under a bias of as high as 1 kV. The leakage current of the 2 mm $\times$ 2 mm detector of thickness 0.5 mm was as low as 10 pA at 20°C with a bias voltage of 500 V. We demonstrated good FWHM energy resolution of 1.1 % and 0.8 % at energies 122 and 511 keV, respectively [75].

Another key technology achieving the required energy resolution is low noise front-end electronics. In addition, the semiconductor Compton camera requires many channels read-out to obtain sufficient position resolution for precise tracking the scattered photon. We have developed the ASIC (application specific integrated circuit) VATA series in collaboration with Gamma Medica-Ideas, Norway. Firstly, we developed the VA32TA [76] based on the design of the VA32C amplifier VLSI and TA32C trigger VLSI that are originally developed by Ideas. It consists of 32 channel of signal read-out. Each channel includes a charge sensitive preamplifier, slow CR-RC shaper, sample/hold and analog multiplexer chain (VA section), and fast shaper and discriminator chain (TA section). The typical noise performance is 50e$^-$ at 0 pF load and 170e$^-$ at 10 pF load with 2 $\mu$s shaping time. With a 4 cm wide and 300 $\mu$m thick DSSD, the energy resolution of 1.5 keV (FWHM) is obtained. As a next step, we developed VA64TA which is expanded into 64 channel inputs. The geometry of the front-end FET and shaping time has been...
optimized. Recently, we developed VA32TA6 which includes on-chip ADC circuitry. We have successfully made VA32TA6 work and have obtained digital pulse height data. The spectral performance is comparable with that of VA64TA.

4.4 Application of Si/CdTe Compton Camera to Future Missions

4.4.1 Soft Gamma-ray Detector (SGD)

The ASTRO-H mission [65, 66], also known as NeXT mission, is a Japanese sixth x-ray astronomy satellite planned to launch in 2013 as a successor to the current Suzaku X-ray mission [2]. The Soft Gamma-ray Detector (SGD) is a soft gamma-ray detector with a 10–600 keV energy range and sensitivity at 300 keV, more than 10 times better than the Suzaku HXD (Hard X-ray Detector) [77, 78, 79]. It outperforms previous soft gamma-ray instruments in background rejection capability by adopting a new concept of narrow FOV Compton telescope. In order to lower the background dramatically and thus to improve the sensitivity as compared the HXD, we mount the Si/CdTe Compton camera inside the bottom of a well-type active shield. Above ~50 keV, we can require each event to interact twice in the stacked detector. Once the locations and energies of the two interactions are measured, the Compton kinematics allows us to calculate the energy and direction of incident gamma-ray by the Compton equation.

The major advantage of employing a narrow FOV is that the direction of incident $\gamma$-rays is constrained inside the FOV. If the Compton ring does not intercept the FOV, we can reject the event as background. Most backgrounds can be rejected by requiring this condition (albeit with an corresponding reduction in instrument effective area). Background photons from the BGO and copper collimator for which the reconstructed Compton ring intersects the FOV, cannot be eliminated if there is no signal detected in the active shield, however this source of background contributes only within a limited range of scattering angle. The concept of a narrow FOV Compton telescope is expected to reduce drastically the background from radio-activation of the detector materials, which is a dominant background in the case of the HXD.

As shown schematically in Fig. 4.4, the telescope consists of 32 layers of 0.6 mm thick Si pad detectors and eight layers of thin CdTe pixelated with a thickness of 0.75 mm. The sides is also surrounded by two layers of CdTe pixel detectors. The opening angle provided by the fine collimator is 0.5 degree and by the BGO shield is ~10 degree at 500 keV, respectively. As compared HXD, the shield part is made compact by adopting the newly developed avalanche photodiode. An additional copper collimator restricts the field of view of the telescope to 30' for low energy photons ($<100$ keV) to minimize the flux due to the Cosmic X-ray Background from the FOV. These modules are then arrayed to provide the required area. We will have two SGD detectors each consisted of four units. Each detector will be mounted separately on two sides of the satellite. It should be noted that when the Compton condition is not used (Photo absorption mode), the stacked Si pad can be used ad an usual photo absorption type detector with the total thickness of 20 mm of silicon. The detector then covers from 10 keV as a collimator-type gamma-ray detector. The effective area of the SGD is $>30$ cm$^2$ at 150 keV in the Compton mode and $>200$ cm$^2$ at 30 keV in the Photo absorption mode. Since the scattering
angle of gamma-rays can be measured when we reconstruct the Compton scattering in the Compton camera, the SGD will also be sensitive to the polarization of the incident gamma-rays.

### 4.4.2 DUAL Mission

Focusing instruments have two tremendous advantages: first, the volume of the focal plane detector can be made much smaller than for non-focusing instruments, and second, the residual background, often time-variable, can be measured simultaneously with the source, and can be reliably subtracted. The DUAL mission, which is based on the concept of Laue gamma-ray lens is very promising approach to extend the focusing capability above several hundred keV to reality \cite{67}.

In order to achieve the ultimate sensitivity for the DUAL mission, the focal plane detector should be designed very carefully. A Compton telescope is a good solution, because the direction of incident gamma-rays could be determined by the Compton reconstruction and therefore effective in discriminating gamma-rays coming from the lens. However, the angular resolution limited by the Doppler broadening is 2.5 degrees for 511 keV and also the ordering of interactions has to be solved before we determine the direction of incident gamma-rays.

The concept of the narrow FOV Compton telescope realized with an active collimator made of BGO scintillator and a stack of Si/CdTe detector is a very attractive solution as the focal plane detector of the gamma-ray lens experiment \cite{80}. The FOV of the active collimator is determined such that it only sees the gamma-ray lens. With this, all we can assume is that the signal gamma-rays come from the FOV of the collimator, and others can be rejected as background. Furthermore a thick BGO scintillator shields gamma-rays from other directions and also reduces the background due to activation in the BGO scintillator itself. This is quite important, because the 511 keV line from the $\beta^+$ decays becomes a major background source for the study of annihilation lines from...
the celestial objects. The fact that the Si/CdTe Compton telescope can be operated at moderate temperatures of 0 to −20 degrees makes the design of the shield easy for satellite applications. The compact design of a stack of Si and CdTe detectors also helps, because, if the volume of the shield becomes large, the dead time caused by the shield becomes significant.

The Si/CdTe Compton Camera could be used for both a focal plane detector and additional detectors for all sky survey mounted in the detector satellite. With this configuration, γ-ray sky is monitored to find interesting sources, and then, we could point the γ-ray lens to obtain data with high angular resolution of the lens.

**All sky survey mode**

Over its lifetime, the proposed mission should produce all sky surveys in the energy range of hard X and soft gamma-rays: i.e. 60 keV to 2 MeV: mapping out in detail the extended distributions of galactic positron annihilation radiation, and of various long-lived cosmic radio activities; surveying a very large sample of galactic and extragalactic compact sources by characterizing their nonthermal spectra, and study their variability on all timescales; constraining the origin of soft gamma-ray cosmic background radiation.

**LLT mode**

Simultaneously to the all-sky survey, a number of selected compact sources shall be observed at gamma-ray lines of highest astrophysical relevance with a narrow line sensitivity of the order of a several $10^{-7}$ ph s$^{-1}$ cm$^2$ – i.e. the 511 keV positron annihilation and the 847 keV radioactive decay line of $^{56}$Co – by measuring the intensities, shifts and shapes of their gamma-ray lines. An energy resolution of 1% is sufficient to address most of the DUAL science goals. Continuum spectra are generally rather smooth, and gamma-ray lines expected from explosions are generally kinematically broadened.

Gamma-ray emission may be substantially polarized due to the non-thermal nature of the underlying emission processes. Studying not only the intensity and the spectrum but also the polarization of the emission will add a new powerful scientific dimension to the observations. Such measurements will allow the discrimination between the different plausible emission processes at work, and will constrain the geometry of the emission sites. A sensitive measurement of the polarization is not only required for the above mentioned populations of compact sources, but will be of capital interest for the study of the prompt emission of gamma-ray bursts.

Based on the scientific goals presented above, the DUAL mission requirements are summarized in Table 4.4.2. The major requirement for the next generation gamma-ray mission is a significant improvement in sensitivity, by at least an order of magnitude with respect to existing instrumentation.
CHAPTER 4. SI/CDTE SEMICONDUCTOR COMPTON CAMERA

Figure 4.5: The DUAL mission concept

Table 4.2: DUAL mission requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>target (LLT)</th>
<th>allsky (CAST)</th>
</tr>
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<tr>
<td>Energy coverage</td>
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<td>60 keV – 2 MeV</td>
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<tr>
<td>Cont. sensitivity ($\Delta E/E = 1/2, 3\sigma$)</td>
<td>$10^{-8}$ ph cm$^{-2}$ s$^{-1}$ keV$^{-1}$ in $10^6$ s</td>
<td>few $10^{-8}$ ph cm$^{-2}$ s$^{-1}$ keV$^{-1}$ in 2 y</td>
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<tr>
<td>Line sensitivity ($\Delta E/E = 3 %$)</td>
<td>$10^{-6}$ ph cm$^{-2}$ s$^{-1}$ in $10^6$ s</td>
<td>$10^{-6}$ ph cm$^{-2}$ in 2 y</td>
</tr>
<tr>
<td>Energy resolution (FWHM)</td>
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<td>1 %</td>
</tr>
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<td>3$\pi$ steradian</td>
</tr>
<tr>
<td>Angular resolution</td>
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<td>1 degree</td>
</tr>
<tr>
<td>Timing</td>
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<td>100 $\mu$s</td>
</tr>
<tr>
<td>Polarimetry (MDP, 3$\sigma$)</td>
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<td>5 % for 100 mCrab</td>
</tr>
</tbody>
</table>
Chapter 5

Development of Si/CdTe Compton camera

5.1 Required technologies

The Si/CdTe semiconductor Compton camera has been established by three technologies (Fig. 5.1); high energy resolution CdTe pixel detectors, high energy resolution Silicon strip detectors, and finally low noise and low power analog ASICs.

Our approach is to modularize the Si and CdTe detector with same electronic interface, which allows us to integrate them into a Compton camera easily. The analog ASIC is the key to realize this concept because the camera consists of many channels \(10^3 - 10^5\) from imaging detectors to precisely track scattered photons in the detector. In addition, the low noise characteristic is critical to achieve high angular resolution (see Chapter 3). We have developed VATA front-end ASIC in collaboration with Gamma Medica-Ideas, Norway. A detailed description of VATA ASIC is described in Appendix A.

In this chapter, we present our development of the first prototype of the Compton camera which can be used for practical experiments. Development of two main detectors, the Double-sided silicon strip detector (DSSD) and In/CdTe/Pt pixel detector, are described.

Figure 5.1: Key technologies for the Si/CdTe Compton camera
5.2 Double-sided silicon strip detector (DSSD)

5.2.1 Design

We have developed the DSSD in collaboration with Hamamatsu Photonics, Japan [72, 74, 81]. Cross-sectional view of the DSSD is shown in Fig. 5.2. Highly doped p-type silicon strips (p+: yellow) and n-type silicon strips (n+: black) are implanted orthogonally to provide two-dimensional coordinate measurements. Each n+ strip is surrounded by a floating p+-doped implantation to be isolated from any adjacent strips. Aluminum (Al) electrodes are directly coupled on each strip with ohmic contact.

The DSSD geometry is carefully optimized to minimize strip capacitance, since the strip capacitance is generally larger than the pixel capacitance due to a large inter-strip capacitance. A wider strip gap reduces the strip capacitance, but also causes high electric field concentration at the edge of the p-n junction. We impose an upper limit of 100 µm on the strip gap in order to avoid possible junction breakdown. Similarly, the optimization of the thickness of the DSSD is a trade off between the interaction efficiency and the depletion voltage. We developed 2.56×2.56 cm and 4×4 cm wide DSSD with detector thickness of 300 µm and 500 µm. The strip pitch is 400 µm for all detectors. The full depletion voltage estimated by a device simulation is 70 V and 200 V for 300 µm and 500 µm thick DSSD, respectively. Results of the test for investigating the basic performance such as the leakage current and the capacitance is described in Appendix B.

![Figure 5.2: Cross section view of the DSSD](image-url)
5.2. DOUBLE-SIDED SILICON STRIP DETECTOR (DSSD)

5.2.2 Imaging and Spectroscopy

Setup

We present the performance for imaging and spectroscopy with 4 cm wide and 300 µm thick DSSD in this section. The detector was operated under 100 V bias voltage at a temperature of −10°C. We show a photograph of the DSSD read-out system in Fig. 5.3 and its schematic diagram in Fig. 5.4. The DSSD is mounted on the structure made of aluminum ceramic and read out with specially designed low noise analog ASIC, VA32TAs. Total of six VA32TAs are daisy-chained and controlled by “VADAC controller” developed by IDEAS. The VA32TA has an input of 32 channels and can be used in both positive and negative input charge. The p-strip are directly connected to the ASIC inputs while n-strips are connected via RC-bias chips from which a positive bias is applied to the DSSD. The RC-bias chip is made of 32 sets of polysilicon bias registers of 5 GΩ and coupling capacitances of 50 pF. This read-out system degrades the noise performance on n-strips due to extra components associated with the AC coupling. The solution to avoid the degradation is presented in the following section 5.2.3.

![Figure 5.3: Photo of the 4 cm wide DSSD](image_url)
CHAPTER 5. DEVELOPMENT OF SI/CDTE COMPTON CAMERA

Figure 5.4: Schematic diagram of the read-out system

Performance

Figure 5.5 shows a $^{133}\text{Ba}$ line image in the energy band from 20 keV to 40 keV. The interaction position is determined by the cross point of strips that give maximum pulse height of P-side and N-side strips. The classic-style car mask, made of 0.3 mm thick brass, was mounted 3 mm above the DSSD. The position resolution is confirmed to be consistent with the strip pitch of 400 $\mu$m. Fig. 5.6 is the flat image in the energy range from 20 to 40 keV. The left panel is the projection to the N-side strips and the bottom panel is that of the P-side strips. The counts measured from the strips located at the edge of the detector are 5–9% less than other strips, due to the different operating condition resulted from different electric potential at the edge. We fitted the distribution of the projected counts by a constant without the edge strips. The reduced $\chi^2$ is 0.88 in P-side and 1.01 in N-side (d.o.f is 62). The flatness of the DSSD is demonstrated under the statistics in this experiment. This indicates that the depletion layer is developed uniformly and signal charge is efficiently collected everywhere.

Figure 5.5: A shadow image ranging from 20 to 40 keV X-ray irradiated $^{133}\text{Ba}$.

The left panel of Fig. 5.7 shows the sum of the $^{241}\text{Am}$ energy spectrum for all 96 strips.
5.2. DOUBLE-SIDED SILICON STRIP DETECTOR (DSSD)

Figure 5.6: The flat image in the rage from 20 to 40 keV on p strips. The shaping time of the RC-CR shaping amplifier was set at 4 µs. The energy resolution was 1.5 keV (FWHM) for 60 keV photo peak, which is almost consistent with the value calculated from the VA32TA noise performance and input capacitance of 12.2 pF (see Appendix B). We also investigate the energy resolution as a function of the shaping time. By changing the shaping time, we could figure out sources of the noise. The result is shown in the right panel of Fig. 5.7 with the estimated values from the preamplifier noise, shot noise by leakage current, and statistical noise. The curve derived from the experimental data is reproduced by the noise estimations. The dominant component is found to be the preamplifier noise due to a large input capacitance (12.2 pF). Therefore, when we develop a larger size DSSD than 4 cm wide as a next step, the design which reduces the load capacitance is essential to achieve the same noise level obtained here.
Figure 5.7: (Left) a spectrum of P-side irradiated $^{241}$Am at a temperature of $-10^\circ$C. (Right) Shaping time vs energy resolution. The capacitance noise is dominant.
5.2. **DOUBLE-SIDED SILICON STRIP DETECTOR (DSSD)**

### 5.2.3 High density stacked DSSD module

As a scattering part of the Compton camera, a high Compton scattering probability is important to obtain a high detection efficiency. Furthermore, in order to be hermetically and symmetrically enclosed by absorbers, the scattering part needs to have a compact structure. Here, we investigate the method to stack DSSDs.

![Photograph of a DSSD board](image1)

![Photograph of the DSSD stack module](image2)

Figure 5.8: High density stacked DSSD module

A photo of the newly developed DSSD board is shown in Fig. 5.8(a). The DSSD used here is a 2.56 cm wide and 300 µm thickness. It consists of one DSSD and two low-noise, low-power consumption VA64TAs which is expanded into 64 channel input, mounted on a small circuit board. In order to reduce the interaction in the passive material, the support structure is made of plastic instead of Al₂O₃ ceramic. The average thickness of the support in the horizontal direction is 1.4 g/cm².

![Schematic diagram of the floating read-out](image3)

Figure 5.9: Schematic diagram of the floating read-out

In order to lower the energy threshold as low as possible, low-noise read-out is needed on both P-side and N-side strips of the DSSD. This is because we need both the P-side
and N-side signal to obtain two-dimensional position information. A set of a decoupling capacitor and a resistor introduces noise. Thus, a DC-coupled read-out which has an advantage to achieve low noise is employed for both sides. The schematic diagram of the floating read-out is illustrated in Fig. 5.9. To apply a reverse bias, the N-side circuit board is biased as a whole. The decoupling is held on a digital isolator after the analog signal is digitalized by the ADC. In addition to the improvement of the noise performance of N-side, this system enables to stack DSSDs with a stack pitch of as short as 2 mm because it does not need decoupling capacitors in front-end.

![Figure 5.10: Schematic diagram of the four-layer stacked DSSD module](image)

Based on new DSSD boards, a four layer stack of the DSSD module is constructed. Figure 5.8(b) is the photograph of the DSSD stack module. The schematic diagram of the whole read-out system is illustrated in Fig. 5.10. Four DSSD board are daisy-chained via a pin array for the interconnection and stacked with a 2 mm pitch. Each side has the same read-out board, the Inter Face Card (IFC), which controls the read-out sequence. The IFC interchanges the digital signal with the external system via the ultra fast digital coupler with 2000 V tolerance.

