

# Applications of Silicon Detectors

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**Abstract**—The principle of operations, the development and applications of silicon detectors are discussed. The application of strip detectors in High Energy Physics follows “Moore’s law” both in the area and the channel count. New developments include pixel and drift detectors. Example of use in space sciences are given, and the growing use in medical applications. The role of silicon detectors in the detection of photons is explained. Frequent reference will be made to papers submitted to the IEEE2000 NSS-MIC.

## I. INTRODUCTION

Silicon detectors have found use in many fields of physical research. Their application extends from the interactions of leptons, quarks, gluons, gauge bosons and the hunt for the Higgs particles at the scale of  $<10^{-20}\text{m}$  to investigations of large scales ( $>10^{28}\text{m}$ ) of the entire Universe. In between these extremes, they are used in Nuclear Physics, Crystallography, and Medicine for imaging and mechanical engineering for alignment. In each of the many applications, they have been modified to fit the energy scale, time structure and signal characteristics of the application.

In the following, the principle of operation of the silicon detectors will be explained briefly. Then the development of silicon strip detectors as tracking detectors in High Energy Physics (HEP) will be traced. On hand of typical examples of the application in HEP, astrophysics and medicine the development and change of the silicon strip detector paradigm will be followed. The development of pixel detectors will be surveyed. The detection of photons in medicine and Astrophysics with silicon detectors will be explained.

## II. PRINCIPLE OF OPERATIONS OF SILICON DETECTORS

One of the primary reason for the common use of silicon as detector material is that it is a semiconductor [1] with a moderate band gap of 1.12 eV. This is to be compared to the thermal energy at room temperature of  $kT = 1/40$  eV. Thus cooling is needed only in ultra-low noise applications or when required to mitigate radiation damage [2], [3]. The energy to create an electron-hole pair is 3.6 eV, compared to the ionization energy of 15 eV in Argon gas, leading to an ionization yield for minimum ionizing particles (MIP’s) of about 80 electron-hole (e-h) pairs per micron. Thus about 23,000 e-h pairs are produced in the customary wafers

thickness of 300  $\mu\text{m}$ , and collected in about 30 ns without a gain stage.

The wafers are normally n-type with a high resistivity of about 5  $\text{k}\Omega\text{-cm}$ , and with a low-resistivity p-implant in form of pads, strips or pixels to create a junction. With a reverse bias of less than 100 V, the detectors can then be fully depleted such that only the thermally generated current contributes to the leakage current. Larger thickness requires much higher voltage because the depletion voltage increases with the square of the thickness. The area of the detectors are limited to the standard wafer sizes used in high-resistivity processing by industry, which has increased the wafer size from 4” to 6” in the last two years. Larger area detectors are now routinely made by assembling and wire bonding several detectors into so-called ladders, with fairly long readout strips.

Searches for a different material which could replace silicon as the semi-conductor of choice in tracking devices have not been successful [4], [5]. One reason for the uniqueness of silicon is its wide technology base (ASIC’s, diodes and detectors), and it has helped to spawn the use of pixel detectors (hybrids, CCD’s, CMOS detectors) for truly 2-dimensional applications.

An important role in the development of silicon detectors has been played by simulations. They cover processing details [6], optimization of the geometry [7], [8] and limiting the breakdown [9].

## III. CHARGED PARTICLE TRACKING

The detection of charged particles is based on the specific energy loss in matter. The signal is proportional to the specific energy loss (“stopping power”) and the thickness of the detector. Figure 1 shows the energy loss in Cu as a function of particle momentum  $p$  [10]. In these units and as a function of  $\beta*\gamma$ , the curve is approximately universal for all materials for particles with the same charge. Three regions are worth emphasizing: the low energy range with  $0.05 < \beta*\gamma < 1$ , where the energy loss is proportional to  $1/p^2$ , and thus can be used to measure the particle momentum. The region of minimum ionization with  $1 < \beta*\gamma < 100$ , where a minimum ionizing particle (MIP) deposits about 1.5  $\text{MeV}/(\text{g}/\text{cm}^2)$ , and the radiation region  $\beta*\gamma > 5,000$ , where most of the energy loss occurs via radiation.

