

Si detectors for high energy particles

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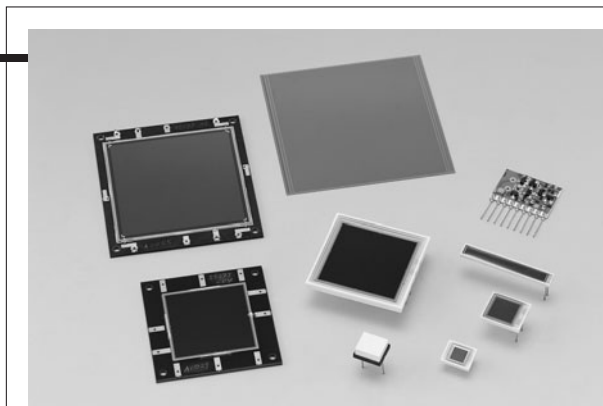
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Si detectors for high energy particles



Si detectors for high energy particles utilize one of two detection methods. One is the scintillator coupling type that indirectly detects high energy particles by converting them into scintillation light, while the other method detects the high energy particles directly. Si detectors used by these two methods include large-area Si PIN photodiodes, Si APD (avalanche photodiodes), large-area PSD (position sensitive detectors), and SSD (Si strip detectors), etc.

The large-area Si PIN photodiodes for scintillator coupling have an active area from 10×10 mm to 28×28 mm made from a single-crystal silicon wafer with high resistivity. Since these photodiodes are used in combination with a scintillator, their spectral response matches the scintillator emission wavelength. Even with the large active area, they deliver high-speed response.

The large-area Si PIN photodiodes for the direct detection method have an active area up to 48×48 mm and a depletion layer thicker than a general PN structure photodiode. These photodiodes offer high detection efficiency and can be used as a ΔE -E detector (detector where a ΔE detector is placed over an E detector).

The Si APD is a high-sensitivity detector capable of high-speed detection of weak light emitted from a scintillator. The large-area PSD is a non-segmented position detector and can also be used as a ΔE detector or E detector as well as a detector of incident charged particle positions.

The SSD is a high-precision Si detector merging photodiode and IC technologies. A number of active areas (PN junctions) are fabricated on the substrate, in the form of strips in widths from a few microns to several dozen microns, so the incident position of high energy particles can be detected in micron units. This performance is widely utilized in high energy physics experiments as an elementary particle tracking detector (Si vertex detector).

HAMAMATSU also provides low-noise charge amplifiers used in combination with our Si PIN photodiodes.

■ HAMAMATSU Si detectors for high energy particles

| Type | Detection method | Features |
|-------------------------------|-----------------------|---|
| Large-area Si PIN photodiode | Scintillator coupling | Excellent bias tolerance, and high-speed response even with large active area by applying a high reverse voltage. Used in combination with scintillator. Active area size: 10×10 mm up to 28×28 mm |
| | Direct detection | Usable as ΔE detector and E detector For detecting energy of high energy particles Active area size: up to 48×48 mm |
| Si APD (avalanche photodiode) | Scintillator coupling | High-speed, high-sensitivity photodiode having internal multiplication function Capable of measuring weak signals Mainly used in combination with scintillator |
| Large-area PSD | Direct detection | Usable as ΔE detector and E detector For detecting energy and two-dimensional incident position of high energy particles |
| SSD (Si strip detector) | Direct detection | For track detection of high energy particles Photodiode strip array achieves high position resolution with low noise. |

1. Structure and operating principle

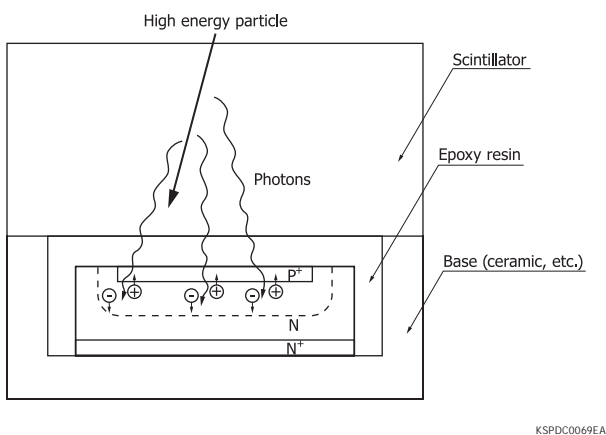
1-1 Features

- Low dark current, low noise
- Excellent bias tolerance
- ΔE detector: excellent thickness uniformity
- Spectral response matching the scintillator emission wavelength
- High radiation hardness