In Fig. 5.11, the sum spectra of both P-side and N-side in each layer are shown. The energy resolution at 59.5 keV is obtained to be 1.6 keV (FWHM) in P-side, which is about 0.3 keV larger than the expected value calculated from VA64TA noise performance and the input capacitance of the DSSD. The difference is explained by the capacitance reside in pitch adapter between the DSSD and ASIC input pads since we observed 1.2 keV (FWHM) for the channels with a short pitch adapter. In spite of the effect of the pitch adapter capacitance, we recognize an improvement of N-side energy resolution from 3.8 keV to 2.8 keV (Fig. 5.11 right panel), compared with AC-coupled read-out with a RC chip. The noise on the N-side is still larger than what was expected from the ASIC performance and the total capacitance load. The origin of this excess noise component is under investigation.
5.2. DOUBLE-SIDED SILICON STRIP DETECTOR (DSSD)

Figure 5.11: Sum spectrum for each layer (left: P-side, right: N-side)
5.3 In/CdTe/Pt CdTe pixel detector

Based on the high energy resolution In/CdTe/Pt Schottky diode \([82]\) (see Appendix C), we have developed a CdTe pixel detector which features the high energy resolution together with the high position resolution from a few mm down to a few hundreds \(\mu\text{m}\) \([83]\). The indium side is used as the common electrode and Platinum electrode is pixelated. After a thin layer of gold is evaporated on the Pt side, a metal pattern for pixels is etched on it.

Figure 5.12 is a photograph of one CdTe pixel detector module. The CdTe detector is stud-bumped (see Appendix C) on the ceramic fanout board and has has 8\(\times\)8 geometry with 1.35\(\times\)1.35 mm\(^2\) size pixels. The gap between the pixels is 50 \(\mu\text{m}\). A 1 mm-width guard-ring electrode surrounds the pixel electrodes. The thickness of the pixel detector is 500 \(\mu\text{m}\). The signals from each pixels is fed into the VA64TA ASIC on-board the FEC from the fan-out board via wire-bonding. Figure 5.13 shows \(^{57}\text{Co}\) spectrum summed over 64 channels under the bias voltage of 600 V and at temperature of 20 \(\text{°C}\). The energy resolution was obtained to be 2.0 keV (FWHM) at 122 keV. Figure 5.14 shows the count map for 122 keV gamma-ray from all 64 pixels. We integrated the counts from each pixel in the energy window from 115 keV to 125 keV. The count distribution is shown in Fig. 5.14(b). The variation of the distribution obtained to be 3.3 %, which is consistent to the statistical error of 3.0 %. This ensures the good uniformity of the CdTe crystal and the stable connection with stud-bump method without considerable damage.

![Figure 5.12: Photograph of one CdTe pixel detector module](image-url)
5.3. IN/CdTe/PT CdTe PIXEL DETECTOR

Figure 5.13: $^{57}$Co sum spectrum obtained with the In/CdTe/Pt pixel detector. The applied bias voltage is 600 V, and the operating temperature is 20 °C.

Figure 5.14: (a) Count map of a 8×8 CdTe pixel detector irradiate with 122 keV gamma-rays. (b) its count distribution
5.3.1 Multi layer stacked CdTe module

Although the 500 µm thickness CdTe detector demonstrated at previous section provides sufficient detection efficiency as a hard X ray imager (100 % up to 40 keV, 60 % at 80 keV), it is not enough as an absorption part of a Compton camera which intends for up to several hundreds keV gamma-rays. The approach to increase the detector thickness is an attractive solution, but it could degrade the position resolution in the depth direction of the detector. Moreover, the good energy resolution with a thick CdTe diode would be difficult to achieve because the bias voltage required for the complete charge collection scales with the second power of the detector thickness. We, therefore, adopted the idea of a stacked detector, in which several thin CdTe diode are stacked together and operated as a single detector module. The idea of stacked CdTe detector itself has been demonstrated previously by using non imaging CdTe sensors [84, 85]. Here, we describe the first CdTe stacked detector with imaging capability.

![Photo of four layer stacked CdTe module](image)

![133Ba spectrum obtained in CdTe stack module](image)

Figure 5.15: (a) Photo of four layer stacked CdTe module. (b) $^{133}$Ba spectra obtained in CdTe stack module. The achieved energy resolution is 2.0 keV (FWHM) at 81 keV at -10 °C.

Figure 5.15(a) shows the photograph of the multi layer stacked CdTe module which consists of 4 layer structure with a 2 mm pitch. One layer consists of four 0.5 mm thick CdTe pixel detectors configured in 2×2 geometry, and two Front End Cards on which a total of four VA64TAs are mounted. Figure 5.15(b) shows $^{133}$Ba spectrum obtained in each layer at a bias voltage of 600 V and at temperature of −10 °C. The energy resolution of 2.0 keV (FWHM) is achieved at 81 keV and that of $\Delta E/E \sim 1$ % for a few hundred keV. Under these conditions, no significant degradation in spectrum performance was observed during continuous operation of up to two weeks.
5.4 Prototype of Si/CdTe Compton camera

5.4.1 Objective
By combining the 4-layer stacked DSSD module (Fig. 5.8) and the 4-layer stacked CdTe module (Fig. 5.15(a)), we constructed a Compton camera for a balloon borne experiment [86]. We aim at the ultimate low background observation by placing the Compton camera on the focal plane of a hard-Xray super mirror [87]. The conceptual view of this experiment is illustrated in Fig. 5.16. In addition to the significant improvement of the signal-to-noise ratio by focussing, the events recorded in the detector are reconstructed by the Compton equation and the direction of incident gamma-ray is calculated for event by event. If the Compton cone does not intercept the direction of the super mirror, one can reject the event as background. The high sensitivity will be realized by those effects brought about by the new combination of a Compton camera and a supper mirror.

Figure 5.16: The conceptual view of the balloon experiment

5.4.2 Detector configuration
Figure 5.17 is the photograph of the Compton camera, and the whole configuration and cross section view are shown in Fig. 5.18. We used forty VA64TAs for the read out of the total of 2560 detector channels. The gap between the DSSD module and the CdTe stack module is 14.4 mm. In addition to the bottom part of the CdTe detectors, the CdTe side modules cover horizontal direction of the DSSD module. Since the energy of recoil electron is larger for larger scattering angle, the CdTe side module significantly improves the detection efficiency around 100 keV, which are difficult to detect in the DSSD–CdTe bottom combination because of very small energy deposit in the DSSD. With this configuration, Compton events with scattering angle from 0° to 68° are detected in the DSSD–CdTe bottom combination and 79° to 107° are in DSSD–CdTe side combination when incident photons are along the Z-axis. Assuming on the 5 keV detection threshold of the DSSDs, incident gamma-ray down to 48 keV can be reconstructed in this system.
CHAPTER 5. DEVELOPMENT OF SI/CdTe COMPTON CAMERA

Figure 5.17: Photo of a Compton camera for a balloon experiment

Figure 5.18: (Left) Whole configuration of detectors and support material. DSSDs are drawn with yellow line and CdTe pixel detectors with green. (Right) Cross section view of detectors
5.4. PROTOTYPE OF SI/CDTE COMPTON CAMERA

5.4.3 Read-out System

For balloon experiment

The schematic diagram of the read-out system for balloon experiment is shown in Fig. 5.19. The data acquisition, command control and communication with balloon telemetry system are performed by small-sized computer called SpaceCube [88] and interface boards based on Space-Wire network interface, which is adopted as the next generation network protocol for onboard detector on satellite.

The 28 V power supply from balloon system is converted by a DC-DC convertor and provides an analog and digital power in our system. Total power consumption is $\sim 13$ W.

In the DSSD part, two low ripple DC-DC convertors and one H.V. module are mounted to provide power for the floating read-out electronics (see Fig. 5.9).

The Compton camera is shielded by 2 cm thick CsI(Tl) scintillator in order to reject background signals generated by the atmospheric gamma-ray or charged particles. The scintillation light of CsI(Tl) is gathered and amplified via the large area $(1 \text{ cm}^2)$ Avalanche Photo Diode (APD). The signal from the APD is amplified by 8 ch Pre-Amp Board optimized for large input capacitance load of a few hundreds pF and fed into 8 ch Shaper Board in which the veto signal is generated. The veto signal is sent to the SpW DIO Board and used as control bit of read out sequence.

For ground experiment

First, the ground calibration test was performed with substitute readout system shown in Fig. 5.20. The readout system is divided into six groups: DSSD Pside, DSSD Nside, CdTe-A, CdTe-B, CdTe-C and CdTe-D. In the CdTe groups, the eight VA64TA1s are arranged in a daisy-chaine configuration, while in DSSD group the four chips are daisy-chained. The read-out sequence of each group is controlled by a dedicated Read Out CTL Unit (ROU). The ROU starts the readout sequence by using an external read start trigger. The event trigger from the Compton camera is fed to the TRIG CTL Unit (TCU) that consists of NIM modules in this version. In order to measure the absolute detection efficiency, the dead-time counter is mounted inside and measures the interval of busy signal of ROU during which the triggers of detector is ignored. In the TCU, a coincidence judgment can be made between the trigger of DSSD and that of CdTe for the effective acquisition of data on Compton events. The coincidence judgment output is then returned to the ROU as a read start trigger. Since this trigger is sent to all ROUs, the pulse heights of all channels are acquired for a coincidence event. The pulse heights converted into digital data in the ROU are then sent to DATA&Command Unit controlled by a PC via the VME bus.
Figure 5.19: A schematic diagram of the read-out system for balloon experiment
5.4. PROTOTYPE OF SI/CdTe COMPTON CAMERA

5.4.4 Analysis

We evaluated the performance of Compton reconstructions utilizing various incident photon energies, including 59.5 keV ($^{241}$Am), 81 keV ($^{133}$Ba), 122 keV ($^{57}$Co), 356 keV ($^{133}$Ba) and 511 keV ($^{22}$Na). The RI sources are irradiated from the direction of the Z–axis, placed at 350 mm above the top of the Compton camera. The system is operated at temperature of −20°C.

We first selected two-hit events such that one is detected in the DSSD module and the other in the CdTe parts, with energy thresholds of 5 keV and 10 keV for the DSSDs and the CdTe detectors, respectively. Figure 5.21 shows 2-dimensional scatter plots of the events in the particular cases of $^{133}$Ba and $^{241}$Am. The X–axis shows the deposit energy in CdTe ($E_{\text{CdTe}}$) and the Y–axis shows that in DSSD ($E_{\text{DSSD}}$). We present the events derived from the DSSD–CdTe bottom combination with black plots and the DSSD–CdTe side combination with red plots (Fig. 5.21(a)). The events that incident gamma-rays are scattered in the DSSD and then fully absorbed in the CdTe detector distribute in the region where the sum of the energy deposit $E_{\text{DSSD}}+E_{\text{CdTe}}$ equals to the incident energy. The branch on a parallel with the horizontal axis which has $E_{\text{DSSD}}$ between 20 keV and 35 keV consists of the fluorescence X-ray events from CdTe, where X-rays from Cd ($K_{\alpha}: 23.1$ keV, $K_{\beta}: 26.1$ keV) and Te ($K_{\alpha}: 27.4$ keV, $K_{\beta}: 31.0$ keV) escape from the CdTe detector and then are absorbed in the DSSD.

We also showed the region with arrows and dashed lines in Fig.5.21, where the Compton scattering events should exist, when we take our detector configuration into consideration. Since the CdTe bottom and CdTe side parts cover different scattering angle, the black and red plots distribute in the different region partitioned by dashed lines. As clearly shown in the case of $^{133}$Ba, the events with a total energy deposit equal to 356 keV are distributed within the region for both bottom and side combination. For a
low energy such as 59.5 keV, we can still detect Compton events from the DSSD–CdTe side combination, while the events that energy deposits occur in the DSSD–CdTe bottom combination are not detectable because they are distributed under the threshold of DSSD set to 5 keV.

The analysis to investigate Compton camera performance is held according to flowchart illustrated in Fig. 5.22. From all two hit event, we excluded the events which have $E_{\text{DSSD}}$ from 20 keV to 35 keV because this region is contaminated by fluorescence X-ray events from CdTe detector. In order to evaluate the angular resolution and its dependence on the energy of incident photon, we selected the events that total energy deposit is within the energy window determined for each line energy (Energy window cut). After that, we reconstructed the events according to Compton Equation on the assumption that incident gamma-ray is scattered in the DSSD and then absorbed in the CdTe. The result is shown in following section 5.4.5. On the other hand, the spectral performance is tested by ARM window cut. We selected the events that have a calculated ARM within $\pm 2 \times \text{FWHM}$. The full deposited Compton events are enhanced utilizing this selection. The result is presented in section 5.4.6.
5.4. PROTOTYPE OF SI/CdTe COMPTON CAMERA

5.4.5 Image Reconstruction

To investigate the angular resolution, we adopted the Angular Resolution Measure (ARM) described in section 3.4.1. First, we extracted the events which have total energy range 346–366 keV for 356 keV photon and 57–63 keV for 59.5 keV photon from the two-dimensional scatter plots shown in Fig. 5.21. Similarly, we used 76–86 keV for 81 keV, 117–127 keV for 122 keV, and 501–521 keV for 511 keV in other RI source cases. Second, we calculate the scattering angle by substitution $E_{\text{DSSD}}$ as the recoil electron energy and $E_{\text{CdTe}}$ as scattered photon energy in the Compton equation 3.2. Figure 5.23 summarizes the Compton back projection images. The images are simply summing the projection of the Compton cones into the RI source plane. The ARM profile for 81 keV, 356 keV and 511 keV are summarized in Fig. 5.24. We determined the FWHM of the ARM profile by fitting the Voigt function (Dotted curve). The function is a convolution of Gaussian and Lorentzian distribution, and offers good approximation of the ARM profile. The angular resolution is 16.5° (FWHM) at 81 keV, 3.5° (FWHM) at 356 keV, and 2.5° (FWHM) at 511 keV.

5.4.6 Spectral Performance

Utilizing the direction information, we can select gamma-rays that directly enter into the camera and deposit their energy fully through a Compton scattering and a photo-absorption. In other words, photons scattered in the room and those escaped from the camera can be discarded. Figure 5.25 gives the spectra obtained for $^{241}$Am and $^{22}$Na. From all two-hit events (dot histogram), we selected the events that had a calculated ARM within $\pm 2 \times$ FWHM (solid histogram). The scattered and escaped events are rejected thanks to the imaging capability of the Compton camera. Even after the Compton reconstruction, the energy resolution is 3.8 keV (FWHM) and 8.0 keV at 59.5 keV and 511 keV, respectively.
Figure 5.23: Compton reconstruction image at various energies.
Figure 5.24: The ARM profile for (a) 81 keV, (b) 356 keV and (c) 511 keV.

Figure 5.25: The spectra obtained for (a) $^{241}$Am and (b) $^{22}$Na. The events that calculated ARM is within $\pm2\times$FWHM are selected (solid line). Dotted lines shows the simple sum of the two-hit events.
Chapter 6

Response of the Compton camera

In order to perform astrophysical observations, a correct understanding of the detector response is of great important. Particularly, the intense study of the response for each detector element, DSSD and CdTe, is crucial to understanding the behavior of the whole detector system of the Compton camera. We utilized the prototype Si/CdTe Compton camera described in Chapter 5. In this experiment, we did not use CdTe side detectors to simplify the interaction in the detector and to obtain clear data for the study of individual Si and CdTe detector.

6.1 Experimental Setup

The Compton camera used here simply consists of one layer of 500 µm thick DSSD and a 4-layer stacked CdTe module (Fig. 6.1). The CdTe module is arranged 14.7 mm underneath the DSSD. The stack pitch of CdTe detector is 2.0 mm. The dimensions of each detector element are listed in Table 6.1. The detectors were operated at the temperature of -15 °C. The CdTe detector and the DSSD were operated at the bias voltages of 600 V and 250 V, respectively. We used 18 VA64TAs to read out the total of 1152 detector channels. With the use of several kinds of RI sources, calibrations of pedestal levels and gains were performed for individual detector channels. The energy resolution of the DSSD was 1.8 keV (FWHM) on average, while that of the CdTe detector was typically 2.0 keV (FWHM) at 81 keV and $\Delta E/E \sim 1\%$ for a few hundred keV (See Fig. 5.15(b)).

<table>
<thead>
<tr>
<th>Detector</th>
<th>Active Area [mm]</th>
<th>Thickness [µm]</th>
<th>Strip Pitch / Pad Size [mm]</th>
<th>Bias [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSSD (Si)</td>
<td>25.6 × 25.6</td>
<td>500</td>
<td>0.4</td>
<td>250</td>
</tr>
<tr>
<td>CdTe pixel</td>
<td>13.2 × 13.2</td>
<td>500</td>
<td>1.35</td>
<td>600</td>
</tr>
</tbody>
</table>

Table 6.1: The dimensions and operated bias voltages of each DSSD and CdTe detectors element.

We investigate the response of the DSSD and the CdTe detectors separately, and also consider the total response as a Compton camera. Utilized RI sources can be regarded as point sources. Table 6.2 summarizes the experimental conditions including the intensity, trigger mode and the position etc. There are two different trigger modes: one is “Photo
One feature of the Compton camera is the wide field of view. By using $^{133}$Ba (356 keV) and $^{22}$Na (511 keV) sources, we investigate the field of view. Each point source was placed on the plane at $z=60$ mm (Fig. 6.2) and shifted to the $y$-direction with 20 mm pitch. The position of $(x,y,z) = (0,100,60)$ corresponds to $120^\circ$ view.
6.2. COMPTON CAMERA SIMULATOR

For investigating the response of Compton camera, we developed a Monte Carlo simulator. The main purpose of Monte Carlo simulation is to accurately reproduce the measurements and to predict the detector performance. At least, the simulator needs to reproduce the followings:

- Spectral shape
- Absolute detection efficiency
- Angular resolution

at various gamma-ray energy.

In the energy band of a Compton camera, the Geant4 Monte Carlo software package [89] is widely used. The object-oriented approach of Geant4 makes the program more adaptable to users’ need. In ISAS, an object-oriented analysis framework named Geant4–ANL has been developed [90]. The system can handle both simulation and experimental data. The interface allows a user to easily approach simulation components that are developed by a collaboration among different geometry maintainer and detector developer groups.

In order to perform accurate simulations, we have to ensure that the simulation program contains all physical processes relevant to the Compton camera energy range. Especially the default package does not contain the effect of Doppler broadening, which fundamentally limits the angular resolution of a Compton camera. In order to take into account this effect, we included the G4LECS extension package developed by Kippen [91, 92]. We compared the simulation output with the G4LECS code with the theoretical values derived from the relativistic impulse approximation [38] in section 3.4.3. The result for Silicon atom is shown in Fig. 6.3. The theoretical values and the simulation values agree very well over the wide scattering angles. We suppose that the G4LECS code is sufficient for practical usage.