The useful thickness of the silicon detectors is limited on one hand by the desire to keep the depletion voltage low, and more importantly by the need to limit the effect of multiple scattering of the particle. While passing through material, the particle will undergo multiple Coulomb interactions, which result in a deflection from the original direction. The multiple

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scattering angle  $\theta_0$  depends linearly on the inverse of the momentum  $p$  and on the square root of the material thickness  $t$  in units of a material constant, the radiation length  $X_0$ :

$$\theta_0 \approx \frac{(13.6 \text{ MeV})}{\beta \cdot p} \cdot \sqrt{t/X_0} \quad (1)$$

Thus, either very thin detectors or high energy particles (or both) are required to allow good position resolution. The typical silicon detector thickness of  $300\mu\text{m}$  amounts to  $0.3\%X_0$ .

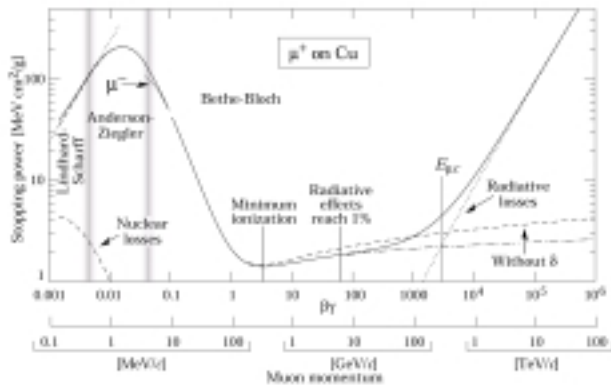


Fig. 1. Energy loss (“stopping power”) of muons in Cu. This curve is universal as a function of  $\beta\gamma$ , indicating that at high enough energies, all particles radiate and at low energies, the momentum of the particle can be determined from the energy loss. From [10].

How well the tracking detector performs depends mostly on the signal-to-noise ratio. It determines how many extra hits are accepted and if superior position accuracy due to charge sharing can be achieved. As mentioned, the signal depends on the detector thickness, and the noise more or less on the area of the detector element, and on the shaping time. Thus detectors with small area readout sections can provide good performance even if the signal is generated only in a thin active volume. Detectors with large area readout sections can achieve good signal-to-noise with long shaping times.

#### IV. THE RISE OF SILICON STRIP DETECTORS

Silicon detectors have been used and are still in use in low-energy spectroscopy [11], [12]. Due to the large e-h yield and low leakage currents, an energy resolution of below 1 keV is routinely achieved. The use of silicon strip detectors in HEP particle tracking got a boost from the introduction of the planar technology by J. Kemmer [13], with fixed target experiments both at CERN [14] and FNAL [15]. Figure 2 show the set-up of the experiment E706: the detectors of the dimensions  $5 \text{ cm} \times 5 \text{ cm}$  are dwarfed by the fan-out which are needed to bring the signals to the large banks of amplifier boards with discrete components [15].

The next step forward came through the development of ASIC amplifier chips of the size that they could be coupled directly to the detectors [16]. In the silicon detector developed for the Mark2 [16] at the SLAC Linear Collider (SLC), shown in Fig. 3, the vertexing errors due to multiple

scattering were reduced by the following **paradigm for vertex detectors**:

- ASIC’s at the end of “ladders”
- Minimize the mass inside the tracking volume
- Minimize distance between interaction point and detectors