1-2 Si detectors for scintillator coupling

Si detectors for scintillator coupling detect light emitted from a scintillator by input of high energy particles. The structure of these detectors is shown in Figure 1-1. Scintillators can usually be made large and thick, so they are effective in cases where particles penetrate through Si direct detectors and not all the energy can be detected. Si detectors for scintillator coupling are widely used to detect charged particles and gamma rays. Since these Si detectors are optically coupled to a scintillator, they use Si PIN photodiodes, etc. that have a high quantum efficiency at the scintillator emission wavelength. These Si PIN photodiodes should have a large active area for optical coupling to a scintillator. The operating principle of the Si detectors for scintillator coupling is the same as that of general photodiodes (refer to Chapter 2, “Si photodiodes”).

[Figure 1-1] Structure of Si detector with scintillator



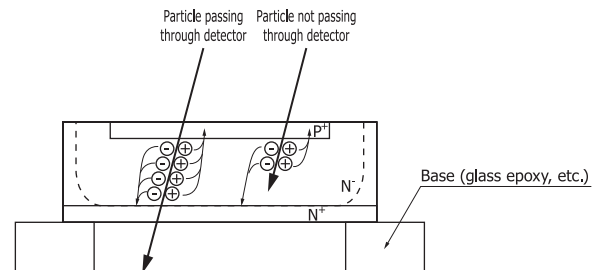
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1-3 Si direct detectors

Si direct detectors including large-area Si PIN photodiodes, PSD, SSD, etc., detect charges internally ionized by radiation energy that directly enters the Si detector. Si direct detectors are bare chips that are not covered with a protective film such as resin. Using these bare chips is intended to suppress the energy

loss that occurs in the dead layer on the Si detector surface where the charge particles enter. Si direct detectors offer high energy resolution, high-speed response, and low noise. Figure 1-2 shows the structure of Si direct photodiodes.

[Figure 1-2] Structure of Si direct photodiode



P⁺-layer, N⁻-layer: dead layer (Charges generated in P⁺-layer and N⁻-layer are not output due to recombination.)

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When charged particles such as alpha rays and heavy ions strike a Si detector, their energy dissipates along a linear track whose length is determined by the type and energy of the incident charged particles, and electron-hole pairs are generated by means of the Coulomb interaction of a charged particle with electrons. The number of the generated electron-hole pairs does not depend on the type of charged particle but rather on the energy loss (at 300 K, one electron-hole pair is generated on average per each 3.62 eV). The energy loss can therefore be estimated by detecting the amount of this charge.

The E detector is a thick detector, so it does not allow the charged particles to pass through, thereby capturing the total energy (E). To achieve this, the E detector must have a depletion layer thick enough to cover the whole track (range) from the incident point to the stop point of the charged particles.

The ΔE detector is a transmission type detector that captures the energy that a charged particle loses as it passes through the detector. When two or more ΔE detectors are stacked on each other, the incident angle of the charged particle can be detected by finding the position where the charged particle passes through each ΔE detector.

When using ΔE -E detectors to identify particles, the ΔE detector must be thinner than the range of the particles to be detected. The specific energy loss (dE/dx) is detected by the upper ΔE detector, and the total energy by the lower E detector. The incident particle can then be identified because the “(dE/dx) \times E” value is unique to the type of particle.

Beta rays differ from alpha rays and heavy ions in that their mass is relatively small, their track is nonlinear, and the range is long because energy loss occurs in the process of emitting electromagnetic waves.