With the simulation, the output information is available with perfect energy and position resolutions. In order to introduce uncertainties with actual measurements, we developed “Detector Response” unit in our simulator. In the unit, as a first step, the detector physical processes which are not simulated by Geant4 are considered and added.
to the output from Geant4. For example, a thermal diffusion of electrons and holes in the semiconductor device, a charge collection efficiency dependent on the position of internal device need to be taken into account. These response of the DSSD and In/CdTe/Pt pixel detector are discussed in section 6.4 and 6.5. Second, we apply the energy resolution and position resolution of real detectors to the simulated data. We account for this by centering the positions in the individual voxels (strips in the DSSD and pixels in the CdTe pixel detector) and applying a Gaussian noise to the energy measurement. Finally, the channel information was fed into the “Hit generator” unit, when the energy exceeds a threshold defined for each detector unit.

In the Compton regime, it is especially hard to stop the initial photon completely, because the result of Compton scattering still remains a photon, ready for the next Compton interaction, until it gets photo absorbed. Thus, it is really important to include absolutely all passive material at the right places. Fig. 6.4 shows the mass model of the Compton camera. In addition to the active area of the detectors, the structures which support the Compton camera, such as plastic frame or Al frame, were included.

### 6.2.1 Hit generator

The experimental and the simulation data which come into this hit generator unit have a common data structure. We can therefore apply the same criteria to judge the detector hit.

The main task is to treat multi hit events over adjacent strips or pixels. As described later in section 6.4 and 6.5, the DSSD has roughly 10% of charge sharing events when 60 keV gamma-rays are absorbed. For the CdTe pixel detector, there are about 10–30% of the charge sharing events in the energy band 60 keV to 511 keV. Therefore, the detection efficiency improves typically by a few tens percents by clustering these charge sharing events.

---

**Figure 6.3:** The angular uncertainty from Doppler broadening effect for Silicon atom. Comparison of G4LECS code with the relativistic impulse approximation [38] (see section 3.4.3).
sharpening events. The energy of the cluster is determined as the total energy of the hits, and the position is determined as the center of energy-weighted hit positions. In the case of a strip detector, the signals of the x and y-strips of one detector are combined into interaction position. The grade information is added according to the degree of the clustering.

6.2.2 Event generator

In this section, we describe how to interpret a hit sequence into an event. Basically, we classify sequences with total number of hits. If the sequence recorded only single hit, it is classified into a photo absorption event category. This category becomes main when the “Photo-absorption mode” observation is performed, in which the data are obtained by only DSSD trigger or CdTe trigger. The Compton events category consists of two hit sequence. All categorized events has grade information according to whether the events include clusterized hits or not.

For the Compton event category, we calculate the probability factor that the event happened this way and is completely absorbed. This probability information is used for event selection. In section 6.3, we show analytical methods with information of two energy deposits, based on Klein-Nishina formula and the cross section of the material. Although this is not perfect because we ignore the topology of hits and the detector geometry, we use this method in this thesis.

6.2.3 High level analysis

At the last step, a high level analysis to derive the spectrum and images from data set is performed.
The event selection is crucial to reduce background events and emphasize the signals from the target. The task is to exclude those bins of the data space that contaminated by most of background events. We prepared tools, for selections in energy window, in scattering angle, in ARM distribution, etc. to investigate optimized selection criteria and to compare the experimental data with simulation data in detail.

### 6.3 Two hit sequence Reconstruction

The Si/CdTe Compton camera has very compact structure. Since the distance of each interaction is short, Time-of-flight measurement is not allowed. We can therefore not determine the interaction sequence directly. If N hits are recorded in the detector, there are N! possible sequences. The objective of sequence reconstruction is to select the most probable sequence among all the possible sequences.

The two-hit event category is most important because usual Compton events are included in this event space. Although the Compton events also distribute in multi hits category (larger than two-hit), the both energy resolution and angular resolution are better by using only two-hit events because the energy uncertainty becomes larger by summing each energy deposits. Moreover, the fraction of the multi-hit event is less than that of the two-hit event in sub-MeV energy region, typically one order of magnitude below 300 keV. Therefore, we focus on two-hit events here. For a simplicity, we assume that a gamma-ray deposits all its energy in two-hit sequence.

#### 6.3.1 Simple selection method

Because the measurement can not give the interaction sequence, we do not know the first interaction of two-hit events directly. However the Compton kinematics provide critical information to determine the correct sequence in some case. From the Compton formula, the maximum deposit energy in the Compton scattering is

\[
max(E'_{c}) = \frac{E_0}{1 + m_e c^2/(2 E_0)} \tag{6.1}
\]

which is known as a Compton edge. Therefore, the deposit energy of first interaction should be less than the Compton edge.

Simple selection method is to extract two-hit events where two possible sequences are limited to one with information of Compton edge. The black region in Fig. 6.5(a) shows the region where simple selection method is applied. Where, \(E_1\) and \(E_2\) are the energy deposits in virtual detector 1 and 2. It should be noted that when the incident gamma-ray energy is below \(m_e c^2/2\), all full deposit two-hit events are collected by this method. This is because the Compton edge for such energy is always less than \(E_0/2\), hence, the lower energy deposit is determined as the first interaction. For incident gamma-rays with energy greater than \(m_e c^2/2\), there is a possibility that both interaction deposit energies less than the Compton edge. They distribute in the double cone zone in Fig. 6.5(a) and are ignored by the simple selection method.

Figure 6.5(b) shows the maximum detection angle of the Compton scattering with the simple selection method. As the incident energy increases, the maximum detection angle decreases, but still covers \(\sim 60\) deg at 500 keV and \(\sim 30\) deg at 1 MeV. Dependent on
6.3. TWO HIT SEQUENCE RECONSTRUCTION

the detector configuration and the source direction, the method gives sufficient detection efficiency. Indeed, for a 511 keV incident photon from vertical direction, greater than 95% of Si and CdTe Compton events are collected only by the simple selection method in case of detector presented in this chapter. Furthermore, the use making a point of high angular resolution may not need the events which have large scattering angles. The simple selection method is useful and sufficient in many case.

To obtain higher detection efficiency the sequence reconstruction in double cone zone is needed. For example, the most of CdTe and CdTe Compton events for above ~400 keV incident photon distribute in the double cone zone, hence, the sequence reconstruction is effective. In addition, the polarization measurement needs the large scattering angle events, because the analyzing power is maximized for large scattering angle events (typically ~ 90° scattering angle). In next section, we discuss the sequence reconstruction of the events which distribute in double cone zone based on the Klein-Nishina formula.

Figure 6.5: Simple selection method

6.3.2 Si/CdTe sequence reconstruction

This is applied to the two-hit events within the double cone zone in Fig. 6.5(a). Figure 6.6(a) shows the double cone event in case of Si and CdTe combination. The P1 cone is drawn on the assumption that the first interaction occurs in Si, while the P2 cone is drawn on the assumption that the first interaction occurs in CdTe. The probability for an incident photon to create a two-hit event with sequence of \((E_{Si}, r_{Si}) \rightarrow (E_{CdTe}, r_{CdTe})\) is expressed by

\[
P_1\{\text{sequence of } (E_{Si}, r_{Si}) \rightarrow (E_{CdTe}, r_{CdTe})\} = \Pr\{\text{The incident photon reaches } r_{Si}\} - \Pr\{\text{The incident photon is scattered and deposit } E_{Si}\}
\]
Pr\{The incident photon reaches }r_{CdTe}\}
Pr\{The scattered photon is photoelectric absorbed\}

Similarly, the probability of the sequence \((E_{CdTe}, r_{CdTe}) \rightarrow (E_{Si}, r_{Si})\) is expressed by

\[
P_2\{\text{sequence of } (E_{CdTe}, r_{CdTe}) \rightarrow (E_{Si}, r_{Si})\} \\
= Pr\{The incident photon reaches }r_{CdTe}\}
Pr\{The incident photon is scattered and deposit }E_{CdTe}\}
Pr\{The incident photon reaches }r_{Si}\}
Pr\{The scattered photon is photoelectric absorbed\}
\]

Figure 6.6(b) shows the map of the value of \(P_1/(P_1 + P_2)\) on the assumption that the probability that the incident photon reaches first interaction point is 1. The device thickness is set to 0.5 mm for each detector and the multiple scattering in the detector is ignored. The value is almost 1 all over the double cone zone. This means that CdTe \(\rightarrow\) Si sequence can be ignored. This is attractive feature of Si/CdTe Compton camera realized by characteristic material selection of Si and CdTe. Although the time-of-flight measurements can not allowed, the determination of the sequence is done with high accuracy in Si and CdTe combination.

Figure 6.6: Reconstruction of double cone events at Si and CdTe combination
6.3.3 CdTe/CdTe sequence reconstruction

The stacked CdTe detector is arranged under the Si detectors. The main role of the CdTe part is an absorber for the scattered photon from Si detector. In addition, the CdTe part works as the Compton camera itself for the incident photon which penetrates the Si part without interactions. Even with 2.0 cm total thickness of Si part corresponding to 40 layers of 0.5 mm thick detectors, about 60% of incident gamma-rays in the energy band of 200–500 keV come into CdTe part without interactions in the Si part. Therefore, it is effective to use CdTe and CdTe Compton events to improve the detection efficiency.

![Diagram](image)

Figure 6.7: Simulated fraction of the two-hit events extracted from simple selection method and from double cone zone

The simple selection method is still available for CdTe and CdTe two-hit events. With this selection, the events which cover scattering angle up to $\sim 60$ deg at 500 keV and $\sim 30$ deg at 1 MeV is collected as mentioned in section 6.3.1. However, in CdTe and CdTe combination, considerable amount of the large scattering angle events are recorded due to the stacking structure. Figure 6.7 shows simulated fractions of the two-hit events extracted by the simple selection method and those extracted from the double cone zone. The gamma-rays are irradiated from the vertical direction. The most of CdTe and CdTe Compton events above $\sim 350$ keV constructed by the events which distribute in double cone zone, hence, the sequence reconstruction is quite important.

Figure 6.8 shows the $P_1/(P_1 + P_2)$ map obtained by the same method described in section 6.3.2. The overall probabilities are small, hence, the accuracy of sequence reconstruction is lower than Si and CdTe combination. We applied the sequence reconstruction to simulation data and showed the fraction of correctly sequenced events as the sum of the simple selection method and the sequence reconstruction in Fig. 6.9. The high accuracy at the low energy end is because most of the events can be correctly sequenced by the simple selection method. The accuracy was minimized at energy around 400 keV, but, about 70% of all CdTe and CdTe two-hit events is still correctly sequenced.
CHAPTER 6. RESPONSE OF THE COMPTON CAMERA

Figure 6.8: Reconstruction of double cone events at CdTe and CdTe combination

Figure 6.9: The fraction of correctly sequenced events
6.4 DSSD response

For the DSSD device, the understanding of the charge sharing events is essential to establish accurate response. The charge sharing is determined by the initial electron-hole pair cloud size and the thermal diffusion. The examination to obtain the parameters of charge sharing is performed.

6.4.1 Charge sharing in DSSD

In order to investigate charge sharing, we irradiated the DSSD with 59.5 keV gamma-ray from $^{241}$Am. The test is performed with 4 cm wide and 300 $\mu$m thick DSSD because the 4 cm DSSD has statistical advantage thanks to its larger effective area, thus it is suitable for a detailed investigation of energy response. Since the attenuation length is 1.34 cm for 60 keV photons, interactions occur almost uniformly over the 300 $\mu$m thickness.

Figure 6.10 is the distribution of the pulse height correlation between two p-side adjacent strips. The distribution which surrounded by a blue rectangle is the charge sharing events for 59.5 keV gamma-rays. The fraction is 5.8 % to the single hit events which illustrated by red rectangles.

![Figure 6.10: The distribution of the pulse height correlation of p-side adjacent strips](image)

The striking feature of the plot is the opposite polarity signals which are of unknown origin. We showed them with yellow rectangles, and found that they occupy 4.2 % to the single hit events. This phenomenon is not observed in the same diagram generated for n-strips. Therefore, we suspected that they occur in the vicinity of the p-side strips. Since the effect is not negligible for the DSSD energy response, we should identify the origin of these strange events.

As the first step, the internal potential of the DSSD calculated using the two dimensional device simulator VENUS-2D [93], developed by Fuji Research Institute Corporation, Japan. The geometry is a cross section perpendicular to the p-strip. We estimate the donor density of n-bulk silicon as $9.0 \times 10^{11}$ cm$^{-3}$ (see section 5.2) and set $p^+$ and $n^+$ dope density as a typical value of $1.0 \times 10^{18}$ cm$^{-3}$. Additionally, we set positive fixed oxide
CHAPTER 6. RESPONSE OF THE COMPTON CAMERA

surface charges in the Si-SiO₂ transition region with a typical value of $1.0 \times 10^{12} \text{e}/\text{cm}^2$ [94]. This geometry fully depletes on bias voltage around 70 V, the value of which is consistent with the actual measurements.

Figure 6.11 is simulated internal potential under full depletion voltage. Positive fixed oxide surface charges induce local minimum potential between the p-strips and in this region electrons are conducted to the center of SiO₂ layer, not to N-side. The local minimum potential region extends to about 1500 $\mu \text{m}^2$ under SiO₂ layer.

Based on the potential simulation, we tried to reproduce the pulse height correlation between the adjacent p-strips for 59.5 keV photo-absorption events. To estimate the charge collection, we introduce simple assumptions as follows:

1. Holes and electrons are fully conducted either to electrodes or to the SiO₂ layers.
2. The trajectory of a charge is simply defined by the potential gradient taking no account of initial momentum.
3. Electrons ($-Q$) conducted to SiO₂ induce the same amount of signal ($+1/2 \cdot Q$) to the adjacent p-strips. (see J.Yorkston et al. [95] for experimental evidence).
4. The initial charge cloud size is defined as $C_{\text{init}} \simeq 0.0171 \times T_e^{1.75} \text{ [\mu m]}$ [96], where, $C_{\text{init}}$ is the 2 sigma cloud diameter and $T_e$ is the initial electron kinetic energy. For example, $C_{\text{init}}=21 \text{ \mu m}$ for 59.5 keV photo-absorption.
5. The spread of the charge cloud by thermal diffusion ($\sigma_{\text{diff}}$) is estimated from the drift time ($t_d$) with the relation of $\sigma_{\text{diff}} = \sqrt{2D t_d}$, where $D = \frac{kT}{q} \mu$ is the diffusion constant. The drift time is simply estimated from gradient of internal potential by integrating the infinitesimal time as $\Delta x / \Delta t = \mu E = -\mu \Delta \phi$. Typically $\sigma_{\text{diff}}$ is about 10 $\mu \text{m}$ in the inter-strip region.

Figure 6.12 is the result of the simulated pulse height correlation. The distribution is like an oblique rectangle which has the apex (q, 0), ($\frac{1}{2}q$, $-\frac{1}{2}q$), ($-\frac{1}{2}q$, $\frac{1}{2}q$), (0, q). This corresponds to the experiment scatterplot (Fig.6.10). The reason of forming this distribution is because the amount of charge collection to p-strips varies according to...
the point where the initial cloud is generated. We can roughly divide the internal region into 8 sections as indicated in Fig.6.13 right, A to G. All holes move to the nearest strip and all electrons move to N-side in A \((q, 0)\) and G \((0, q)\). All holes move to the nearest strip and electrons are shared between SiO\(_2\) and N-side in B (between \((q, 0)\) and \((\frac{1}{2}q, -\frac{1}{2}q)\)) and F (between \((-\frac{1}{2}q, \frac{1}{2}q)\) and \((0, q)\)). All holes move to the nearest strip and all electrons move to SiO\(_2\) in C \((\frac{1}{2}q, -\frac{1}{2}q)\) and E \((-\frac{1}{2}q, \frac{1}{2}q)\). Holes are shared between strips and all electrons move to SiO\(_2\) in D (between \((\frac{1}{2}q, -\frac{1}{2}q)\) and \((-\frac{1}{2}q, \frac{1}{2}q)\)). Holes are shared between strips and all electrons move to N-side in H (between \((0, q)\) and \((q, 0)\)).
Table 6.3: Comparison of event distributions between the experiment and simulations.

Table 6.3 shows a comparison of event distributions between the experiment and simulations. Simulations are performed in two cases, with or without the thermal diffusion. By considering the thermal diffusion, the charge sharing events in region H increases, and the simulation well agrees with the experiment. The simulated events which have opposite polarity pulse are less than experimental value. This implies that actual local minimum potential under SiO$_2$ layer spreads than expectation. The events around D region becomes “dead events”, actually, they are not detected in the experiment due to the trigger threshold (Fig. 6.10). Although the threshold of measurement and mixed response for different energy photons in the diagram of pulse height correlation make it difficult to measure the probability of “dead events”, we predict from simulation that their contribution is in the order of 0.1 \%.

From the experiment and simulations described above, we obtained some knowledge for the DSSD response.

- The local minimum potential exist under SiO$_2$ layer. It results in the opposite polarity pulse.
- The “dead events” exists due to the local minimum potential and trigger threshold. However, their contribution is in the order of 0.1 \%.
- The thermal diffusion gives considerable effect to the charge charing. The value is typically about 10 $\mu$m.

In the next section, we implement our knowledge into the simulator and check the consistency between experiments and simulator outputs.

### 6.4.2 Implementation of the DSSD response into the Simulator

In this section, we include the energy and position response of the DSSD into simulator, and check consistency between the experiments and simulator.

In the previous section, we showed the existence of local minimum potential region under SiO$_2$ layer between p-strip. This region results in the opposite polarity pulse and the contribution to all events is about 5 \%. But, the size and the geometry of that region is still not understood perfectly. Consequently, we perform further experiments to investigate the behavior of the region in detail. From the stability test in a long-term operation, it is implied that the size of the region increases with time. There is a possibility that the charges trapped in the local minimum change the geometry of internal potential. We have not yet included these effects caused by the local minimum potential.
6.4. DSSD RESPONSE

It into the simulator. Therefore, the simulator efficiency would differ from the experimental efficiency at least ~5% level, but it is known origin.

In the Compton camera energy band, the approximation of initial hole-electron cloud by Gaussian distribution is not an accurate description of physics because the electron energy is high enough to travel 10-100 µm length in the DSSD. We represented the size and shape of initial cloud by electron tracking code included in Geant4 library. We take the multi scattering, ionization, and bremsstrahlung radiation into consideration.