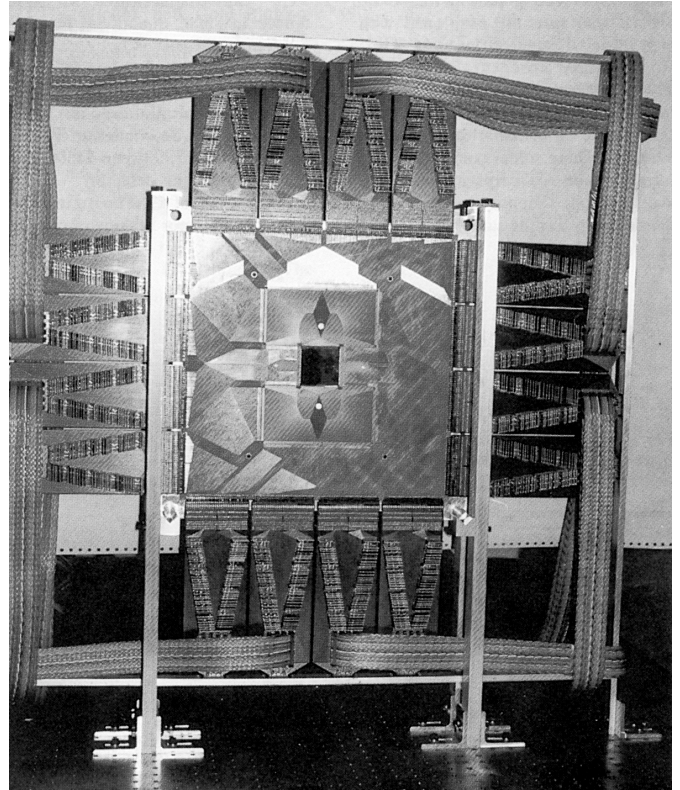


Fig. 2. The early years: experimental set-up with silicon strip detectors in fixed target experiment (E706 at FNAL). The  $5 \text{ cm} \times 5 \text{ cm}$  silicon detectors are seen in the center, with the fan-out cables and amplifier banks dominating the picture. From [15].

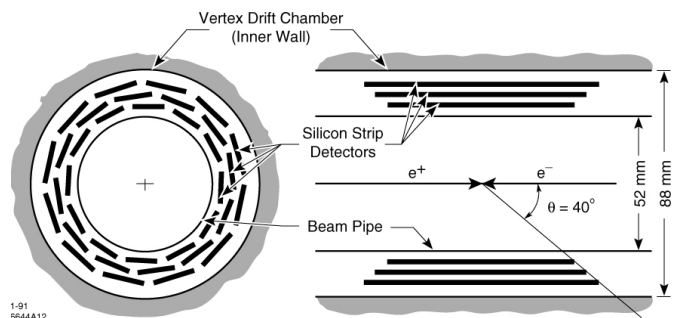


Fig. 3. Vertex detector paradigm embodied in the Mark2 silicon vertex detector: The inner radius is only 2.5 cm, the ASIC’s (not shown) are at the end of the ladders outside the tracking volume and the detectors are very thin. From [16].

Vertex detectors enabled a new area of heavy flavor physics both in fixed target and colliding beam experiments. For example, all four LEP experiments had vertex detectors using silicon strip detectors [17]. The next step came in the use of radiation-hard electronics [18], and the realization that

high luminosity experimentation will require special attention to radiation damage effects (see [2], [3] for details). Still following the vertex detector paradigm are the vertex detectors for the B-factory detectors, Belle [19] and Babar [20]. The colliding beams have different energies, such that the center-of-mass is moving, allowing the determination of asymmetries between the decay times of particle and anti-particle. The presence of many low-energy particles in the decays requires that the detectors present the minimum amount of material in the active volume.

Silicon strip detectors have been introduced into space sciences, following their successful use as tracking detectors in accelerator experiments. A large tracking system in a magnetic field has been developed for AMS [21], still following the vertex paradigm to minimize the mass inside the tracking volume. This accounts for the extremely long ladders of 65 cm.

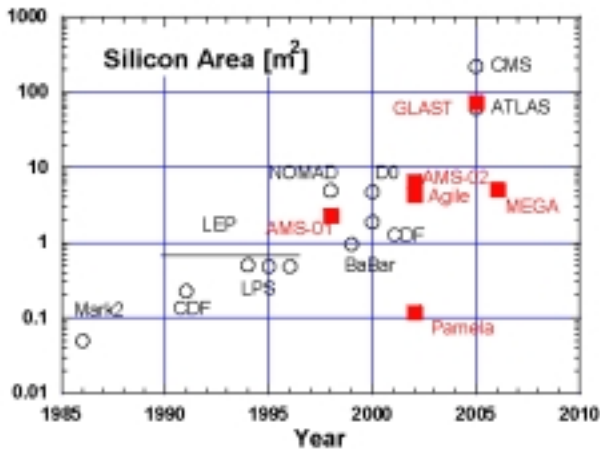


Fig. 4. The rise of the silicon detector: area of silicon detectors in experiments as a function of time. The full squares denote space based instruments. The exponential growth of the area with time is an example of a “Moore plot”.

A shift in paradigm occurred with the development of tracking detectors for hadron colliders. Starting with CDF and D0 [22], the new emphasis is not only on vertexing, but on full tracking including momentum determination in the magnetic field. The detectors become so large, that the electronics, cables and cooling can't be kept outside the active volume but are an integral part of the detector modules. This paradigm shift from vertex detector to inner tracking detector is continuing in the LHC detectors ATLAS [23] and CMS [24], where the accumulated material in the inner detector reaches the order of a full radiation length in large parts of the detectors. That these detector systems exhibit satisfactory performance with that much material in the active volume is only possible because of the increased energy of the particles.