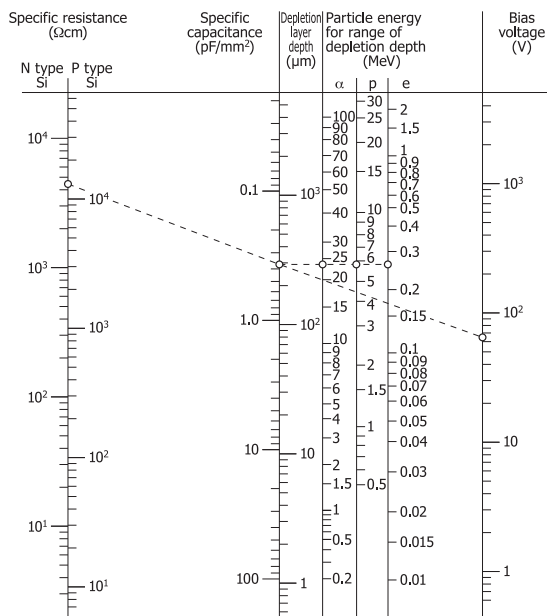
Figure 1-3 shows the relationship between the energy of typical charged particles (α : alpha rays, p: protons, e: electrons), the resistivity of the silicon wafer, the capacitance value (specific

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capacitance) per unit area, the depletion layer thickness (depth) required to detect the charged particle, and the reverse voltage (bias voltage) applied to extend the depletion layer. Use this nomograph as a guide to select the Si detector that matches the application.

[Figure 1-3] Si detector parameter nomograph



1 μm Si=0.2325 mg/cm²
 1 mg/cm² Si=4.3 μm
 Nomograph showing mutual relation between Si detector parameters (similar to nomograph originally reported by J. L. Blankenship)

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Reference

IEEE Transactions on Nuclear Science, Vol. NS-7, 190-195 (1960)

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2. Characteristics

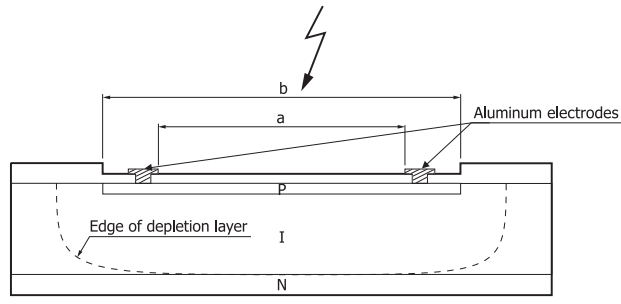
2-1 Active area

Light cannot pass through aluminum electrodes, but high energy particles pass through them easily. The active area of Si direct detectors is therefore defined as the P-layer region including the aluminum electrodes, while the active area of Si detectors for scintillator coupling is defined as the P-layer region excluding the aluminum electrodes [Figure 2-1].

If light strikes the periphery (not light-shielded) of a PN junction on a Si detector with scintillator, the carriers generated there are output as a signal. Likewise, radiation entering outside the active area of a Si direct detector generates a signal. Energy loss also occurs in the insulation film on the Si detector surface, at the aluminum electrodes, and in the P-layer. However, these areas serve as dead layers because the energy lost there does not result in signal generation.

When a reverse voltage is applied to the Si detector, the depletion layer extends horizontally to some extent as well as along the detector thickness. If the active area must be accurately specified, then a P-layer as a guard ring is sometimes formed around the active area in order to absorb the excess carriers generated outside the guard ring.

[Figure 2-1] Cross-section diagram of Si detector



Active area a: Si detector for scintillator coupling b: Si direct detector

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2-2 Dark current and junction capacitance

When a reverse voltage is applied to a Si detector, a small amount of current flows even in a dark state. This current, called the dark current or leakage current, becomes larger as the reverse voltage is increased and is a major cause of noise. Dark current consists of two components: a thermally generated current and a current generated from defects in the silicon crystal and from the interface of the silicon oxide film and the silicon substrate. These currents flow in a reverse direction of the diode.