Figure 6.14: Hit pattern of DSSD (a) 59.5 keV peak irradiated with $^{241}$Am (b) 122 keV peak irradiated with $^{57}$Co

Figure 6.15: The distribution of $E_{\text{min}}$ and $E_{\text{max}}$ ratio. (a) 59.5 keV peak irradiated with $^{241}$Am (b) 122 keV peak irradiated with $^{57}$Co

In order to check the consistency between experiments and simulations, we irradiated the DSSD with 59.5 keV gamma-ray from $^{241}$Am and 122.1 keV gamma-ray from $^{57}$Co. Figure 6.14 shows the multiplicity of the hits in the DSSD. We defined the threshold of hits at 10 keV both the experiment and simulation. Multiplicity 2 means the events
recorded by adjacent two strips, 3 means adjacent three strips, etc. We extract the events from energy window 55–65 keV for 59.5 keV gamma-ray and 117–125 keV for 122.1 keV gamma-ray. The blue line shows the simulation result which takes into account only the electron tracking, while the red line is together with 10 µm of the thermal diffusion. The multiplicity was well reproduced by electron tracking and thermal diffusion in both 59.5 keV and 122.1 keV. Moreover, we investigated the distribution of \( E_{\text{min}} \) and \( E_{\text{max}} \) ratio for the events recorded by the adjacent two strips (multiplicity 2). This distribution is sensitive for the degree of reproduction of the charge sharing because it includes additional information concerning about the division of energy. The result is shown in Fig. 6.15. In both 59.5 keV and 122.1 keV cases, the distribution agrees well with the simulation which takes the thermal diffusion component into account.

![Figure 6.16](image)

Figure 6.16: Comparison of experimental spectrum with simulated spectrum. Note that we use an absolute normalization, given intensity of the source, which is the same for the energy spectrum in both left (59.5 keV) and right (122.1 keV) panel.

Finally, we compared the spectrum and presented the result in Fig. 6.16. The single hit (multiplicity 1) and double hit (multiplicity 2) spectra are illustrated. Note that we use an absolute normalization both for the left (59.5 keV) and right (122.1 keV) panel, given intensity of the sources. The simulation includes 10 µm thermal diffusion together with electron tracking. The spectra are amazingly well reproduced. This means that the charge sharing is properly implemented into the simulator.
6.5 In/CdTe/Pt pixel detector response

6.5.1 The Shockley-Ramo theorem

For the CdTe device, the assumption that the carriers are fully collected to the electrode like a common silicon device is not acceptable because of the slow mobility and short lifetime of holes. The charge collection efficiency is a function of the interaction position in the detector. In order to simulate the energy response of these kinds of detectors, the information of the amount of the charge induced in the read-out electrode as a result of the charge drift until it is trapped is required. Here, we adopt an idea of the weighting potential based on the Shockley-Ramo theorem.

Although the detail is described in the Zhong He et al [97] and A. Zumbiehl et al [98], we briefly introduce the method. The Shockly-Ramo theorem states that to calculate the induced charge on an electrode the weighting potential is first determined by solving Poisson equation throughout the detector volume under the conditions that the space charge is removed and the electrode under inspection is given a unit potential and all other conductors are grounded. The induced charge $Q$ by single carrier is then directly proportional to difference in weighting potentials between the initial $(x_i)$ and final positions $(x_f)$ of the moving charge generated in the detector. The leading sign is determined by the sign of the charge carrier (positive for hole and negative for electron).

$$\nabla^2 \phi_0 = 0 \quad Q = \pm q[\phi_0(x_f) - \phi_0(x_i)]$$

in which, $\phi_0$ is the weighting potential. Because the weighting potential is given by only the shape of the detector and the configuration of the electrode, we can easily apply to a pixel detector. The mean free path of a charge is characterized by the product of mobility ($\mu$) and lifetime ($\tau$) of a charge and internal electric field.

$$\lambda_e = (\mu \tau)_e E, \lambda_h = (\mu \tau)_h E$$

(6.2)

Therefore, if one can obtain the $\mu \tau$ products and the strength of internal electric field, induced charge can be calculated.

6.5.2 Extraction of $\mu \tau$ product

The “$\mu \tau$-model” spectral fitting method was developed by our group and firstly applied to the response study for total of 32K CdZnTe detectors [99] onboard Swift/BAT detector. The detailed description of this method is given in [100]. Briefly saying, this is fitting algorithm which reproduces the pulse hight and the spectrum shape. Then, the $(\mu \tau)_e$ and $(\mu \tau)_h$ are extracted as best fitting parameters. The $(\mu \tau)_e$ is sensitive to the peak channel in a spectrum, while $(\mu \tau)_h$ determines the amount of the tail component.

One difficulty is the treatment of the electric field. Some of papers [101][102] report the non-uniform strength of the electric field in the Shottoky CdTe detectors. In addition, the time variation of the electric field which results in the polarization effect is widely known. But, no unified view has yet been reached on the formation and time variation of the internal electric field of a CdTe device. In this study, we assume the ideal situation in which the electric field throughout the detector volume is constant. The time variation
Figure 6.17: The "$\mu\tau$-model" spectral fitting results obtained by 4×4 mm size and thickness of 0.5 mm planar type In/CdTe/Pt detector. (left) 59.5 keV peak, (right) 122.1 keV peak

Figure 6.17 shows the fitting results of the spectrum (59.5 keV and 122.1 keV) which obtained by 4×4 mm size and thickness of 0.5 mm planar type In/CdTe/Pt detector. The fitting region was properly selected to minimize Compton scattering component from the surrounding materials because it produces an excess in the lower region of the tail structure. We simultaneously fitted the spectrum obtained with three different bias voltage, 100 V, 200 V and 300 V in order to restrict fitting results. The best fitted $\mu\tau$ parameters for four detectors with different thickness are summarized in Table 6.4. Ideally, the $\mu\tau$ product should be the common value for various detector thickness. For the $(\mu\tau)_e$, the value is about $5\times10^{-3}$ cm$^2$/V for each detector thickness. While, the value of $(\mu\tau)_h$ drastically decrease as the detector becomes thicker. This is probably due to the non-uniform internal electric field. For a thicker device the electric field generated by external bias becomes small, thus, the electric field by internal space charge will not be negligible. Since the $(\mu\tau)_h$ is one or two order of magnitude less than $(\mu\tau)_e$, the hole drift

<table>
<thead>
<tr>
<th>Detector size [mm]</th>
<th>Gamma-ray Energy [keV]</th>
<th>$\mu\tau$ products [10$^{-3}$cm$^2$/V]</th>
<th>Electrons</th>
<th>Holes</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 × 4 × 0.5</td>
<td>59.5</td>
<td>5.3 ± 0.2</td>
<td>0.15 ± 0.0007</td>
<td></td>
</tr>
<tr>
<td></td>
<td>122.1</td>
<td>2.0 ± 0.2</td>
<td>0.16 ± 0.003</td>
<td></td>
</tr>
<tr>
<td>4 × 4 × 0.75</td>
<td>59.5</td>
<td>4.2 ± 0.05</td>
<td>0.11 ± 0.001</td>
<td></td>
</tr>
<tr>
<td></td>
<td>122.1</td>
<td>5.9 ± 0.4</td>
<td>0.08 ± 0.005</td>
<td></td>
</tr>
<tr>
<td>4 × 4 × 1.0</td>
<td>59.5</td>
<td>5.0 ± 0.03</td>
<td>0.06 ± 0.005</td>
<td></td>
</tr>
<tr>
<td></td>
<td>122.1</td>
<td>7.9 ± 0.35</td>
<td>0.035 ± 0.005</td>
<td></td>
</tr>
<tr>
<td>4 × 4 × 2.0</td>
<td>59.5</td>
<td>4.0 ± 0.02</td>
<td>0.022 ± 0.004</td>
<td></td>
</tr>
<tr>
<td></td>
<td>122.1</td>
<td>4.9 ± 0.05</td>
<td>0.008 ± 0.0005</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.4: The best fitted $\mu\tau$ parameter for four different thick detectors
is much sensitive to the effect of non-uniform electric field. As a result, the \((\mu \tau)_h\) derived from the assumption on constant electric field is strongly affected by detector thickness.

The CdTe pixel detector used in the Compton camera has a 0.5 mm thickness and it is operated at a bias voltage of 600 V. In this condition, the constant electric field would be valid approximation. Hereafter, we use the values of \(5 \times 10^{-3} \text{cm}^2/\text{V}\) and \(1.5 \times 10^{-4} \text{cm}^2/\text{V}\) for electrons and holes, which derived from \(\mu \tau\)-model spectral fitting method for the 0.5 mm thick detector.

### 6.5.3 Charge collection efficiency

As described in section 6.5.1, the position dependence of the charge collection efficiency can be simulated by the weighting potential and the attenuation of the carriers. Now, the attenuation can be calculated with the \(\mu \tau\) parameters determined in above section and the assumption of the constant electric field.

![Figure 6.18: The cross section of 3-dimensional weighting potential at the points illustrated in left panel.](image)

The 3-dimensional weighting potential for the CdTe pixel detector used in this study is shown in Fig. 6.18. We showed the cross section of weighting potentials for a certain pixel at the point of A(0,0), B(6.3,0), C(6.3,6.3) and D(7.7,0) which illustrated in the left panel. At the center of pixel, the weighting potential is almost linear function to the depth direction, which is the same as a planer type detector. The pixel effect on the border (position B and C) can be seen, and this effect allows the charge induction even if the carrier motion occurs underneath the adjacent pixel (position D).

By using the 3-dimensional weighting potential and \(\mu \tau\) product, we calculated 3-dimensional position dependence of the charge collection efficiency. Figure 6.19 shows the charge collection efficiency for a pixel illustrated in the left panel of Fig. 6.18 at the point A, B, C and D. We compared the bias voltage of 50 and 600 V. For the operation voltage of the Compton camera at 600 V, the charge collection efficiency is larger than 98% anywhere in the detector and the carrier motion under the adjacent pixel can be
negligible. Based on this 3-dimensional charge collection map, we simulate the induced charge for each pixel electrode with the information of the interaction position and the energy deposits derived from Geant4 output. One issue which should be considered is the timing response of the carrier motion for the shaping time of the filtering circuit. We monitored the CSA output and found that the typical time constant of carrier motion is within a few hundreds nano second even for the hole signals. This can be negligible to the shaping time of a few micro second, therefore, we do not have to consider the pulse attenuation in the final output signal.

![Figure 6.19: The charge collection efficiency at the point A,B,C and D illustrated in the left panel of Fig. 6.18. (left) bias of 50 V, (right) bias of 600 V.](image)

6.5.4 Charge sharing

Another issue on modeling the response of a pixel detector is the treatment of the thermal diffusion. A brief estimation of the quantity of the thermal diffusion can be obtained from the timing response of the hole motion. By monitoring the CSA output of hole signal, the induced current continues during about 300 nsec. This can be regarded as typical drift time inside the detector, and the spread of the hole cloud by thermal diffusion ($\sigma_{\text{diff}}$) is calculated at the order of 10 um. Although the pixels size (1.4 mm) is three order of magnitude larger than the diffusion factor, it found that this factor gives considerable effect to the charge sharing. Therefore, the embedment of the diffusion component is required for detailed modeling of the detector response.

Some clues can be derived from the experimental data. One is the hit pattern of the detector, which is directly characterized by the quantity of the charge sharing. Moreover, the distribution of $E_{\text{min}}$ and $E_{\text{max}}$ energy ratio for the event recorded by the adjacent pixels is an important clue because it includes the information concerning about the division of energy. Our approach for modeling the charge sharing is to extract the diffusion parameter which reproduces the experimental result.

We implemented the thermal diffusion effect into the simulator as follows. First, the energy deposit is corrected with 3-dim charge collection efficiency map. Second, the position and corrected energy deposit is smeared by 2-dim gaussian distribution characterized by $\sigma_{\text{diff}}$. We have not taken account of the position dependence of the diffusion factor.
We compared the experimental result with simulations of three different diffusion parameters, 10 µm, 20 µm and 30 µm. Figure 6.20 shows the fraction of the double hit event to the single hit event for 59.5 keV, 122.1 keV and 511 keV incident gamma-rays. We defined the threshold of a hit at 10 keV both for the experiment and simulation. The double hit events means two hits at adjacent two pixels which mostly consists of the charge sharing events and fluorescence escape events. The double hit events with energy sum of 50–65 keV for 59.5 keV, 110–125 keV for 122.1 keV and 490–520 keV for 511 keV gamma-rays are selected. The fraction increases as the incident gamma-ray energy increases because the electron tracking length in the detector becomes longer. For the case of 10 µm diffusion, the simulated fraction is obviously less than the experiments. The experimental value is reproduced at diffusion factor of 20–30 µm.

![Fraction of double hit event](image)

Figure 6.20: The fraction of the double hit event to the single hit event for 59.5 keV, 122.1 keV and 511 keV incident gamma-rays.

The distributions of $E_{\min}$ and $E_{\max}$ energy ratio for the double hit events are shown in Fig. 6.21. The peak structure in the distribution consists of the fluorescence escape events from Cd and Te. The left side of the each distribution is sensitive to the change of the diffusion parameter because it consists of small $E_{\min}$ around 10 keV. Comparing the experimental distribution with the simulated distribution with three cases of diffusion parameters, the case with 30 µm diffusion parameter gives the best reproduction for all incident gamma-ray (59.5 keV, 122.1 keV and 511 keV). This implies that the diffusion, the amount of fluorescence escape events, and the energy resolution of the detector etc. are well simulated. Therefore, we use 30 µm diffusion parameter in this study.
6.5.5 Reproduced spectrum

In Fig. 6.22, we present the experimental spectrum together with the reproduced spectrum by the simulator. We selected the single hit events within one pixel detector and summed them up over all the 64 pixels. Absolute normalization between the experiment and the simulation were compared after the dead-time correction. In order to investigate the contribution of the $\mu\tau$ model and the diffusion parameter, the three cases of the simulated result are illustrated; (a, blue) the both $\mu\tau_e$ and $\mu\tau_h$ are infinite. (b, green) the values of $\mu\tau_e=5\times10^{-8}\text{cm}^2/\text{V}$ and $\mu\tau_h=1.5\times10^{-4}\text{cm}^2/\text{V}$ are used, which extracted by applying the $\mu\tau$ model to the planer type CdTe detector as described in section 6.5.2. (c, black) (b) and the diffusion parameter of 30 $\mu$m.
The difference between the case (a) and (b) is simply the tail structure in the spectrum. Because of the finite value of $\mu \tau$, especially small value of $\mu \tau_h$, a certain fraction of carrier is trapped before arriving at an electrode, as a result, the fraction of the peak structure of spectrum (a) is transferred into lower energy tail of the spectrum (b). Although the tail structure of spectrum (b) includes both Compton scattering component from the surrounding materials and the $\mu \tau$ effect, it seems to be difficult to explain the tail structure of the experimental spectrum for both cases of 59.5 keV and 122 keV gamma-rays. The experimental spectrum is well reproduced when the diffusion effect is embedded (c). This is because the events generated at edge of a pixel shift a fraction of its energy into the adjacent pixel.

![Comparison of experimental spectra with simulated spectrum. See text for details.](image-url)


6.6 Absolute detection efficiency

The absolute Si/CdTe Compton camera detection efficiency at different energies and incident angles were derived with a set of nominal event selection parameters. These are the following:

1. DSSD energy threshold: 15 keV
2. CdTe energy threshold: 10 keV.
3. Fluorescence X-ray events recorded between the DSSD and the CdTe 1st layer is excluded. We eliminated events distributed in DSSD’s energy window between 20 keV to 35 keV. (Cd: $K_\alpha$ 23.1 keV, $K_\beta$ 26.1 keV; Te: $K_\alpha$ 27.4 keV, $K_\beta$ 31.0 keV)

Then, we applied simple selection method (section 6.3.1) for both experiment and simulation data. The nominal selection can be supplemented by secondary selection, selection in derived ARM, selection in measured energy deposits, and selection in the event grade which come from event clustering in the detectors. The criteria of the grade of the Compton event is defined as below:

1. Grade 1: Single hit for both the DSSD and CdTe detectors. For the DSSD, the hit recorded at the single strip on both p-side and n-side was extracted. For the CdTe detectors, the hit recorded by only one pixel was selected.
2. Grade 2: Clustering occurs at least one time at DSSD or CdTe detectors. The clustering is performed for adjacent two strips or pixels. The higher degree of the charge sharing events, for example three or four adjacent pixels, were ignored, but their contribution to the detection efficiency is less than 1 %.

6.6.1 Photo absorption mode

First, we investigated the absolute photo-peak efficiency of each DSSD and CdTe detector. We accumulated the data with DSSD and CdTe triggers, and selected a single hit event for both the DSSD and CdTe detector. The error bars on the following data points include 10 % systematic uncertainties of the radioactive source. The statistical uncertainties are negligible.

Figure 6.23(a) shows the absolute efficiency of the DSSD. We used the energy line of 17.9 keV, 59.5 keV ($^{241}$Am) and 122.1 keV ($^{57}$Co). The peak area was obtained by fitting with the Gaussian function. The simulation result is also shown with the dotted line together with three experimental data points. The absolute efficiency is well reproduced by simulation. Typical efficiency is 1.0 % at 59.5 keV and 0.1 % at 122.1 keV. The reason for decrease of the efficiency below 25 keV is the absorption of the incident gamma-rays by passive materials between the source and the DSSD, for example, air, an aluminum window and a thermal insulator.

The absolute detection efficiency of the CdTe detectors is shown in Fig. 6.23(b). We used 59.5 keV ($^{241}$Am), 122.1 keV ($^{22}$Na), 356 keV ($^{133}$Ba) and 511 keV($^{57}$Co) lines and integrated the peak counts over ±5 keV energy range around each line energy. We summed the counts of four CdTe pixel detectors consisting of one layer and compared the absolute efficiency of each layer with simulation. The detection efficiency of the second, the third and the forth layers drastically decrease below 100 keV because most incident
6.6. ABSOLUTE DETECTION EFFICIENCY

Figure 6.23: The absolute photo-peak efficiency of each DSSD and CdTe detector.

gamma-ray are already absorbed in upper layers. The experimental and simulation values are consistent within 10 % systematic error induced by uncertainties of the radioactive sources, except 511 keV incident gamma-ray. For 511 keV gamma-ray, the experimental detection efficiency is 20 % less than simulation value. One reason is that we do not take account of the broadening of 511 keV line in simulation due to the initial momentum of an electron before the pair annihilation, which is typically a few keV. When we expand energy window into $511 \pm 10$ keV, the experimental detection efficiency agrees with simulation within 10 % systematic error.
6.6.2 Compton mode

The absolute detection efficiency of Compton mode is investigated with $^{57}$Co, $^{133}$Ba, and $^{22}$Na radioactive sources. The data was obtained by the coincidence trigger between the DSSD and the CdTe detectors. As shown in Table 6.2, $^{133}$Ba and $^{22}$Na sources were placed at (x,y,z) = (0,0,150), and $^{57}$Co was placed at (0,-60,30). Thus, the gamma-rays of $^{57}$Co (122.1 keV, 136.0 keV) are incident from the direction of 63.4 °. Although the detection of such low energy gamma-rays is difficult due to the small energy deposit in the DSSD, it is still possible to detect events with wide scattering angle, where, the energy deposits in DSSD become large enough to be detected with the DSSD energy threshold of 15 keV.