The **new paradigm for inner trackers** is

- Cover a large area with many layers
- Detector modules including ASIC's and services inside the tracking volume

- Module size limited by electronic noise due to fast shaping time of electronics.

With CMS, the silicon strip detectors have arrived: the entire inner tracking system up to a radius of 1.1 m will be built with silicon detectors, with a total silicon area of 230 m<sup>2</sup> and about 10 Million readout channels. The overriding issue at the LHC is radiation hardness, which has to be mitigated by cooling, and quality assurance, requiring detailed studies of the detector performance before and after irradiation [25].

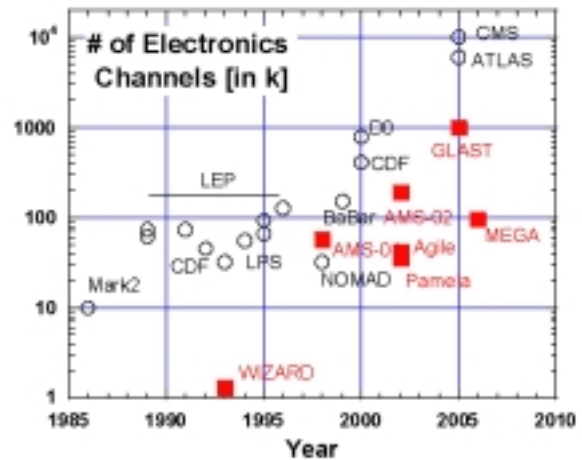


Fig. 5. The rise of the silicon detector: number of electronics channel of silicon detectors in experiments as a function of time. The full squares denote space based instruments. The exponential growth of the number of channels with time is an example of a “Moore plot”.

The development of the silicon strip detectors follows a version of “Moore’s law”, which implies exponential growth as a function of time. This is true for the detector area, shown in Fig. 4, and in the number of electronics channels used, shown in Figure 5.

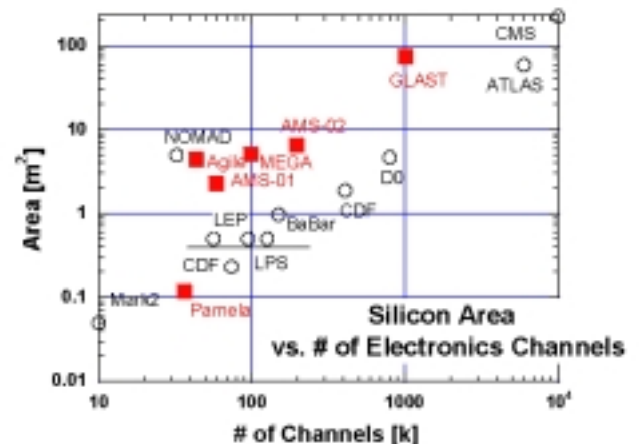


Fig. 6. The rise of the silicon detector: area of silicon detectors vs. number of electronics channels. The space based experiments (full squares) exhibit much lower channel count than their ground-based counterparts, indicating that power consumption is a severe limitation of space sciences.

The difference between ground-based and space-based application is evident in Fig. 6, where the silicon area is shown for the number of electronics channels needed: the space based detectors (full symbols) are overcoming the

limited resources (mainly power) in space by employing fairly large detector, either with very long readout channels or coarse pitch, and fewer electronics channels.

Even the cost of silicon strip detectors follows “Moore’s law”, but now with a negative slope! Since the first commercial detectors, the price per detector area has dropped by a factor of about 40. This was made possible by a number of factors: the wafer area increased by changing from 4” to 6” wafers, the wafers area is being utilized better by designing the detectors to be square, the cost of wafer processing was reduced by a factor 4, partly due to the much larger orders, and a close collaboration between industry and experimenters is bearing fruit. The price for an AC coupled detector is now only 5 times the cost of the blank high-resistivity wafer. At the same time, the quality of the detectors improved steadily: e.g. GLAST detectors [26] show a leakage current of less than  $2\text{nA}/\text{cm}^2$ , with the fraction of bad channels below  $2 \cdot 10^{-4}$ .