The junction capacitance of a Si detector is determined by the area of the P-layer and the thickness of the depletion layer, and

can be approximated by equation (1).

$$C = \frac{\epsilon_0 \epsilon_s S}{W} \dots\dots\dots (1)$$

C : junction capacitance
 ϵ_0 : permittivity in vacuum
 ϵ_s : specific permittivity in silicon
 S : area of P-layer
 W : thickness of depletion layer

The junction capacitance is minimized when the I-layer is fully depleted.

The recommended reverse voltage for each Si detector is the voltage required for full depletion of the substrate. Operating a Si detector at its recommended voltage not only minimizes the junction capacitance but also lowers the series resistance as the I-layer is fully depleted. Lowering the junction capacitance and series resistance will also improve the response speed and reduce noise.

2-3 Response speed

There are two major factors that determine the response speed of Si detectors. One factor is the time constant determined by the terminal capacitance, series resistance of the Si detector, and the externally connected load resistance. The other factor is the time required for the signal charge generated in the silicon to reach the electrode (carrier collection time). This carrier collection time is also categorized as the time during which the carriers flow as a diffusion current outside the depletion layer and the time (drift time) during which carriers flow in the depletion layer due to the electric field. When fully depleted by reverse voltage, the drift time determines the carrier collection time. If the time constant of the Si detector is small, then the response speed is limited by the carrier collection time.

3. Si direct detectors

3-1 Thickness of depletion layer

The E detector must have a depletion layer whose thickness is more than the range of the charged particles to be detected. The following points must be considered when setting the depletion layer thickness.

- Increasing the reverse voltage extends the depletion layer and lowers the terminal capacitance and series resistance which are major causes of noise.
- Increasing the electric field on the depletion layer improves the response speed but increases the dark current, resulting in larger noise.

When the depletion layer is partially extended relative to the Si detector substrate thickness, this state is called “partial depletion.” On the other hand, a state where the depletion layer is fully widened and cannot be extended any further even by increasing the reverse voltage is called “full depletion.” The ΔE detector is used under the full depletion condition.

3-2 Channeling effect

In charged particle track detection, attention must be given to the channeling effect. The channeling effect is a phenomenon in which charged particles moving along the crystal lattice lose less energy and therefore reach deeper. If this channeling effect occurs, charged particles that should normally stop inside the depletion layer might instead reach the outside of the depletion layer or might pass entirely through the detector.

3-3 Pulse height defect

In actual Si detector operation, the generated electron-hole pairs are not completely detected, and this causes pulse height defects. Even if charged particles with the same energy enter the detector, their outputs are not always the same. This phenomenon occurs from the following three factors.

The first factor is thin dead layers on the front and rear sides of the Si detector, which do not become depleted. In E detectors, dead layers made up of a protective film and diffusion layer section on the front surface can cause pulse height defects. In ΔE detectors, the dead layer caused by the rear side diffusion layer can also cause pulse height defects.

The second factor is the crystal defects formed in the depletion layer. Radiation entering the Si detector forms crystal defects in the depletion layer, causing an increase in dark current. The dark current increases almost in proportion to the amount

of absorbed radiation, and gradually degrades Si detector performance. Because the crystal defects that form in the depletion layer serve as recombination centers, some of the electron-hole pairs recombine there and are not output.

The third factor is the recombination of electron-hole pairs that occurs due to high-density plasma created along the particle track.

Effects caused by the second and third factors can be reduced by increasing the electric field strength in the depletion layer since this lowers the probability that electron-hole pairs will recombine.

3-4 Noise and energy resolution

The most important point to consider in measuring the energy resolution is statistical noise. Since statistical noise exists as a fundamental factor, the total number of electron-hole pairs generated is not consistent even when particles with the same energy enter the detector. This statistical noise cannot be ignored when measuring the energy resolution. Assuming that incident particles will generate “n” pairs of electrons and holes on the average, the energy resolution (R) determined by the statistical noise is expressed in equation (2).

$$R = 2.35 \sqrt{F/N} \dots\dots\dots (2)$$

Here, F is a coefficient called the Fano factor. Many experimental results using Si detectors have reported that this F value is approx. 0.1.