An absolute normalization is calculated with given intensity of the source and dead-time correction. We applied a secondary selection for the events where the calculated ARM is included within ±10 ° range. In addition, we selected Grade 1 Compton events which has no charge sharing for both the DSSD and CdTe detectors.

Figure 6.24 shows the experimental Compton mode spectra of $^{57}$Co and $^{133}$Ba together with the reproduced spectra by simulation. In the case of $^{57}$Co, the both the shape and the area of spectrum seem to be well reproduced. For the higher energy lines from $^{133}$Ba, the experimental spectrum shows slightly longer tailing structure than the simulated spectrum, as a result, the area of each line seems to become less than simulation. But this does not mean the disagreement of absolute efficiency between experiment and simulation. Indeed, the ratio of integrated counts over 266–386 keV energy range including four lines of $^{133}$Ba becomes a consistent value, exp(266–386 keV) / sim(266–386 keV) = 0.96, when taking account for 10 % uncertainty of source intensity. Although more precise study of the spectral shape would be needed, the absolute detection efficiency is mostly consistent with the simulation.

The energy dependence of detection efficiency is summarized in Fig. 6.25. We integrated the counts of each line from –10 keV to +5 keV energy window centered on the line energy. The error bar of each point is 10 % error induced by uncertainty of source intensity. The experimental value agrees well with simulation. The absolute detection efficiency is $10^{-3}$–$10^{-2}$ % over 250–511 keV energy window.
Figure 6.24: Comparison of experimental absolute Compton mode spectrum with simulated one. (a) $^{57}$Co, (b) $^{133}$Ba
6.6.3 Field of view

In the above section, we demonstrated the consistency of absolute detection efficiency between experiment and simulation for incident gamma-ray from vertical direction. By using 356 keV and 511 keV gamma-ray point sources, we investigated the detection efficiency as a function of incident direction. The point source was placed on the plane at $z = 60$ mm (See 6.2) and shifted to the $y$-direction with 20 mm pitch. The same criteria of event selection is applied, which used to study the absolute detection efficiency in above section 6.6.2. We normalized the efficiency to unity at the center position of $(x, y, z) = (0, 0, 60)$, thus the uncertainty of the source intensity is canceled. The 1-$\sigma$ statistical error is applied to each point for both experiment and simulation.

The experimental result is summarized in Fig. 6.26 together with the simulation result. The relative efficiency at $y = 100$ mm corresponding to 60° direction is 36 % for 356 keV and 17 % for 511 keV. The efficiency curves almost agree with simulation. For the very large incident direction, the experimental result is 10–20 % larger than simulation, which is not explained only by applying the statistical error. The origin of this inconsistency is under investigation.

Considering the results obtained from this and above sections, it is possible to say that we reproduced the absolute detection efficiency of the Compton camera within 10 % systematic error induced by the source intensity except very large incident angle.

Figure 6.25: The energy dependance of detection efficiency.
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6.6.4 Effect of a clustering

Until now, we handled only Grade 1 Compton events. The detection efficiency can be improved by using Grade 2 Compton events, which includes the charge sharing events. Figure 6.27 shows the Compton mode $^{133}$Ba spectrum in the two cases of Grade 1 and 2. No secondary selection is applied. The fraction of the Grade 2 event to the Grade 1 events is 10–15 %. This is consistent with estimation from the hit pattern of the DSSD and CdTe detector. Thus, the detection efficiency is improved about 10 % by joining Grade 2 events into analysis. But, it should be noted that the energy resolution of Grade 2 events is degraded in comparison Grade 1 events because the electronic noise of each channel is also summed when clustering the energy deposits.

Figure 6.26: The field of view (left) 356 keV, (right) 511 keV.

Figure 6.27: The spectrum of Grade 1 selection and Grade 2 selection
6.7 Angular resolution

In order to investigate the angular resolution, we utilized the data obtained with the Compton camera fabricated for the balloon experiment. This is because in this version of Compton camera the horizontal direction of the DSSD is surrounded by the CdTe pixel detector, thus, high detection efficiency is achieved even for low energy photons below 100 keV.

The energy dependence of angular resolution is summarized in Fig. 6.28 with open circles. The estimation based on the analytical method described in section 3.4.1 is shown together with the experimental results. We separately estimated the contribution from the energy uncertainty caused by Doppler broadening and the energy resolution, and from the position uncertainty. Then, we calculated total angular resolution by simply a square sum of two components

$$\Delta \theta_{\text{total}} = \sqrt{(\Delta \theta_{\text{energy}})^2 + (\Delta \theta_{\text{position}})^2}$$

(6.3)

The energy dependence of the angular resolution is well reproduced. The contribution from the energy uncertainty is dominant below 300 keV, while that from the position uncertainty is dominant above 300 keV. We also illustrated the Doppler broadening limit. Roughly speaking, we obtained the angular resolution close to the Doppler broadening limit above \(\sim\) 300 keV. In lower energy band around 100 keV, the angular resolution is far from the Doppler broadening limit. To achieve the Doppler broadening limit in this band, higher energy resolution less than 1 keV is required. The estimation by Monte Carlo simulation is also shown in Fig. 6.28 with cross points. The results also well agree with the experimental results.

Figure 6.28: The FWHM of ARM distribution for various energies. The dots is the estimation based on the analytical method described in section 3.4.1. (open circle) Experiment, (cross) Montecarlo simulator output.
6.8 Summary

The Monte Carlo simulator considering the DSSD and CdTe detector responses was developed for detail study of Compton camera response. We compared experimental results and the simulator outputs, particularly about the spectral shape, absolute detection efficiency and angular resolution. The spectral shape of 122 keV and 134 keV from $^{57}$Co is well reproduced (Fig. 6.24(a)). In the case of $^{133}$Ba, it is almost good, but the experimental spectrum shows slightly longer tailing structure than the simulated spectrum. The absolute detection efficiency is well reproduced for both “Photo Absorption Mode” and “Compton Mode” within 10 % systematic error induced by the uncertainty of the intensity of RI source (Fig. 6.23(a), 6.23(b), 6.25). The angular resolution is also well reproduced in wide energy band from 59.5 keV to 511 keV (Fig. 6.28).

These results imply that our Monte Carlo simulator reproduces actual experiments at least 10 % level. This accuracy is sufficient for the estimation of the detector performance for following developments.
Chapter 7

Compton imaging capability by Si/CdTe Compton camera

In this chapter, we demonstrate the Compton imaging capability with various kinds of gamma-ray targets such as a point source, arranged point sources and an extended source. As a deconvolution method, we selected List-Mode Maximum Likelihood Expectation Maximization, and applied it to several kinds of experimental data. The Compton back projection images of arranged point sources and an extended object were successfully deconvolved.

We prepared various kinds of gamma-ray targets with liquid RI source ($^{131}$I, 356 keV) such as arranged point sources and an extended source to evaluate the imaging capability of the Compton camera. Although the imaging of a extended source is very important and challenging because some attractive astrophysics target (SNR, Galactic Center) have their own shapes, the imaging capability for such objects with a Compton camera has not been studied well so far. Figure 7.1(a) shows a acrylic plate with 2 mm diameter holes arranged regularly. The sources were mounted at 20 mm pitch. The variability of intensity of each source is less than 10 %. The objective is to investigate the resolving power and accuracy of positional determination. Figure 7.1(b) and Fig. 7.1(c) shows two type of extended objects. One has circle shape with 20 mm diameter and the other was shaped like inverted “C” with a gap of 3 mm. The intensity is regarded as almost uniform.

Figure 7.1: Photo of three targets.(a) a acrylic plate with 2 mm diameter holes arranged regularly. The sources were mounted at 20 mm pitch. (b) circle shape with 20 mm diameter. (c) inverted ”C” with a gap of 3 mm.
CHAPTER 7. COMPTON IMAGING CAPABILITY BY SI/CDTE COMPTON CAMERA

7.1 The simple back projection algorithm

The simple back projection (SBP) image is the simple accumulation of Compton cones over all events. The overlapping position of the Compton cones is determined as the origin of the gamma-ray.

In Fig. 7.2, we showed various experimental examples of the SBP image. We selected the events from the energy window of ±5 keV around the line energy of each source, and projected the Compton cones to the RI source plane. We drew an ellipse which appears as interaction points of a cone and plane to be unity as a whole, thus the intensity of the image is proportional to the existence probabilities of the source. Figure 7.2(a) is the 356 keV point source image of $^{133}$Ba, and Fig. 7.2(b), 7.2(c), and 7.2(d) are the 364 keV images of $^{131}$I.

Figure 7.2(b) is the image of acrylic plate with 2 mm diameter holes arranged regularly (9×9), which placed at 60 mm from the detector. The liquid $^{131}$I sources were mounted at 20 mm pitch (∼85 kBq/hole). The uncertainty of strength of each source is about 10 %. Although the point sources arranged around the center are resolved, the sources apart from the center can not be distinguished.

Figure 7.2(c) and 7.2(d) are the images of the extended targets placed at 30 mm from the detector. One has circle shape with 20 mm diameter and the other is shaped like inverted “C” with a gap of 3 mm. In case of circle shape, we can recognize that the source image spreads to about 20 mm diameter, which is consistent with the shape of the source. However, the accurate decision of the source shape is difficult because the point source image shown in Fig. 7.2(a) has relatively large extension. For the case of inverted “C” shape, we barely recognize the gap in the image.

Although the simple back projection is fast and straightforward, its spatial resolution is not high and most parts of a cone not overlapping with a source become background. Imaging capability should be improved using a deconvolution method that properly accounts for the response of the Compton camera.
7.1. THE SIMPLE BACK PROJECTION ALGORITHM

Figure 7.2: Simple back projection (SBP) image for various target (a) The 356 keV point source image of $^{133}$Ba. (b) The image of acrylic plate. (c) Circle shape. (c) Inverted "C" shape.
CHAPTER 7. COMPTON IMAGING CAPABILITY BY SI/CDTE COMPTON CAMERA

7.2 The result of List-Mode Maximum Likelihood Expectation Maximization algorithm

The List-Mode Expectation Maximization Maximum Likelihood algorithm (LM-ML-EM) has been originally developed for medical imaging \cite{103} and is wide-spread currently in the field of Compton imaging \cite{104}, \cite{105}.

In the LM-ML-EM method, the data is treated as a list, not binned. List-mode methods are appealing in Compton camera image reconstruction because the total number of data elements in the list is significantly smaller than the number of possible combination of position and energy measurements, leading to a much smaller problem than that faced by traditional iterative reconstruction technique. For Compton cameras, the number of elements of the system matrix $M_s$ is as large as 10 billion per pixel of the image space. For an $N \times N$ image, direct reconstruction in 2D would involve inversion of $M_s N^2$ dimensional matrices, and iterative methods would require $10^{14}$ recursive multiplications. In the general case, the number of detected events $N_r$ will be much smaller than the number of system elements $M_s$. In the List-mode, each events is treated as a point in a continuous data space, rather than as contributing a count to a position and energy bin. Since $N_r << M_s$, the sizes of the matrices are greatly reduced and so the number of operations required in solving the problem will be reduced by a like amount. In addition, this technique has the advantage of preserving accuracy of measurement data that might otherwise be lost in discretizing of energy and position during binning procedure.

This algorithm tries to determine an image by maximizing the expectation of the underlying likelihood function. This results in an image which fits the data best. The basic iterative reconstruction algorithm is given by

$$\lambda_{j+1}^l = \frac{\lambda_j^l}{s_j} \sum_{i=1}^I \frac{t_{ij} \lambda_k^l}{\sum_k t_{ik} \lambda_k^l}$$

(7.1)

where, $\lambda_j^l$ denotes the image-bin content at iteration level $l$, $s_j$ the probability that an event emitted from $j$ would be detected anywhere, and $t_{ij}$ the probability that a photon emitted from $j$ is measured with the parameters of event $i$ (response). From image space, estimated data space is calculated with a response matrix (the term of $\sum_k t_{ik} \lambda_k^l$). Then, by comparing the expected data and measured data, corrections are made to image space.

The conservation of counts is proven from Eq. 7.1,

$$\sum_{j=1}^J \lambda_{j+1}^l s_j = \sum_{j=1}^J \lambda_j^l \sum_{i=1}^I \frac{t_{ij}}{\sum_k t_{ik} \lambda_k^l} = \sum_{i=1}^I \frac{\sum_j t_{ij} \lambda_j^l}{\sum_k t_{ik} \lambda_k^l} = \sum_{i=1}^I 1 = \text{number of measured photon}$$

which means that the sum of the estimation of the detected photons is preserved to be the total number of measured photon. Therefore, the width of image space should be determined to contain the all sources. If not so, the correct estimation of the intensity is difficult because the counts from outside sources remain in the image space.
The primary difficulty in applying the list-mode technique is in determining the parameters which describe the response of the imaging system \(s_j\) and \(t_{ij}\). The easy way to determine the \(s_j\), which is the average value as whole detector, is Monte-Carlo simulations or using experimental result directly. The \(t_{ij}\), the absolute probability that a photon emitted from \(j\) will rise to event \(i\) described by the measured quantities of \((x_1, E_1)\) and \((x_2, E_2)\), where \((x_1, E_1)\) is the measured position and energy deposit in the first detector, and \((x_2, E_2)\) is that in the second detector. Straightforward computation of the \(t_{ij}\) would not be impossible, but is daunting because it must take into account the finite position and energy resolution of the system, as well as Doppler broadening of the scattered photon energy distribution. We used the approximate way as follow.

Wilderman et al. [103] takes

\[
t_{ij} = p^\dagger_{ij}s_j \quad \text{with} \quad \sum_j p^\dagger_{ij} = 1
\]

where the \(p^\dagger_{ij}\) are the probabilities that a given event \(i\) emanated from an emission in pixel \(j\). They state that the \(p^\dagger_{ij}\) can be determined by back-projection cone determined by event \(i\), which traces out a conic section in the image plane. Only those points on the conic can be potential source points. This method gives approximately correct response for the real Compton scattering events recorded as event \(i\) which scattered in the first detector and then fully absorbed in the second detector. In this study, we drew the back-projection cone which has the gaussian width corresponding to the angular resolution, and then sampled the value of pixel \(j\) as \(p^\dagger_{ij}\).

### 7.2.1 The point sources

First, we test the algorithm with data sets obtained from the point source. We used the 356 keV gamma-rays from \(^{133}\)Ba and selected 1500 events which distribute in the energy window from 351 keV to 361 keV. Figure 7.3 summarize the decovolved images which placed at \((x, y, z) = (0, 0, 60), (0, -40, 60)\) and \((0, -80, 60)\). For the understanding of the property of the algorithm, we set \(s_j = 1\) all over the image space.

The total counts in the image space are preserved during the iterative operation, 1491, 1496, and 1497 for \((0, 0, 60), (0, -40, 60)\) and \((0, -80, 60)\) case, respectively. The slight decrease of the counts is due to the background events that the projected cone does not cross image space. The counts successfully gathered around the real source position within 10 operations, and stable at least 300 iterations that we examined. The black curves in the Fig. 7.4 shows the integrated counts of 25\(\times\)25 pixels corresponding 25\(\times\)25 mm around the source positions. The counts becomes less as the source approaches edge of the image space. This is due to the the asymmetry of the provability \((\sum_i t_{ij})\), which obviously recognized in the SBP image. As a result, the shape of the deconvolved point source is distorted for the source placed apart from the center position. In addition, as shown in the SBP in the case of \((0, -80, 60)\), the fake structure around \((x, y) = (0, 20)\) is generated in the opposite side of the real source position. This structure is stranded even after the deconvolution. For the sources located in the large inclination angle, this effect is emphasized.
Figure 7.3: The point source deconvolved images which placed at \((x, y) = (0,0), (0, -40)\) and \((0, -80)\). \(z\) is 60 mm for all.
7.2. THE RESULT OF LIST-MODE MAXIMUM LIKELIHOOD EXPECTATION MAXIMIZATION ALGORITHM

This fake structure arises a difficult problem for the estimation of the source intensity, particularly in the case that there are multiple sources in the image space. We combined the data obtained from (0,0,60) and (0,-80,60), then co-deconvolved the image with LM-ML-EM algorithm. The integrated counts within 25×25 pixels are also shown in Fig. 7.4 with red curves. The counts of (0,0,60) sources increased, while that of (0,-80,60) sources decreased than the counts obtained by single deconvolution. This is because the fake structure induced by edge source are absorbed in the central sources. This effect is an essential problem of the Compton imaging applying not only the LM-ML-EM algorithm.

![Figure 7.4: The integrated counts within 25×25 pixels around source position with respect to iteration numbers. (Black) : single deconvolution. (Red): co-deconvolution. see text for detail](image)

7.2.2 The extended sources

The result of the deconvolution for the extended source is shown in Fig. 7.5. We also showed the sensitivity map \( s_j \) used here (Fig. 7.5(a)) and the result of point source (7.5(b)) for the sake for comparison. The sensitivity map is calculated by Monte-Carlo simulation for the 356 keV gamma-ray. As shown in section 6.6.2 and 6.6.3, the difference between the simulated sensitivity and the experimental value is about 10 %. The asymmetry of the sensitivity is due to the detector configuration. We corrected the intensity of the deconvolved images by the effective observation time and absolute gamma-ray intensity of isotope \(^{133}\text{Ba}\) for point source and \(^{131}\text{I}\) for extended source). Therefore, the intensity of the images is in unit of Bq/area. We used \(6\times10^5\) events for both the circle and the inverted “C” shape sources, and showed the image after 10 iterations for all sources.

The imaging capability is improved when comparing of the deconvolved image with the SBP image. The shape of the source is well reproduced for both the circle and the
inverted “C”. The gap of 3 mm which corresponds to 4.8 \degree is clearly resolved. This results constitutes a good demonstration of the performance of the LM-ML-EM algorithm.

![Figure 7.5](image)

Figure 7.5: (a) The sensitivity map ($s_j$) obtained by Monte Carlo simulation. (b) The deconvolved image of point source for the sake or comparison. (c) The deconvolved image of circle shape. (c) The deconvolved image of inverted “C” shape.