## V. PIXEL DETECTORS

Two dimensional information is needed for most tracking application. Depending on the particle density, different approaches can supply the 2-D information. For low particle density, projective geometry with 90 degree stereo angle, very often in double-sided detector, are used, like in the LEP and B-Factory detectors. For higher particle densities where more than one particle might strike a detector on the average, small angle stereo is used, like in the ATLAS silicon tracker. For higher particle density, as encountered in high intensity colliders very close to the beam pipe, pixel detectors are needed.

Pixel detectors are characterized by their very large number of channels. Their power consumption and need for cooling are a challenge, and if fast readout is required, the need for clever readout architecture. Several different types of pixel detectors are being used: Drift detectors, CCD’s, Hybrid Pixels and Monolithic Active Pixels. Because of their low-noise operation, excellent position resolution can be achieved when the charged sharing with neighboring pixels is exploited [27], [35]. Many pixels work in the “digital” mode, where the rate above a fixed threshold is counted.

### A. Drift Detectors

In drift detectors, one coordinate is determined from the measured drift time and the well known drift velocity in a uniform field. Drift detectors have been designed and built for the Star experiment at RHIC [28], and are the subject of intense research. One challenge is to prevent the drifting charge to diffuse into neighboring strips [29], [30], the other is to allow the charge to be time marked for the use in X-ray applications [31].

### B. CCD Detectors

The development of CCD detectors was paced by their use as photon detectors in the visible band: they have completely replaced photographic plates in astronomy applications. Like silicon strip detectors, their use is following Moore’s law,

with the proposed SNAP satellite [32] having over  $10^9$  pixels, and the cost falling by many orders of magnitude over 20 years of application, with the quality improving at the same time.

In HEP, the most advanced application of CCD’s has been in the vertex detector of SLD, which ultimately had 300 Million channels [33]. The slow repetition rate of the SLC collider and the low trigger rate were the ideal condition for the use of CCD’s, which require fairly long readout time because the charge has to be shifted across the rows and columns of pixels to the readout. Figure 7 shows a “typical” picture of a Z decay into three jets, tracked with the SLD CCD detector. For the use in the next generation e+e-colliders, a faster readout scheme is being developed [34]. An intense area of R&D is the radiation hardness of CCD detectors.

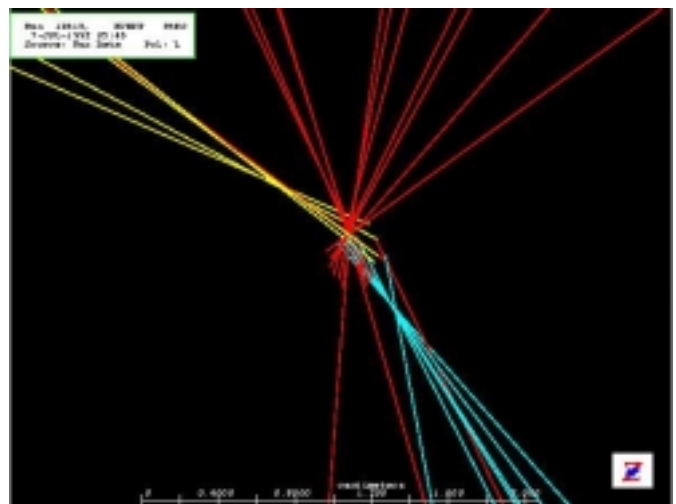


Fig. 7. “Beautiful” event picture from the 300 Megapixel SLD vertex detector. The view is along the beam line of the SLC, and shows a Z decay into a gluon jet (red) and two jets containing a beauty and an anti-beauty quark (blue, yellow). The heavy quark jets show detached vertices relative to the Z decay vertex.

### C. Hybrid Pixel Detectors

Hybrid detectors use high resistivity detectors like strip detectors, but with much reduced area. The active area of a pixel detector is of the order  $50\mu\text{m} \times 300\mu\text{m}$  and is determined by the size of the readout chip, which is customarily bump-bonded to the surface of the detector in flip-chip fashion. Separate optimization of detector and chip technologies can proceed, and the readout is designed to be fast enough for hybrid pixels systems to be built for the use at the LHC, for BTeV [35] and the next Linear Collider [36].

### D. Monolithic Active Pixels

Monolithic Active pixels (MAP) [37] have grown out of the commercial application of CMOS circuits with associated photodiodes in pixel cameras. In a certain sense, a paradigm shift is occurring: the detector is integrated in the chip instead of vice-versa. Only the charge deposited in the epitaxial layer is collected by diffusion within about 150ns. Industry has



solved the need for low power operation. The drive of the CMOS industry to smaller feature sizes increases the radiation hardness, but also decreases the thickness of the epi layer. Potentially this could lead to a relative small signal-to-noise ratio when compared with other pixel detectors.