Another factor that affects energy resolution is random noise generated throughout the entire system including the Si detector and its circuit. This random noise increases as the dark current and junction capacitance of the Si detector become larger (see “9. Charge amplifiers” in Chapter 10, “Module products”).

During ΔE detection of charged particles such as alpha rays and protons, there is a basic fluctuation (2 to 3% on average) in the particle range. The number of electron-hole pairs generated relative to the same thickness is therefore not constant and so degrades the energy resolution. Non-uniformity in detector thickness also adversely affects the energy resolution.

4. Si detectors for position detection

The following sections describe large-area PSD and SSD that are Si direct detectors capable of position detection.

4-1 Large-area PSD

The large-area PSD has a uniform, highly resistive P-layer or N-layer on which four electrodes are formed. A charge produced by the input of a high energy particle is collected by the four electrodes through the highly resistive layer. The energy loss of the particle can be detected from the total amount of the charge. The position of the incident particle can also be detected because the ratio of the charge collected by each electrode correlates with the position where the charge was produced.

The PSD offers the advantages of a simple structure and a capability of position detection on its large active area. However, if two or more particles simultaneously enter a PSD (multi-hit), then detecting the particle positions is impossible. Furthermore, since the electrodes are connected to each other through the resistive layer, the thermal noise becomes higher than in photodiodes. The PSD is for this reason usually used to detect heavy ions whose specific energy loss is large among charged particles.

4-2 SSD (Si strip detector)

The SSD has a photodiode array structure of strips in widths of several dozen microns. The active area consists of a large number of strips (channels), so when a particle enters the SSD, signal outputs are distributed to one or multiple strips corresponding to the position of the incident particle. The position of the incident particle can be obtained at a resolution smaller than the strip pitch. The SSD has low noise and detects positions even if multiple particles enter simultaneously (multi-hit detection). HAMAMATSU SSDs have the following features:

- Low voltage operation due to using high-resistivity silicon substrate
- Stable operation maintained due to low dark current and excellent bias tolerance
- Low defect channel ratio (less than 1%)
- AC readout type provides high radiation hardness by using poly-silicon biasing.

Readout method

SSDs are grouped into the following types according to the

readout method.

(1) DC readout and AC readout

In the DC readout type, each strip diffusion layer is DC-coupled to an aluminum electrode. In the AC readout type, however, each strip diffusion layer is AC-coupled to an aluminum electrode. Compared to the DC readout type SSD, the AC readout type SSD has the advantage of good compatibility with the readout IC chip since the dark current (DC current) from each strip does not flow into the signal line. In the AC readout type SSD, a reverse voltage must be applied to each strip from the bias line. This reverse voltage is applied by the “punch-through” method or the “poly-silicon” method. HAMAMATSU SSDs use the poly-silicon method as standard because of its superior radiation hardness.

(2) All-channel readout type and charge-division readout type SSDs that read out signals from all strips are called the all-channel readout type, while SSDs that read out signals from one among several strips are called the charge-division readout type.

▣ Ladder module assembly using double-sided SSD

Although the SSD is sometimes used as a single piece, multiple SSDs are normally used while arrayed or stacked. For example, when using SSDs as particle tracking detectors in elementary particle experiments, multiple SSDs are joined in a ladder configuration and a readout circuit is attached to the end piece to form a so-called ladder module. A large active area can then be obtained by placing this module in a concentric circle at the point where particle collision (annihilation) takes place. The particle track can then be measured by processing data captured by these SSDs.

When assembling a ladder module capable of detecting a two-dimensional position by bonding two SSDs back-to-back, the readout electrode pads from both sides must be placed on the same edge. In this case, one method (double metal layer readout type) places the readout electrodes in a direction different from the strips, using either side having a double metal layer (DML) structure. In another method (nonorthogonal readout type) the strip angle on one side is tilted slightly to the other side. The structure of the nonorthogonal readout type has poorer position resolution on either side. However, this structure is simpler since no DML is used.