In addition to the shape of the target, the intensity also gives an important information concerning high energy phenomenon. We extracted the value from the image pixels (1 \times 1 mm) corresponding to the real source shape, and calculated the mean of the distribution. The result is shown in Fig. 7.6 as a function of iteration number. The average intensity is preserved after 10 iterations up to 50 iterations. The intensity of source is obtained 4.3 kBq/mm$^2$ and 1.4 kBq/mm$^2$ for the circle and inverted “C” target, respectively. The prepared quantities of liquid $^{131}$I source soaked in the targets were
7.2. **THE RESULT OF LIST-MODE MAXIMUM LIKELIHOOD EXPECTATION MAXIMIZATION ALGORITHM**

11.4 kBq/mm² and 3.4 kBq/mm² for each target. The measured value differs from the prepared value about factor of three, but relative value between the two targets coincides well. The origin of the difference of the absolute value is under investigation. While the integrated intensity of the point source within 10×10 mm region around the source position is 2.3 MBq, which well agree with the real intensity of 2.7 MBq.

![Image](image.png)

**Figure 7.6**: The obtained source intensities with respect to iteration numbers

7.2.3 **The grid sources**

We performed image deconvolution by using the LM-EM-ML method for the grid source. A total of 1×10⁵ events are utilized in this process. Figure 7.7 shows the deconvolution results for the experimental data after the 100 times iterations. In the deconvolved image, the point sources placed at the edge become apparent in correct positions, while only the sources located in the central region are resolved in the SBP image (Fig. 7.2(b)).

It is also important to study the accuracy of positional determination of the point sources. We derived the center position of the sources from the deconvolved image shown in Fig. 7.7. For the 25 sources arranged in 5×5, the center position of each source was determined by calculating the weighted center around the largest counts pixel. The center positions are plotted as shown the left panel of Fig. 7.8 with open squares. Then based on the assumption that the sources are at the intersection of cross lines at a right angle, we fit the center positions. The red grid in the left panel of Fig. 7.8 shows the fitting results. The right panel of Fig. 7.8 summarizes the differences of these positions of all 25 sources as distributed within ∼1 mm. Thus, this experiment demonstrates positional determination accuracy of at least 1 mm for the point source.
Figure 7.7: The deconvolution results of the arranged point sources after the 100th iteration.

Figure 7.8: Left: measured source positions (open square) derived from the deconvolved image shown in the right panel of Fig. 7.7. The grid with red cross lines is the fitting result. Right: distribution of the difference of all 25 sources.
Chapter 8

Polarization measurement

Polarization measurements in the hard X-ray or gamma-ray band are expected to provide a powerful probe into high-energy photon emission mechanisms as well as the distributions of magnetic fields, radiation fields and interstellar matter. The physical processes such as synchrotron radiation, bremsstrahlung and Compton scattering generate polarized gamma rays. However, past and present gamma-ray instruments in orbit were not optimized to measure the photon polarization. Due to intrinsic polarization dependence of the Compton scattering angles, Compton cameras are one of the most promising polarimeters in the gamma-ray band.

We investigated the polarization measurement capability of the Si/CdTe semiconductor Compton camera by the experiment using synchrotron X-ray beam with nearly 100% linear polarization. We also evaluated the minimum detectable polarization of our Compton camera, which is critical to use it for gamma-ray polarization astrophysics.

8.1 Measurement of the degree of polarization and its direction

As described in section 3.5, the distribution of the azimuth angle of the Compton scattering depends on the polarization parameters of the incident gamma ray. This relationship can be used to deduce the polarization parameters from the azimuthal angle distribution observed in the detector.

Here, we define the experimental azimuthal angular distribution as \( N_{\text{pol}}(\phi) \). It is biased by detector configuration and individual response of the detectors. Past experiments rotated a whole detector system to reduce the effect of the azimuthal angle dependence of the detector response. Since rotating detector system is not easy to realize, we take alternative approach here. We utilize the detector response for the non-polarized gamma ray, \( N_{\text{non}}(\phi) \), which can be derived from a simulation or measured experimentally using non-polarized gamma-ray source. The corrected azimuthal angle distribution, \( N_{\text{true}}(\phi) \) is can calculated as

\[
N_{\text{true}} = \frac{N_{\text{pol}}(\phi)}{N_{\text{non}}(\phi)}
\]

When simulation is used to obtain \( N_{\text{non}}(\phi) \), it it critical to validate the simulation by experiments.
We define the measured modulation ratio as,

\[ R(\phi) = \frac{N_{\text{true}}(\phi) - N_{\text{true}}(\phi + \pi/2)}{N_{\text{true}}(\phi) + N_{\text{true}}(\phi + \pi/2)} \]  

(8.2)

This ratio is minimum in the direction of the incident polarization direction and the amplitude, \( Q = R_{\text{max}} - R_{\text{min}} \), is proportional to the degree of polarization. Thus the degree of the polarization can be given by

\[ \Pi = \frac{Q}{Q_{100}} \]  

(8.3)

where \( Q_{100} \) is the amplitude for 100% linearly polarized gamma rays. \( Q_{100} \) is known as the analyzing power of the instrument and needs to be determined by experiments or simulations.

### 8.2 Experimental setup

#### 8.2.1 Si/CdTe Compton camera configuration

We modified our detector system described in chapter 6 to optimize the configuration to improve the polarization sensitivity. The modulation of azimuth scattering angle (\( \eta \)) is maximized at the Compton scattering angle (\( \theta \)) of \( \sim 90 \) degree as shown in Fig. 3.12 in chapter 3. CdTe pixel detector are placed to maximum the detection efficiency of gamma rays scattered in the DSSD with a scattering angle of \( \sim 90 \) degree. Figure 8.1 shows the photograph of the Compton camera. Thirty four VA64TA ASICs are used to readout 2176 detector channels. The left panel of Fig. 8.2 shows the configuration of the Si/CdTe Compton camera. The CdTe pixel modules on the horizontal side of the DSSD covers the scattering angle of 80 to 105 degrees for incident gamma rays along the z-axis.

The right panel of Fig. 8.2 shows the mass model of the DSSD. The non-uniform passive material around the DSSD is main contributer to the axial asymmetry of the system. Although the average thickness of support material around the DSSD is reduced to 1.4 g/cm\(^2\), the effect of passive material is still significant and needs to be modeled in the simulation as precisely as possible. We include the plastic frame, circuit boards and ASICs according to the design of the DSSD.
Figure 8.1: Photograph of the Compton camera for polarization measurements
8.2.2 Beam line setup

The experiment was performed at synchrotron beam line BL08W in SPring-8 [106] on 23–25 October 2008. The schematic view of our experimental setup is shown in Fig. 8.3. The incident beam energy was 250 keV and the beam intensity was $2 \times 10^{10}$ photons/s which is too intense for our detector system. In order to reduce the beam intensity, we used photons scattered horizontally to the beam direction in a aluminum block placed in the beam line. As shown in the schematic view of the experimental setup, the Compton camera is shielded by Pb in such way that only photons with a scattering angle of $90 \pm 1.5^\circ$ are viewed by the detector. The resulting energy and polarization degree of the incoming photon are $168 \pm 1.4$ keV and 92.5 %, respectively.

The data of the various incident polarization vector can be obtained by rotating the Compton camera itself. As shown in Fig. 8.3, we rotated the Compton camera for seven angles of polarization vector at 0, 15, 22.5, 30, 45, 90 and 180 $^\circ$ with respect to the Compton camera coordinate.
8.2. EXPERIMENTAL SETUP

Figure 8.3: The schematic view of experimental setup at beam line.
8.3 Measurement of experimental azimuthal angular distribution

We used the events recorded in the DSSD and the CdTe side detectors. The left panel in Fig. 8.4 shows the 2-dimensional scatter plot of energy deposited in the DSSD and the CdTe side detectors. The peak around Si energy deposit of $\sim 40$ keV and CdTe energy deposit of $\sim 130$ keV should correspond to the events that incident 168 keV gamma-rays are scattered in the DSSD into the horizontal direction and then fully absorbed in the CdTe side detectors. We selected the events which satisfy $165 \text{ keV} < E_{\text{Si}} + E_{\text{CdTe}} < 175 \text{ keV}$ and $35 \text{ keV} < E_{\text{Si}} < 50 \text{ keV}$ (red lines in the scatter plot of Fig. 8.4). The right panel in Fig. 8.4 shows the ARM distributions; the black dotted line shows the ARM distribution of all events, and the red line shows that of events selected in the energy. With this selection, the desired events that incident gamma-rays were Compton-scattered in the DSSD and were absorbed in the CdTe side detectors were picked up effectively, and, most of other type events were removed.

Figure 8.4: (Left) Two dimensional scatter plot of energy deposited in the DSSD and CdTe side detector. We use the events surrounded by led lines for analysis. see text for detail. (Right) The ARM distribution before energy range cut (black) and after energy range cut (red)

The azimuth scattering angle was derived from the positions of energy deposit in the DSSD and the CdTe detectors. Figure 8.5 show the azimuth scattering angle distribution, \( N_{\text{pol}}(\phi) \), without any correction of the detector response for $\phi_{\text{pol}} = 0^\circ$ (see. Fig. 8.3). The experimental data (black histogram) are compared with the simulation result (red points) for incident gamma rays with an energy of 170 keV and 92.5 % polarization. The counts around $-90$ and $+90^\circ$ are much higher than those around 0 and $180^\circ$ due to the polarization of incident gamma rays. The simulation reproduced the features of the experimental data very well, including the $\sim 10\%$ difference of the counts between $-90^\circ$ and $+90^\circ$, which results from the asymmetry of passive materials around the DSSD.
8.4 Results

The azimuth scattering angle distributions for all measured data of the polarization vector direction are shown in Fig. 8.7. In order to correct for the detector response in the experimental results, we have simulated the $N_{\text{non}}(\phi)$, the azimuth scattering angle distribution for non-polarized gamma rays with an energy of 170 keV as shown in Fig. 8.6. In this simulation, dispersion of the incident gamma-ray direction ($\pm 1.5$ deg) is ignored. We added 3% systematic error in addition to the statistical error of each point to account for uncertainties of the simulator. The gap around $-135, -45, 45$ and $135^\circ$ corresponds to the absence of the CdTe detector on the side. According to Eq. 8.1 and 8.2, we obtained $N_{\text{true}}(\phi)$ distribution and calculated the modulation ratio. The modulation ratio plots for all experimental setups are shown in Fig. 8.8 together with the best fitted model function. The function is obtained by fitting the $N_{\text{true}}(\phi)$ distribution with model function of $p_0 + p_1 \cos (2(\phi - \phi_0))$. Note that we ignored the angle bin of $-135 \pm 10^\circ, -45 \pm 10^\circ, 45 \pm 10^\circ$ and $135 \pm 10^\circ$, where the direction is not covered by the CdTe detectors.

The fit results are summarized in Table 8.4. The amplitudes were determined to be in the range of 0.82–0.85, which have errors of 0.02–0.03. The amplitude for 100% polarization at 170 keV, $Q_{100}$, obtained to be 0.925 ±0.03 from the simulation. From Eq. 8.3, the degree of polarization of the incident beam is determined to be 89.7 ±3.6%, which is consistent with the incident polarization degree of 92.5% expected for our experimental setup. The directions of the polarization vectors were determined for all measurements within accuracies of 1 degree. It should be noted that both polarization degree and the
Figure 8.6: The simulated non-polarization response. The gap structures around -135, -45, 45 and 135 ° direction are due to the geometrical effect.

direction of the polarization vector can be determined well at the unfavorable direction of the polarization vector (e.g. $\phi_{\text{pol}}=45^\circ$) where the detection of the azimuth scattering angle peaks at the direction corresponding the gap of the detector response.

<table>
<thead>
<tr>
<th>Setup</th>
<th>$\phi_{\text{pol}}$ (°)</th>
<th>Amplitude</th>
<th>Polarization vector</th>
<th>$\chi^2$/ndf</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>0.82 ± 0.02</td>
<td>0.6 ± 0.5</td>
<td>66.4/53</td>
</tr>
<tr>
<td>2</td>
<td>15.0</td>
<td>0.82 ± 0.02</td>
<td>14.7 ± 0.7</td>
<td>56.0/53</td>
</tr>
<tr>
<td>3</td>
<td>22.5</td>
<td>0.83 ± 0.02</td>
<td>23.4 ± 0.6</td>
<td>48.0/53</td>
</tr>
<tr>
<td>4</td>
<td>30.0</td>
<td>0.85 ± 0.02</td>
<td>30.0 ± 0.6</td>
<td>52.8/53</td>
</tr>
<tr>
<td>5</td>
<td>45.0</td>
<td>0.83 ± 0.03</td>
<td>45.0 ± 0.5</td>
<td>52.6/53</td>
</tr>
<tr>
<td>6</td>
<td>90.0</td>
<td>0.83 ± 0.02</td>
<td>89.3 ± 0.6</td>
<td>44.5/53</td>
</tr>
<tr>
<td>7</td>
<td>180.0</td>
<td>0.82 ± 0.02</td>
<td>180.1 ± 0.6</td>
<td>59.4/53</td>
</tr>
</tbody>
</table>

Table 8.1: Fitting results
Figure 8.7: The azimuth angle distribution for all experimental setup.
Figure 8.8: The obtained modulation ratio for all experimental setup.
8.5 Discussion to the detection limit of polarization

For most polarized astronomical source, 10–20 % polarization is expected. This means that the systematic error of the measurement must be reduced to better than a few %. In our case, uncertainties of the detector response for non-polarized photons are the dominant source of the systematic error.

The best way to evaluate the systematic error is to perform polarization measurements with low degree of polarized gamma-ray sources. Since we do not have such experimental data in hand, we synthesized dummy data with arbitrary degree of polarization by sampling events from experimental data at \( \phi_{pol} = 0^\circ \) and \( \phi_{pol} = 90^\circ \) with appropriate ratio. The dummy cross section is

\[
\left( \frac{d\sigma}{d\Omega} \right)_{\text{dummy}} = \alpha \left( \frac{d\sigma_{KN}}{d\Omega} \right)_{\phi} + \beta \left( \frac{d\sigma_{KN}}{d\Omega} \right)_{\phi + \frac{\pi}{2}}
\]  

(8.4)

The amplitude of the modulation ratio in this case,

\[
\frac{d\sigma(\phi = \pi/2) - d\sigma(\phi = 0)}{d\sigma(\phi = \pi/2) + d\sigma(\phi = 0)} = Q_{100} \left( \frac{\alpha - \beta}{\alpha + \beta} \right)
\]  

(8.5)

where \( Q_{100} \) is the amplitude for 100 % polarized gamma-rays. Although this synthesized data is not real data, it is useful to evaluate systematic bias due to uncertainties of the detector response simulation.

We synthesized dummy data samples for 10 % and 0 % polarization using the experimental data samples from setup 1 and 6 (See Fig. 8.3). Figure 8.9 shows resulting modulation ration distribution. We can clearly recognize the modulation due to polarization in the 10 % sample while we observe no apparent modulation in the 0 % sample.

This result demonstrates that the systematic uncertainties due to the detector response does not significantly affect the measurement of 10 % polarization.
Figure 8.9: (Upper panel) The modulation ratio derived from "dummy" data for 0 % polarization. (Bottom panel) The modulation ratio derived from "dummy" data for 10 % polarization.
Chapter 9

Performance study for a satellite mission

9.1 Soft Gamma-ray Detector onboard ASTRO-H

Based on the detector technologies established in this thesis, Soft Gamma-ray Detector (SGD) has been proposed [65, 66, 107, 108, 109, 110] as a soft gamma-ray detector onboard ASTRO-H (http://astro-h.isas.jaxa.jp/). ASTRO-H is the sixth in a series of Japanese x-ray astronomy satellite after Suzaku [2], planned to be launched in 2013. SGD combines the concept of Si/CdTe Compton camera and the narrow FOV active collimator (See Section 4.4), and is designed to achieve ultimately low background observation by utilizing the Compton kinematics.

Figure 9.1: (Left) The effective area of SGD. The sum of eight modules are presented. (Right) The estimated background level per geometrical area.

Figure 9.1 shows the effective area and the estimated in-orbit background level shown in the proposal. The effective area is calculated by using Monte Carlo simulation specially tuned for SGD. One SGD module consists of central 32 layers of 0.6 mm thick Si detectors surrounded by eight layers of CdTe bottom detectors and two layers of CdTe side detectors with thickness of 0.75 mm. The geometrical area of one SGD module is $5.12 \times 5.12 \text{ cm}^2$. We select two-hits events, which satisfy Compton kinematics and have the Compton cone...
corresponding to the incident direction limited by active collimator, for both Si/CdTe and CdTe/CdTe combination. The total effective area of 30–40 cm$^2$ could be achieved by eight modules of SGDs in the energy band from several tens keV to a few hundred keV. The background level shown in Fig. 9.1 (right) is calculated for the orbit with an altitude of $\sim$570 km and an inclination of 32$^\circ$, which is equivalent to the Suzaku orbit. In-orbit data taken with HXD-PIN Silicon detector [77, 78, 79] onboard Suzaku is used to estimate the flux of non-Xray background. According to recent studies [111], atmospheric neutrons are the major contributor to the residual background in HXD-PIN. In the case of SGD, this background is drastically reduced by requiring Compton kinematics. Based on the data taken from experiments done at accelerator [112], we add background due to activation caused by cosmic particles hit on CdTe detectors. The calculated SGD background is about two orders of magnitude lower than that of HXD. More detailed studies about in-orbit performances are now under way.

Figure 9.2 shows the continuum sensitivity of SGD estimated from the effective area and the background level. The sensitivity of less than 1 mCrab (100 ksec) would be achieved from the 80 keV to 300 keV energy window. This sensitivity is one order of magnitude better than existing observatories. Furthermore, line sensitivity of $10^{-5}$count/sec/cm$^2$ for 511 keV gamma-ray provides detailed spectral analysis of the electron-positron annihilation line from the Galactic Center region or X-ray binary system.

![Figure 9.2: Detection limits of SGD (green) for point source as function of gamma-ray energy, where the spectral binning with $\Delta E/E = 0.5$ and 100 ksec exposure are assumed.](image)

The polarization measurements of black hole candidates, pulsar or TeV blazar could be possible in the hard X-ray or gamma-ray band for the first time. Table 9.1 shows the key polarimetric characteristics of SGD and Fig. 9.3 shows the estimated minimum detectable polarization (MDP) [32] with respect to observation time. Note that we didn’t take account of the uncertainty from the non-polarized photon response and the error in background subtraction. These factors degrade the polarization sensitivity, therefore, it is important to improve the accuracy of the response and to model the in-orbit background precisely. Potentially, SGD realizes the MDP of 1.1 % for 1 Crab source and that of 3.6 % for 100 mCrab source after observation time of 100 ksec.
9.2 Study for future all-sky survey mission

One more attractive mission for a Compton camera is the all-sky survey. Such observation addresses the diffuse structure in the universe, such as the Galactic center region or SNR and the transient phenomenon such as gamma-ray burst or flaring AGNs. We aim at sensitivity improvement of a factor of 10 over COMPTEL with significantly more compact instrument utilizing powerful background rejection capabilities resulting from the instrument’s high energy and angular resolution. As a next generation all-sky monitor, the requirements for an instrument are less than 2° angular resolution and 1 mCrab sensitivity through the mission interval. The Si/CdTe Compton camera potentially satisfies this over a wide energy band from a very low energy threshold of 500 keV gamma-ray, which is proved experimentally in Chapter 5.