## VI. SPECIAL TRACKERS

Silicon detectors have found applications in many instances where reliable tracking information is needed. In an unusual application on space station Mir, a silicon detector telescope was strapped in front of Cosmonaut Adveev, who triggered readout of events when he saw the well-documented flashes astronauts observed while in orbit. The recorded data showed a close correlation between the flash recordings and regions of increased cosmic ray flux during the orbit [38].

An application in the medical field is in nano-dosimetry, where the interaction of ionizing particles with matter, here DNA, is investigated at the microscopic level [39]. Ions from the ionization process are drifted through a low-pressure area and are recorded. In this set-up, the direction of the incoming and outgoing proton tracks are recorded in silicon detectors, and because the proton energy is low, the energy loss in the silicon detector allows to measure the proton momentum (see Fig. 1).

Silicon strip detectors are used for alignment of larger detector elements. One group uses semi-transparent silicon strip detectors in a laser beam and achieves sub-micron resolution [40].

## VII. PHOTON DETECTION

For photon as for charged particles, the determination of the direction is crucial. In addition, in most cases, an energy determination is needed. The energy loss of photons is highly energy dependent and there are three distinct interactions with the medium, which determine how much of the photon's directional information is retained in the detection. This is shown in Figure 8, where the photon cross section for carbon is shown as a function of the energy [10]. The cross section, or its inverse, the absorption coefficient, is somewhat dependent on the material, with higher  $Z$  materials exhibiting larger cross sections and a shift to higher energy. Three distinct regions are evident: at lower energy, the photo electric effect is dominant, with the cross section changing by 5 orders of magnitude. No directional information is available in the detection of photons, and external devices like a lens, mirror, collimator, coded mask, "proximity focus" are needed to determine the direction of the photons. In the 0.1 to 10 MeV region, the Compton effect allows partial reconstruction of the direction. At high energy, pair production retains the directional information of the gamma. At that point, the absorption coefficient is  $7/9$  of the radiation length  $X_0$ , i.e. in one radiation length of material, 54% of the gammas are converted.

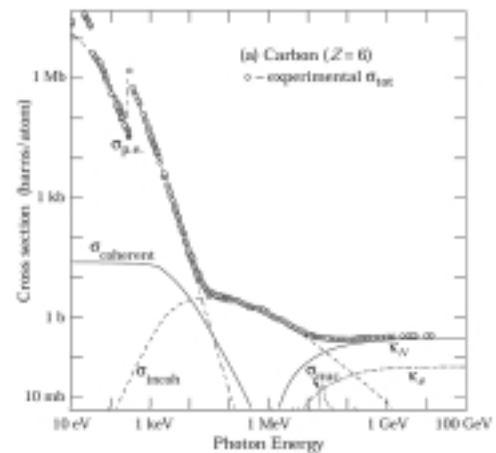


Fig. 8. Cross section for photon interaction in carbon. Three distinct regions are evident: at lower energy, the photo electric effect is dominant, with the cross section changing by 5 orders of magnitude. No directional information is available here. In the 0.1 to 10 MeV region, the Compton effect allows partial reconstruction of the direction. At high energy, pair production retains the directional information of the gamma. From [10].

## VIII. X-RAY IMAGING

A large part of medical imaging is in the X-ray energy range of about 20-30 keV, where tissue and bones or calcifications have very different absorption coefficients, thus making high contrast pictures possible. The physical size of the objects is fairly large, proximity focusing is being applied, and silicon strips seem to be an obvious detector candidate. One of the problems with using silicon strip detectors [41] is that in the interesting energy range, the absorption length of silicon is of the order of mm, i.e. only a fraction of the X-rays are converted in the commonly used 300 $\mu$ m thick detectors. The other problem is that for high rate application, double-sided detectors with crossed strips generate so-called "ghosts", i.e. wrong combinations of the two coordinates. Both of these problems can be eliminated by rotating the strip detectors by 90 degrees, such that the strips are almost parallel to the X-rays, essentially forming pixels with an area of pitch times detector thickness, and the full strip length available for the absorption. The strips are connected to a ASIC which works in digital mode by simply counting the rate of photons which deposit charge above a pre-set threshold. The X-ray tube, a collimator and the detectors are then scanned across the object [42]. In an application using a synchrotron light source, the patient is moved across the X-ray beam [43]. The X-ray pictures show excellent contrast, and the required dose is lower when compared to conventional film use [42].