5. New approaches

In high energy physics experiments, there is a growing demand for larger size detectors due to the larger amounts of energy that must be detected. To meet this demand, HAMAMATSU has developed large-area Si detectors including photodiodes, PSD, and SSD that are so large that only one chip can be made from a single 6-inch silicon wafer.

In order to tile multiple Si detectors, we are also developing photodiodes compatible with flip-chip bonding and fully depleted photodiodes having small dead space.

We have already developed thin type ΔE detectors (10 μm thick or more) and are also developing thin dead layer type detectors. In the next particle collision experiments such as the SLHC (Super LHC) scheduled to start from 2015 or later, the environments where track detectors are placed will be subject to a five to ten times greater radiation intensity than in the LHC project (experiments started in 2008). HAMAMATSU is currently developing a high radiation tolerant SSD that can be used under these environments.

Si APD and MPPC (see Chapter 2, “Si photodiodes”) are detectors capable of detecting very weak scintillation light. Because of their advantages of being compact, highly stable, and unaffected by magnetic fields, these detectors are likely useful not only in high energy physics experiments but also in new fields such as medicine and bioscience. A new type of MPPC is currently being developed to deliver enhanced characteristics.

6. Applications

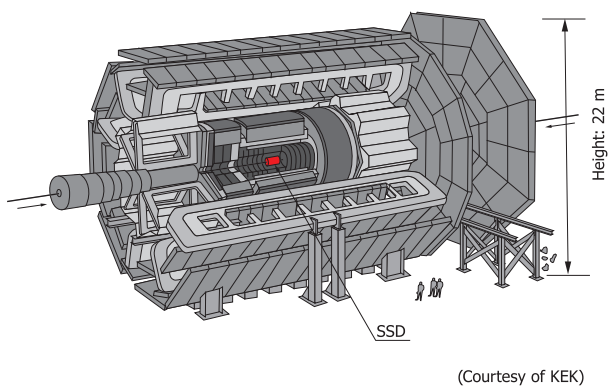
6-1 Particle collision experiments

SSDs are used as position detectors for high energy particles in many particle collision experiments (DELPHI, KEK-B, CDF, CLEO, ZEUS, etc.). Multiple SSD layers are arranged near the particle collision point in order to detect the tracks of elementary particles generated by the collision.

In the LHC (Large Hadron Collider) project (experiments started in 2008) by the European Organization for Nuclear Research (CERN) in Switzerland, an accelerator ring approx. 27 km in circumference is accelerating protons up to seven trillion electron volts in order to produce proton-proton collisions. The elementary particles resulting from these collisions are then detected. The major objective of this experiment is to verify the existence of the Higgs boson which is thought to be the only particle that has not yet been observed (it is generally considered a particle that gives mass to matter). In this LHC project, the ATLAS experimental apparatus [Figure 6-1] uses approx. 14000 SSDs as particle track detectors, and the CMS experimental apparatus [Figure 6-2] uses approx. 22000 SSDs as particle track detectors. Our SSDs are also used in the ALICE and LHC-b experiments to detect particle tracks with accuracy down to a few dozen microns.

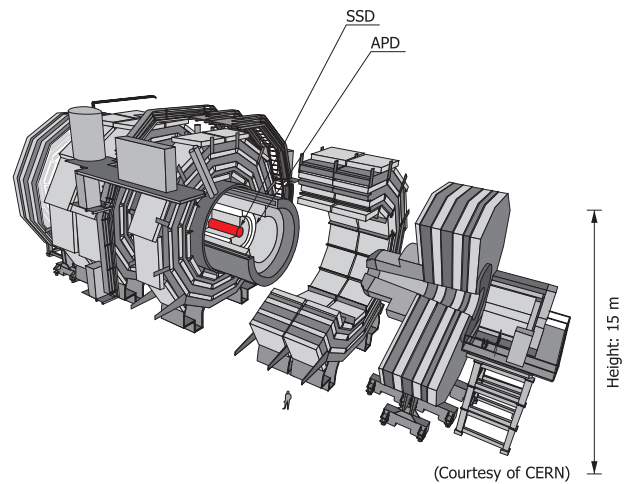
The electromagnetic calorimeter in the CMS experimental apparatus also uses 14000 APDs as photodetectors for lead-tungstate scintillators.