For the all-sky survey, because of the high penetrating power of the gamma-ray, it is important to gain higher detection efficiency by optimizing the detector system. In addition, the estimation of the background level induced by cosmic photons, albedo photons, albedo neutrons and activation of the detector system itself is an important task. We have demonstrated the consistency of our Monte Carlo simulation through the various experiment described in this thesis. The experimental efficiency and angular resolution were well reproduced. In this chapter, we investigate the performance for future all-sky survey mission with the simulator.

### Table 9.1: The key polarimetric characteristics of SGD.

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>Modulation factor</th>
<th>Efficiency</th>
<th>Area (cm²)</th>
<th>Background (counts/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SGD 80–300 keV</td>
<td>0.58</td>
<td>8.7 %</td>
<td>210</td>
<td>~1×10⁻²</td>
</tr>
</tbody>
</table>

Figure 9.3: Minimum Detectable Polarization (MDP) of SGD with respect to observation time
CHAPTER 9. PERFORMANCE STUDY FOR A SATELLITE MISSION

9.3 Optimization of Si/CdTe Combination

For the Si/CdTe Compton camera, the optimization of the combination of the Si and CdTe detector is essential to obtain high detection efficiency. We compare the five types of combinations by using Monte Carlo simulation. Figure 9.4 illustrates the mass models of the Compton cameras. They consist of 96 layers of semiconductor detectors with a pitch of 2.5 mm. The geometrical area of the detector is $25 \times 25 \text{ cm}^2$. The thickness of the Si detector is 500 $\mu$m, we also prepared two types of CdTe detector with a thickness of 500 $\mu$m and 2 mm for comparison. The X-Y position resolution of the detectors is 400 $\mu$m, which had been already established in our laboratory. For the energy resolution, we considered the 1.5 keV (FWHM) electronics noise and statistic noise with 0.1 Fano factor and 4.0 eV average ionization energy for both Si and CdTe devices.

![Diagram of Compton camera configurations](image)

Figure 9.4: The configuration of Compton camera for the optimization study. (a) All Si layers, (b) Si : CdTe = 3 : 1, (c) Si : CdTe = 1 : 1, (d) Si : CdTe = 1 : 3, (e) All CdTe layers.

Figure 9.5 summarizes the detection efficiency for the full energy deposit Compton events (more than one Compton scattering and final photo absorption) for 511 keV (red filled circle: 2 mm thick CdTe, red open circle: 500 $\mu$m thick CdTe) and 1.8 MeV (black filled square: 2 mm thick CdTe, black open square: 500 $\mu$m thick CdTe) gamma-rays. Gamma-rays are injected at the center of the top layer. The X-axis is the ratio of the number of CdTe layers to all layers. By using the 2 mm thick CdTe detector, the detection efficiency improves factor 2–3 and 4–5 for 511 keV and 1.8 MeV gamma-rays, respectively. Potentially more than 40 % of detection efficiency is achievable for 511 keV and more than 20 % for the 1.8 MeV by Si and 2 mm thick CdTe combination. Although the angular resolution is worse due to the Doppler broadening effect and short distance of interaction, a high detection efficiency of 70 % is feasible for the case of the Compton camera comprising all the CdTe detectors. Figure 9.6 shows the detection efficiency of Si/CdTe Compton events that the sequence starts from Compton scattering in Si and ends in CdTe by absorption. The detection efficiencies of 13 % for 511 keV and 6 % for 1.8 MeV gamma-rays are achievable with the combination of 3:1 or 1:1 (Si : CdTe).
9.3. OPTIMIZATION OF SI/CdTe COMBINATION

Figure 9.5: The detection efficiency for the full energy deposit Compton events (more than one Compton scattering and final photo absorption) for 511 keV (red filled circle: 2 mm thick CdTe, red open circle: 500 μm thick CdTe) and 1.8 MeV (black filled square: 2 mm thick CdTe, black open square: 500 μm thick CdTe) gamma-rays.

Figure 9.6: The detection efficiency of Si/CdTe Compton events that the sequence starts from Compton scattering in Si and ends in CdTe (2 mm thick) by absorption.
One more important criterion for the optimization is angular resolution. Figure 9.7 shows the average angular resolution for each combination. For the 511 keV incident gamma-rays, we selected simply two-hit events and calculated the ARM. On the other hand, for the 1.8 MeV gamma-rays, the probability of such simple Compton and photo absorption events in the two-hit data space is very low because the scattered electron passes through several layers of the stacked Si detectors and records a lot of hit information. We clustered such electron tracking events as described in section 9.4, then calculated the ARM. As the number of Si layers decreases, the angular resolution becomes worse. This is because the accuracy of the determination of the Compton cone axis is deteriorated due to the shorter interaction distance of Si and CdTe events. For the case of the 3:1 (Si:CdTe) combination, the best angular resolutions of 1.6° (FWHM) for 511 keV and 1.8° (FWHM) for 1.8 MeV are obtained. The angular resolution of 1.8 MeV gamma-rays is worse than that of 511 keV despite the lower Doppler broadening effect because the uncertainty of the energy determination is transferred when we add up the electron deposit energies; however, such events make it possible to restrict the direction of the incident gamma-rays to the arc, therefore good background rejection capability would be achievable. The Compton camera consisting of all the layers of the CdTe detectors is not suitable for the all-sky survey below the 1 MeV region due to poor angular resolution, but would be suitable in the region above a few MeV. As shown in Fig. 9.6, the Si/CdTe Compton camera with combination of a 3:1 and 1:1 type has almost the same detection efficiency. From the point of view of the angular resolution, we should select the 3:1 combination for practical use. Hereafter, we will continue our study with the Compton camera consisting of the 3:1 (Si:CdTe) combination.

![Simulated Angular Resolution](image-url)

Figure 9.7: The average angular resolution for each combination
9.4 Detection efficiency

In section 9.3, we showed that the detection efficiency of Si/CdTe Compton events, which start sequences by Compton scattering in Si and end by CdTe in photo absorption, is 13% for 511 keV and 6% for 1.8 MeV gamma-rays (see Fig. 9.6). However, this is only the potential detection efficiency. We have to find the Compton events from the data space of the Compton camera. The number of events correctly obtained from data space reflects the real detection efficiency.

In the Compton camera, various kinds of hits are recorded. Figure 9.8 shows an example of the Si and CdTe Compton event which does not appear in the simple two-hit data space. In the scattering site, the scattered electron tends to escape from the single Si layer above several hundreds keV. In the case of 1.8 MeV incident gamma-rays, the typical energy transferred to the electron is about 600 keV for 30° Compton scattering (maximum is 1.5 MeV). In this case, the electron penetrates the 500 μm thick Si detector and passes though several Si layers. In the absorption site, the interaction which increases hit information also occurs. As shown in the diagram, the fluorescence X-ray from Cd (Kα: 23.1 keV, Kβ: 26.1 keV) and Te (Kα: 27.4 keV, Kβ: 31.0 keV) occasionally escape from the CdTe detector, and is then absorbed in another detector. These kinds of Compton events are recorded in the higher degree of the events space. Figure 9.9 shows the multiplicity of the hits for 511 keV (left) and 1.8 MeV (right). The multiplicity increases as the energy of the incident gamma-ray becomes larger. For 1.8 MeV incident gamma-ray, the percentage of the hits above 4 is 52%, in which most Compton events exist.

Figure 9.8: An example of the Compton event which increases hit information.
CHAPTER 9. PERFORMANCE STUDY FOR A SATELLITE MISSION

8.50 4+ hits
12.00 4 hits
24.00 3 hits
31.40 2 hits
24.10 1 hit

511 keV gamma-rays (Raw Data)

Figure 9.9: The multiplicity of the hits for 511 keV (left) and 1.8 MeV (right).

One idea is to compress the hits according to a certain criteria, thus we have developed the compression method as follows:

- Compression of the CdTe fluorescence X-ray event. First, we search the hit which has an energy deposit in the ± 2 keV window of the fluorescence energy; they are suspects. This search is performed for all CdTe layers and a total of 12 Si layers near the CdTe detector. The mean free pass of the 30 keV photon in Si is 3 mm, therefore almost 90 % of the fluorescence X-ray should be absorbed in 12 Si layers. Then, we search the parent, whether there is a hit adjacent layer or not. When there are suspects in the Si layer, the target is nearest the CdTe detector. If the parent hit is found, we compress the suspect into this parent hit.

- Compression of electron tracking event. First, we search the continuous hits in the detector. Then, we compare the sum of the two-hits located on the edges of the track. The edge with the lower energy deposit is judged as the start point of the track because the energy deposit increases at the end of the electron pass.

After operating this method, the higher degree of multiplicity is compressed as shown in Fig. 9.10. The performance of this method is summarized in Table 9.2 for 511 keV and Table 9.3 for 1.8 MeV incident gamma-rays. The numbers in the tables show the detection efficiency for each sequence. The red figures show the Si/CdTe Compton events. For the 511 keV gamma-rays, we can recognize a total of 9.7 % Compton events in compressed two and three-hit spaces, which is 74.6 % for all Compton events (13 %, see Fig. 9.6). In the case of 1.8 MeV, a total of 3.62 % Compton events are recognized, which is 60.3 % for all Compton events (6 %, see Fig. 9.6).
Figure 9.10: The multiplicity of the hits after hit compression, for 511 keV (left) and 1.8 MeV (right).
Table 9.2: The detection efficiency for various sequences. Before and after hit compression. The 511 keV incident gamma-rays injected at the center of the top layer. “Abs” means photo absorption and “Comp” means Compton scattering.

<table>
<thead>
<tr>
<th>Multiplicity</th>
<th>Events</th>
<th>Raw Data</th>
<th>Compressed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Hit</td>
<td>CdTe (Abs)</td>
<td>7.96%</td>
<td>15.67%</td>
</tr>
<tr>
<td></td>
<td>Si (Abs)</td>
<td>0.36%</td>
<td>0.55%</td>
</tr>
<tr>
<td></td>
<td>Si (Comp)</td>
<td>10.75%</td>
<td>14.74%</td>
</tr>
<tr>
<td></td>
<td>CdTe (Compton)</td>
<td>3.12%</td>
<td>9.06%</td>
</tr>
<tr>
<td></td>
<td>Others</td>
<td>0.80%</td>
<td>3.95%</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>22.99%</td>
<td>43.98%</td>
</tr>
<tr>
<td>Two Hit</td>
<td>Si (Comp) CdTe (Abs)</td>
<td>3.13%</td>
<td>5.57%</td>
</tr>
<tr>
<td></td>
<td>CdTe (Comp) CdTe (Abs)</td>
<td>11.05%</td>
<td>8.91%</td>
</tr>
<tr>
<td></td>
<td>2 Times Compton</td>
<td>7.32%</td>
<td>13.94%</td>
</tr>
<tr>
<td></td>
<td>Others</td>
<td>8.47%</td>
<td>4.55%</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>29.97%</td>
<td>32.97%</td>
</tr>
<tr>
<td>Three Hit</td>
<td>Si (Comp) Si (Comp) CdTe (PhotoAbs)</td>
<td>1.31%</td>
<td>1.96%</td>
</tr>
<tr>
<td></td>
<td>Si (Comp) CdTe (Comp) CdTe (Abs)</td>
<td>3.35%</td>
<td>2.17%</td>
</tr>
<tr>
<td></td>
<td>CdTe (Comp) CdTe (Comp) CdTe (Abs)</td>
<td>7.06%</td>
<td>2.16%</td>
</tr>
<tr>
<td></td>
<td>3 Times Compton</td>
<td>2.78%</td>
<td>4.74%</td>
</tr>
<tr>
<td></td>
<td>Others</td>
<td>8.42%</td>
<td>2.60%</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>22.92%</td>
<td>13.6%</td>
</tr>
<tr>
<td>Four Hits</td>
<td>Total</td>
<td>12.15%</td>
<td>3.76%</td>
</tr>
<tr>
<td>Multi Hits</td>
<td>Total</td>
<td>7.37%</td>
<td>1.06%</td>
</tr>
</tbody>
</table>
Table 9.3: The same as Table 9.2, but for 1.8 MeV incident gamma-rays.

<table>
<thead>
<tr>
<th>Multiplicity</th>
<th>Events</th>
<th>Raw Data</th>
<th>Compressed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Hit</td>
<td>CdTe (Abs)</td>
<td>2.33%</td>
<td>8.13%</td>
</tr>
<tr>
<td></td>
<td>Si (Abs)</td>
<td>0.03%</td>
<td>0.28%</td>
</tr>
<tr>
<td></td>
<td>Si (Comp)</td>
<td>1.11%</td>
<td>8.46%</td>
</tr>
<tr>
<td></td>
<td>CdTe (Compton)</td>
<td>5.81%</td>
<td>9.33%</td>
</tr>
<tr>
<td></td>
<td>Others</td>
<td>0.19%</td>
<td>6.20%</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>9.47%</td>
<td>32.39%</td>
</tr>
<tr>
<td>Two Hit</td>
<td>Si (Comp) CdTe (Abs)</td>
<td>0.18%</td>
<td>1.90%</td>
</tr>
<tr>
<td></td>
<td>CdTe (Comp) CdTe (Abs)</td>
<td>1.83%</td>
<td>5.71%</td>
</tr>
<tr>
<td></td>
<td>2 Times Compton</td>
<td>1.61%</td>
<td>7.00%</td>
</tr>
<tr>
<td></td>
<td>Others</td>
<td>3.54%</td>
<td>10.76%</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>7.17%</td>
<td>25.37%</td>
</tr>
<tr>
<td>Three Hit</td>
<td>Si (Comp) Si (Comp) CdTe (PhotoAbs)</td>
<td>0.02%</td>
<td>0.60%</td>
</tr>
<tr>
<td></td>
<td>Si (Comp) CdTe (Comp) CdTe (Abs)</td>
<td>0.20%</td>
<td>1.12%</td>
</tr>
<tr>
<td></td>
<td>CdTe (Comp) CdTe (Comp) CdTe (Abs)</td>
<td>1.12%</td>
<td>1.92%</td>
</tr>
<tr>
<td></td>
<td>3 Times Compton</td>
<td>0.38%</td>
<td>2.22%</td>
</tr>
<tr>
<td></td>
<td>Others</td>
<td>7.39%</td>
<td>7.04%</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>9.12%</td>
<td>12.91%</td>
</tr>
<tr>
<td>Four Hits</td>
<td>Total</td>
<td>10.82%</td>
<td>4.36%</td>
</tr>
<tr>
<td>Multi Hits</td>
<td>Total</td>
<td>39.79%</td>
<td>1.32%</td>
</tr>
</tbody>
</table>
Finally, we reconstructed the events according to the Compton equation. Figure 9.11 shows the spectrum generated from compressed Si and CdTe two-hit data space. Black shows all Si/CdTe events. Green shows the spectrum after $3\sigma$ ARM selection. The continuous component caused by Compton escape events is reduced drastically. The detection efficiency of photo peak events remaining after the ARM selection is $5.8\%$ for 511 keV gamma-rays and $1.7\%$ for 1.8 MeV gamma-rays. These results are consistent with the value of “Two Hit Si(Comp) CdTe (Abs)” events in the Table 9.2 and 9.3. Red shows the remaining spectrum after “horizon cut” selection. In this selection, we excluded the events that the Compton cone interacts with the horizon plane on the detector coordinate. This selection can reduce the background events coming from the backward direction such as albedo gamma-rays. The remaining full peak efficiency is $4.8\%$ for 511 keV gamma-rays and $1.6\%$ for 1.8 MeV gamma-rays, respectively. The energy resolution obtained is $0.6\%$ (FWHM) and $0.3\%$ for 511 keV and 1.8 MeV, respectively.

Figure 9.11: The spectrum generated from compressed Si and CdTe two-hit data space. (black) All Si/CdTe events. (green) After $3\sigma$ ARM selection. (red) ARM selection and “horizon cut” selection
9.5 Background Estimation and sensitivity

Besides the detection efficiency, the study of the background is also important because the sensitivity is limited by the orbital background caused by albedo gamma-rays, albedo neutrons, cosmic protons and cosmic photons etc. By using Compton imaging capability, we can extract the signals from the celestial target, but it is still contaminated by the background remaining after background reduction.

In the simulation we assumed an equatorial orbit at 550 km altitude to avoid passage through the South Atlantic Anomaly (SAA) and thus prevent activation of the detector material by trapped protons. In the simulation, the contribution from the cosmic photon, cosmic proton, albedo photon and albedo neutron is studied. The other particles such as cosmic electron or positron would not give considerable effect according to the previous satellite mission. The input spectra based on the CREME96 [113] package are shown in Fig. 9.12. CREME96 is widely used to give dose predictions for determining satellite electronics design constraints and has been shown to be accurate at predicting galactic cosmic ray, anomalous cosmic ray, and solar flare components of the near-earth environment for the different components. Due to the geomagnetic cutoff, cosmic protons need energy at least of 10 GeV to reach the low earth orbit (LEO) as shown with blue line in Fig. 9.12. We simply assumed that albedo photon and neutron come from the direction below the horizontal plane, and the cosmic photon comes from 0–90° direction from the zenith. In order to simulate the activation of heavy materials caused mainly by cosmic protons, we used an MGGPOD [114] package developed to simulate the physical processes relevant for the production of instrumental backgrounds. This has been successfully applied to modelling the instrumental backgrounds of the TGRS [115] and RHESSI [116] instruments consisting of Ge detectors. In our case, the reproduction of the activation of the CdTe materials is most important. Detailed verification of the code by testing with accelerator is our next assignment.

Figure 9.12: Input spectra for the background simulation.
As a mass model for the performance study, we used 96 layers of Si and CdTe stack detectors with the combination of 3:1, which was studied in section 9.3 and proved to have the maximum detection efficiency and better angular resolution. Geometrical area of the detector is $25 \times 25 \text{ cm}^2$. The main detector is surrounded by active BGO shield with the thickness of 4 cm (Fig. 9.13). As shown in Fig. 9.12, above a few hundreds keV, the flux of the albedo gamma-ray is one order of magnitude larger than that of cosmic photon and becomes a main contributor to background events. The active 4 cm thick BGO can stop over 99% of 500 keV and 80% of 800 keV gamma-rays. This model detector consists of 144 kg of materials, of which 5.2 kg are Silicon, 17.5 kg CdTe, and 121 kg BGO.