Imaging at 30keV is being reported with a silicon detector of 300  $\mu$ m thickness with pixels of 170  $\mu$ m x 170  $\mu$ m, read out by a chip with a 15-bit pseudo-random counter. Even though the photon detection efficiency is only 20%, good contrast pictures can be obtained [44].

For X-ray crystallography at somewhat lower energy where the photons can be efficiently absorbed in the usual thickness

of silicon detectors, hybrid pixel detectors are being developed. Using a matrix of 512 fast photon counting chips assembled on 64 detectors with  $200\mu\text{m} \times 200\mu\text{m}$  pixels developed for the DELPHI detector at LEP, a total area of  $25\text{ cm} \times 25\text{ cm}$  is instrumented [45]. Very high counting rates and very high dynamic range, i.e. contrast, are possible.

An interesting alternative to the hybrid pixel detectors is the “3-D” detector [46], which replaces the silicon detector paradigm of the planar processing with a new fabrication process where the implants are in columns between the two faces of the wafer. Because the depletion voltage depends on the distance of the columns instead of the detector thickness, this approach allows to decouple the signal size ( $\sim$  to the thickness) and the depletion voltage ( $\sim$  to the square of the column distance). Obvious applications in X-ray detection and tracking in very high radiation fields will await the practicality of having to etch the many holes into the silicon bulk and fill it with p-doped poly.

### IX. COMPTON AND PAIR IMAGING

At photon energies above 100 keV, the directional information is preserved when the photon interacts with a single electron or nucleus. In the Compton effect, only part of the photon energy is transferred to the electron, and the original direction is either reconstructed on a cone, or if the direction of the scattered electron is measured, on part of a cone (see Fig. 9). As proposed in [47], [48], measuring the energy transfer to electrons in successive Compton interactions allows the direction and energy of the photon to be reconstructed accurately.

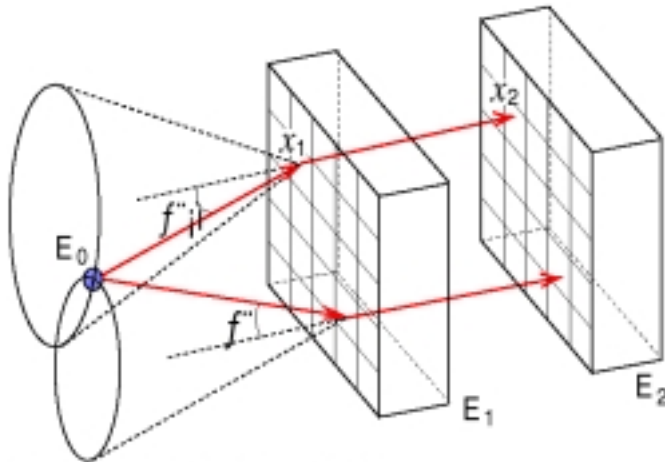


Figure 9: The principle of the Compton camera for multibeam imaging.

Fig. 9. Principle of Compton telescope: each measurement reconstructs the photon to be on a cone around the outgoing gamma direction. From [48].

In the Compton camera, the energy transfer and the location of the scatter are detected in a silicon pad detector with self-triggered readout chip, while the direction and energy of the scattered photon is detected in a ring of calorimeters [49]. The use of the Compton effect is

sometimes referred to as “electronic collimation”, replacing the mechanical collimation in clinical Anger cameras.

For hard X-ray detection in Astrophysics, a Compton telescope consisting of many layers of double-sided silicon detectors is being proposed [50]. Thick silicon detectors would increase the energy and direction resolution and the detection efficiency, but will require very high resistivity detectors. An 11 layer Compton telescope prototype with a active area of  $18\text{ cm} \times 18\text{ cm}$  has been built as a first step towards the Medium Energy Gamma-ray Astronomy telescope (MEGA) [51].