[Figure 6-1] ATLAS experimental apparatus



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[Figure 6-2] CMS experimental apparatus



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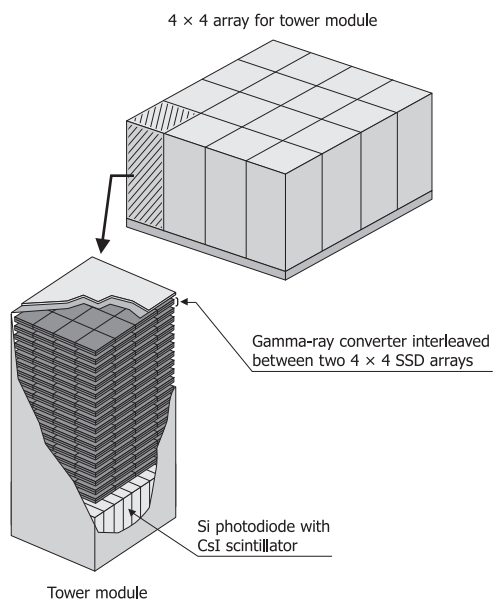
6-2 FGST (Fermi Gamma-ray Space Telescope) detector*

The FGST (NASA satellite launched and experiment started in 2008) is a space project for observing gamma rays. The objectives of this project include understanding many mysteries in the universe such as gamma-ray bursts that release a huge amount of energy equal to that from the entire life of a sun in a short time ranging from only several seconds to several hundred seconds. Other phenomena to observe include the formation of colossal jets extending to several dozen light-years in the active galaxy nuclei and mechanisms that release gamma rays at ultra-high energy of several billion to one trillion electron volts from active galaxy nuclei, etc.

Figure 6-3 shows the tower module (tower detector) used in the FGST detector. A gamma-ray converter (converting gamma rays into electron-positron pairs) is interleaved between two 4×4 SSD arrays. This set is stacked in more than a dozen layers to build the tower module. A total of approx. 9000 SSDs are used in the tower module and play an important role in detecting the directions from which gamma rays arrive. The calorimeter installed in the lower section of the tower module utilizes our Si photodiodes.

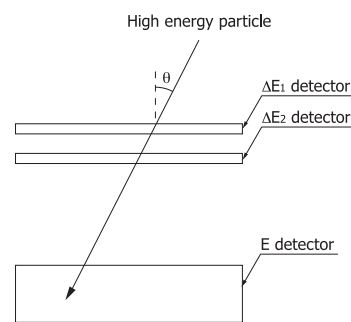
* Former name: GLAST detector

[Figure 6-3] Tower module used in the FGST detector



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[Figure 6-5] ΔE_1 - ΔE_2 -E detector



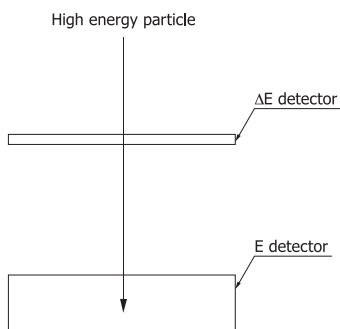
This is used when detecting the incident angle and position.

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6-3 ΔE -E detectors

ΔE -E detectors are used to identify particles. As shown in Figure 6-4, a transmission type ΔE detector is placed over a thick E detector. The ΔE detector detects the specific energy loss (dE/dx), and the total energy (E) of the particle is then calculated from the sum of the ΔE detector and E detector outputs. Here, the particle can be identified since the $(dE/dx) \times E$ value is unique to the type of particle. The incident angle and the position of the particle can be detected by using two PSDs as the ΔE detectors [Figure 6-5].

[Figure 6-4] ΔE -E detector



This is used when the incident angle is known.

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