Figure 9.13: Mass model of the Compton camera for background estimation

Figure 9.14 shows the results of the background simulation. For comparison, we showed the count rate of Crab like source (assumed $10 \times 10^{-2.0}$ counts/sec/keV/cm$^2$) on the vertical direction with the black line. The red line is the component of cosmic photon and the green one is the albedo photon, blue is that of albedo neutron and yellow is that of activation of the CdTe detectors. The upper panel shows the entire Si/CdTe two-hit event spectrum and the bottom panel shows the remaining spectrum after background reduction. In this case, we exclude the events where the calculated cone does not cross the vertical direction within $3 \sigma$ of the ARM. Furthermore, we use the “horizon cut” selection described in section 9.4. The background events are suppressed about one or two orders of magnitude, but the reduction of the celestial signals is only factor of two or three.

Sensitivity describes the weakest source which can still be detected with a certain
Figure 9.14: Background rate of model detector. Upper: All Si/CdTe two-hit events, Bottom: After background rejection. (Black) Crab like source, (Red) Cosmic photon, (Green) Albedo photon, (Blue) Albedo neutron, (Yellow) CdTe activation.
significance. For point sources the following equation holds:

\[ F_z = \frac{z\sqrt{N_S + N_B}}{T_{eff}A_{eff}} \]  

(9.1)

where \( F_z \) is the \( z\sigma \) sensitivity limit, expressed in terms of the flux, a source must be detected at this sensitivity limit, \( N_S \) is the number of source photons, and \( N_B \) is the number of background photons in the resolution element. \( A_{eff} \) is the effective area of a detector, and \( T_{eff} \) is the effective observation time. In this work, the resolution element is defined by an ARM and the energy window around the known source position.

Figure 9.15 shows the 3 \( \sigma \) continuum (Top) and narrow line (Bottom) sensitivity estimated from the background level and the detection efficiency. We make a comparison between them and the sensitivity achieved by SPI (blue line) onboard INTEGRAL and the COMPTEL (green line) onboard CGRO, which is the best sensitivity achieved in the energy band from 100 keV to 10 MeV (see Fig. 1.1). It should be noted that the sensitivity of COMPTEL is average after a nine-year mission. The continuum sensitivity of the model detector is at least 5 times better than that of SPI below 1 MeV under the same condition of 10\(^6\) observation time. Utilizing the wide field Compton camera, we can obtain effective observation time of \( 3 \times 10^7 \) on average after 3–5 years operation. In that case, sensitivity better than 1 mCrab is obtained, which is one order of magnitude better than any past and existing observatories. The narrow line sensitivity also exceeds the level achieved by SPI using Ge detectors. After 3–5 years observation, the line sensitivity better than \( 1 \times 10^{-6} \) photons/cm\(^2\)/sec can be achieved for all 511 keV, 847 keV (\(^{57}\)Co), 1157 keV (\(^{44}\)Ti) and 1809 keV (\(^{26}\)Al).

Finally, we present the simulated sky image of the anti-galactic center region after the effective time of 67 ksec in Fig. 9.16. The EGRET third catalog sources [117] are scaled to the 500 keV to 10 MeV with a simple power law model as well as the appropriate amount of background. We operated the LM-ML-EM algorithm (see Chapter 7) with 100 times iteration. We can already recognize several tens mCrab sources after 100 ksec level exposure.
Figure 9.15: (a) $3\sigma$ continuum sensitivity (b) $3\sigma$ narrow line sensitivity
Figure 9.16: Simulated sky image of the galactic anticenter as seen by model Compton camera after effective time of 67 ksec. The EGRET sources are scaled to the 500 keV to 10 MeV with simple power law model as well as the appropriate amount of background.
Chapter 10

Conclusion

The Compton camera consisting of the Si and CdTe semiconductor was successfully developed. Through the experimental studies concerning detection efficiency, angular resolution, imaging capability and ability for polarization measurement, we obtained the following results.

- The Compton reconstruction was successfully performed in the energy band from 59.5 keV to 662 keV. The upper limit is simply due to the dynamic range of the analog ASICs used in this study.

- The detailed detector response study for both Si and CdTe detectors was performed. The absolute detection efficiency of the Compton camera for two main observation modes, “Photo-absorption mode” and “Compton mode”, was well reproduced by the Monte Carlo simulator into which a thermal diffusion of electrons and holes in the semiconductor device and a charge collection efficiency dependent on the position of internal device were implemented.

- The angular resolution obtained was 3.5 ° (FWHM) at 356 keV and 2.5 ° (FWHM) at 511 keV gamma-rays. These are consistently understood as the sum of position uncertainty and energy uncertainty, which is caused by the finite position and energy resolution of the real-life detector and the Doppler broadening effect. More improvement closing to 1 ° at 511 keV is possible by optimizing the detector configuration.

- The Compton imaging capability for the extended source and adjacent point sources was demonstrated utilizing the maximum likelihood iteration algorithm. These results open up possibilities for the Si/CdTe Compton camera for all-sky imaging.

- The direction of the polarization vector is determined within an accuracy of 1 degree. The modulation factor for the 170 keV incident gamma-rays obtained was 0.82–0.85, which is consistent with the estimation value derived from 92.5 % polarized gamma-rays in our experimental setup.

Based on the Monte Carlo simulator verified by various experiments in this thesis, the in-orbit performance for a all-sky survey mission was studied with a Compton camera model consisting of 96 layers of Si and CdTe semiconductor detectors with a geometrical area of 25×25 cm² and mass of ~100 kg. We confirmed that the Si/CdTe Compton
camera can achieve one order of magnitude better continuum sensitivity than any past
and existing observatories in the energy band from 500 keV to a few MeV after 3–5 years
operation. Line sensitivity of more than $1 \times 10^{-6}$ photons/cm$^2$/sec can be achieved for
511 keV, 847 keV ($^{57}$Co), 1157 keV ($^{44}$Ti) and 1809 keV ($^{26}$Al) gamma ray.
Appendix A

VATA analog ASIC

A VATA chip consists of two sections as illustrated in the block diagram of Fig. A.1. The VA section includes a charge sensitive preamplifier, slow CR-RC shaper, sample/hold and analog multiplexer chain. A detailed description of Viking-architecture (VA) chip is given elsewhere [118][119]. The sample/hold is started by external trigger signal. In usual operation, we make the trigger signal based on a fast trigger generated by TA section which consists of fast shaper and level sensitive discriminator. The front-end MOSFET geometry for the preamplifier was originally optimized for small capacitance load in the AMS 1.2 µm process. The FET geometry was optimized in the 0.35 µm process for the low power consumption, which is important issue for a satellite mission, to be a few micro hundreds Watt per channel. The typical noise performance is 50e− at 0 pF load and 170 e− at 10 pF load with 2 µs shaping time (variable from 1 to 4 µs). Feedback resistors for the preamplifier, as well as slow and fast shapers, are realized with MOSFETs. Gate voltage of the feedback MOSFETs are controlled by internal DACs on chip. Bias currents for various components are also controlled by the internal DACs. Threshold levels can be adjusted for each channel using individual DACs to minimize threshold dispersion. Majority selector logic circuitry has been utilized for these registers to ensure the tolerance against single-event upset (SEU), which is important for space applications. This majority selector circuitry uses three flip-flops for each bit and takes a majority of the three when they becomes inconsistent. This logic also generates a signal when such inconsistencies are detected. The SEU tolerance of single latch is measured to be greater than 70 MeV/µm². Two latches needs to be upset at the same time to permanently upset a register bit. More detailed description is given in [76]. The spectrum performance connecting to a silicon strip detector or a CdTe pixel detector is demonstrated in Section 5.2 and C.1.
Figure A.1: VATA block diagram [76]
Appendix B

Basic parameter of DSSD

C-V measurement

The test to investigate the width of depletion layer and doping profile was performed through C-V measurement. These parameters directly affect to the effective area and the uniformity of the detectors. The width of the depletion layer can then be found from the capacitance measurement as [120]

\[
W = \frac{\epsilon \epsilon_0}{C}
\]  

(B.1)

where, \( W \) is the width of the depletion layer and \( C \) is the body capacitance of the DSSD. The body capacitance means the capacitance between P-side plane and N-side plane. For the measurement of the doping profile at \( W \), we must look at the variation of the inverse square of capacitance with the applied voltage \( \frac{\partial}{\partial V} \left( \frac{1}{C^2} \right) \),

\[
\frac{\partial (1/C^2)}{\partial V} = \frac{2}{qN_D \epsilon \epsilon_0}
\]  

(B.2)

Figure B.1(a) shows the relation between the bias voltage and the body capacitance for the 300 \( \mu \)m and 500 \( \mu \)m thick DSSD. The measurements was done by HP4284A multimeter at frequency of 1 MHz. With Eq. B.1, the width of depletion layer was calculated and shown in Fig. B.1(b). The 300 \( \mu \)m thick DSSD was fully depleted around 70 V, while the 500 \( \mu \)m thick one was around 150 V. The plots of the inverse square of capacitance with respect to applied voltage are shown in Fig. B.1(c). The plots are approximated by straight line for both 300 \( \mu \)m and 500 \( \mu \)m thick device. This implies the good uniformity of the device. We obtained low impurity density of 9.0 \( \times \)10\(^{11} \) [cm\(^{-3} \)] for 300 \( \mu \)m and 5.0 \( \times \)10\(^{11} \) [cm\(^{-3} \)] for 500 \( \mu \)m thick DSSD, respectively.

The inter-strip capacitance is an important parameter to achieve low noise read-out because it becomes relatively large value in case of a strip detector. Since the inter-strip capacitance is approximately proportional to the strip length, it restricts the device size. We measured the inter-strip capacitance of 4 cm wide DSSD with detector thickness of 300 \( \mu \)m. The strip length of this detector is 3.84 cm, which is largest among our developments. The result is shown in Fig. B.2 with the value of the body capacitance per strip. The body capacitance per strip becomes constant at a value of 5 pF above a bias of 70 V which corresponds to full depletion voltage. However, the N-side inter strip capacitance still decreases even above 70 V and becomes constant around 100 V. This...
APPENDIX B. BASIC PARAMETER OF DSSD

(a) Bias voltage vs Body capacitance
(b) Bias voltage vs Depletion width
(c) $1/C^2$ dependence

Figure B.1: Various parameters of DSSD with respect to bias voltage

fact suggest that actually a 100 V bias is required to make the N-side inter strip fully isolated. Since total input capacitance is a sum of the body capacitance and the inter strip capacitance, we can estimate it as 12.2 pF and 14.2 pF at the P-side and N-side, respectively.

I-V measurement

Next, we measured I-V curve using KEITHLEY 237 multimeter. The I-V curve with respect to various temperatures and bias voltages is presented in the left panel of Fig. B.3. The result for 300 µm thick DSSD is illustrated with red line and that of 500 µm thick one with black line. The current under full depletion voltage is 26 pA/strip for 300 µm thick (100V) DSSD and 43 pA/strip for 500 µm thick (200V) one at the temperature of $-10^\circ$C. The junction breakdown was not observed in both detector. Although the 500µm thick device has $\sim$1.66 times larger leakage current than the 300µm thick device, it is not serious for the noise performance at the operation temperature of $-10^\circ$C.
These current was mainly generated in the depletion layer under our operation conditions, as shown in right panel of Fig. B.3. The current is proportional to the width of depletion layer.

Figure B.3: (Left) The leakage current of 4cm wide DSSD. (black) thickness of 500 µm, (red) thickness of 300 µm
Appendix C

In/CdTe/Pt diode detector

The crucial problem for the spectrum performance of CdTe device is the slow mobility and short lifetime of holes ($\mu_h$ and $\tau_h$). The mean drift path of the charge carrier is expressed as the product of $\mu \tau E$, where $E$ is the applied electric field in the device. The induced charge is a function of carrier extraction factor $\mu \tau E/D$, where $D$ is the detector thickness, and a function of the interaction depth. If a detector with thickness $D > \mu_h \tau_h E$ is used, only a fraction of the generated signal charge is induced at the detector electrode. The fraction and the resultant pulse height depend on the interaction depth. This position dependancy produces a shoulder (tailing) in the peaks of gamma-ray lines towards the low energy region.

The charge collection efficiency can approach 1 if the carrier extraction factor is roughly greater than about 50. For CdTe, the $\mu_h \tau_h$ is around $1 \times 10^{-4}$ cm$^2$/V. For a normal operating electric field of 1000 V/cm, the maximum detector thickness is only $2.0 \times 10^{-3}$ cm, in order to get a carrier extraction factor of about 50. To achieve sufficient detector thickness and high spectrum performance at once, high electric field is definitely required. Although CdTe has a high resistivity of $\sim 4 \times 10^9$ $\Omega$cm, application of very high bias voltage to improve the charge collection increase the leakage current and electronic noise. Our approach is to utilize indium as the anode electrode on the Te-face of the p-type CdTe wafer. A high Shottoky barrier formed on the In/p-CdTe interface lead us to the operation of the detector as a diode [75, 84].

C.1 Schottky CdTe diode

The Schottky CdTe diodes used in this study were fabricated with the prescription described in Ref [121]. We used Cl-doped CdTe single crystals grown by the traveling heater method (THM) [122]. We formed a Shottky junction of the Te-face of the wafer by evaporation indium after heating the wafer to 200-300°C. On the opposite face (Cd-face), Pt was formed by electroless plating. As shown in Fig. C.1, the detectors show I-V characteristics typical to a diode. A significant suppression of the leakage current is obtained in the reverse bias operation of the In(anode)/CdTe/Pt(cathode) configuration [75, 82, 84, 123, 124, 125]. The leakage current of the $2 \times 2 \times 0.5$ mm simple planar detector was 0.7 nA with a bias voltage of 400 V at 20 °C. When cooled to -20 °C, the leakage current was measured to be 30 pA even with a bias voltage of 800 V corresponding to an internal electric field of 16 kV/cm.
After the establishment of CdTe diode, we have found that the leakage current of CdTe diode increase with the square root of the area of the detector. It implies that the surface leakage through the side edge dominates over the bulk current. We made a detector with a guard ring that surrounds the Pt cathode \cite{126,127}. Figure C.2(a) is the photograph of the detector which consists 2×2 mm size read-out electrode surrounded by 1 mm width guard ring electrode. We measured the current of each electrode at -20 °C and showed in Fig. C.2(b). Almost all leakage current is reduced by adopting the guard ring. The leakage current is about 1 pA even if we applied 1000 V bias voltage corresponding to 20 kV/cm. Figure C.3 shows the energy spectrum of gamma-rays from $^{241}$Am and $^{57}$Co. A bias voltage of 1000 V corresponding to 20 kV/cm was applied and the operating temperature was -20 °C. The FWHM of the 59.5 keV and 122.1 keV peak was 0.99 keV ($\Delta E/E = 1.67\%$) and 1.2 keV ($\Delta E/E = 0.98\%$), respectively. This is close to the energy resolution of HPGe detectors cooled at liquid nitrogen temperature.
C.1. SCHOTTKY CdTe DIODE

(a) Photograph of guard-ring type CdTe detector
(b) leakage current at -20 °C

Figure C.2: CdTe detector with a guard ring surrounding the Pt cathode [128]

Figure C.3: The energy spectrum of gamma-rays from $^{241}$Am and $^{57}$Co. In/CdTe/Pt CdTe diode with guard ring electrode at -20 °C. [128]
C.2 Stability

The improvement of the energy resolution by adopting the Schottky junction is drastic, but it found that the degradation of gain and resolution of pulse height is significant for the Schottky CdTe detector operated with a low bias voltage and at room temperature [82]. This is widely known as a polarization effect. According to Yao et al., this effect can be explained by the non-uniform electric field due to the charge accumulation [129]. The polarization effect starts to appear when the internal electric field by the accumulate charge becomes comparable to the electric field generated by the external bias. Therefore, the high electric field is the key to obtain the long-term stability. The operating temperature is another important factor for the long term stability because the internal charge accumulation is the function of the temperature.

Figure C.4 (a) shows the relative change of the peak channel of the 60 keV line of $^{241}$Am at different bias voltage under the same temperature of 20 °C. The size of the detector was 2 × 2 mm$^2$ and a thickness of 0.5 mm. The drift of pulse hight starts after a stable period. At the low bias voltage of 40 V, the drift started 5 minutes after the bias voltage was applied. While, at a later bias of 400 V, the drift started 10 hours after bias supply. The degradation of the spectrum started later of higher bias voltage. Figure C.4 (b) shows the peak drift with respect to the change of the temperature at a bias voltage of 100 V. At 30 °C, the drift started after 20 min. By lowering the operating temperature, degradation of the spectrum started later. At 0 °C, the peak stayed at the same pulse hight for 10 hours. When we cooled the detector down to -20 °C, the detector performed consistently for more than two weeks at the bias voltage of 600 V without distortion of the spectrum.

![Figure C.4](image)

Figure C.4: (a) Drift of the pulse hight taken with the Schottky CdTe detector at 20 °C with respect to different bias voltage. (b) Drift of the pulse hight taken with the Schottky CdTe detector at different temperatures with a bias voltage of 100 V. [82]
C.3 Bump bonding

One of the most difficult parts of realizing CdTe and/or CdZnTe pixel detectors is to establish a simple and robust connection technology for these fragile devices. It should be noted that high compression and/or high ambient temperature would damage the CdTe crystal. Also, the coplanarity of the CdTe wafer is measured to be 2 µm at most, which is much worse than that of usual silicon wafers. Usual indium-ball soldering might not be appropriate for this purpose. Also, indium is easily oxidizable and needs flux which could contaminate the detector surface.

Therefore, we adopted a stud-bump method [83, 130]. To prevent possible stress on the device, we choose a combination of soft metal, gold and indium, as a stud. In order to attain good connection between the bond pad on the readout board and the pixel electrode on the CdTe wafer, a needle-shaped stud consisting of two stages of gold studs is prepared on the bump pad (Fig. C.5). Studs are made from a gold stud bonder with a 25 µm diameter gold wire, and a thin layer of indium is printed on the top of the stud to improve connectivity. The total height of the stud from bottom to top is 150–200 µm. The CdTe wafer and the fanout board are then pressed together with 20 g of compression per bump under controlled temperature conditions. To increase mechanical strength, epoxy resin with low viscosity is filled into the space between the CdTe wafer and the fanout board.

![Figure C.5: Photograph of studs][83]
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