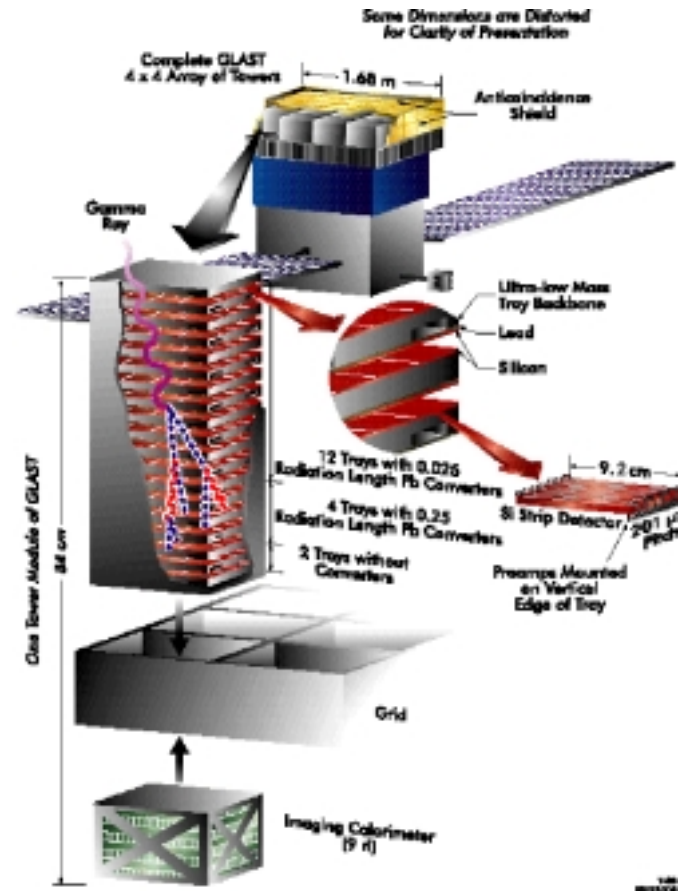


Fig. 10. Schematic view of the GLAST Large Area Telescope. The satellite based detector consists of an  $4 \times 4$  array of towers, each containing silicon tracker and CSI calorimeter. The tracker towers are subdivided into 18 converter planes, each followed by silicon strip detectors with crossed strips. An anti-coincidence shield surrounds the whole instruments and vetoes charged particles. Photons convert in the converter foils and are tracked in the silicon layers. From [57].

At the highest photon energies, above 100 MeV, the prevalence of pair production allows the photon detection to be done by using well established charged particle tracking: the gamma rays convert into electron-positron pairs, which are tracked in fine grained detectors. But a subtle paradigm shift is needed: while the charged particle tracking in magnetic fields tries to minimize the amount of material in the active volume, pair conversion trackers have to introduce extra material in order to allow enough conversions to take place, leading to the **pair conversion tracker paradigm**:

- Maximize the area
- Intersperse tracking layers with converters
- Keep individual converters thin.

Given that the conversion rate is proportional to the amount of material, and the angular resolution is proportional to the square root of the material due to multiple scattering of the electron and positron, a careful optimization of the amount of converter material has to be done, based on the science program. A safe but expensive solution to the problem is to distribute the converters over many layers with interspersed tracking planes, which allows to determine the directions of the charged particle pair before they multiple scatter too much.

A large pair conversion telescope for astronomical investigations is the Large Area Telescope on GLAST (shown in Fig. 10), which is being constructed to be launched in 2005 [52], [53]. It has a large area, and to minimize the schedule risk, it will be built in 16 identical "tower", each containing a silicon converter-tracker built with silicon strip detectors and a CsI hodoscopic calorimeter. The tracker will have 18 converter planes with about 3% $X_0$  or 18% $X_0$  converters, respectively, each followed by an x-y measurement using crossed single-sided silicon detectors. A prototype tower has been built and successfully tested in a beam test [54]. The final instrument will have close to 80m<sup>2</sup> of silicon area, 1Million channels of ultra-low power readout electronics [55], and will need about 5 million wire bonds to assemble the wafers to ladders. The special requirements of the launch, the space environment and the remoteness of operation have been driving the design of the tracker and detectors to be extremely simple and robust [56], [57]. With the launch of GLAST, one will be able to say that silicon detectors have arrived in Space.

## X. SUMMARY

The development of silicon detectors has led to many applications in many fields, only limited by the imagination of the scientists in the field. The success of this technology can be traced to forces outside and within the science community:

### Outside:

- Existence of industrial base
- Sophistication of fabrication
- Improvement in quality
- Reduction in cost

### Inside:

- Maturity of designs
- Growth of expertise
- Improvement of assembly techniques
- Progress in ASIC design

At the end, real progress was made when the two communities, industry and science, started a fruitful collaboration.

## XI. ACKNOWLEDGMENT

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