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THE USE OF SEMICONDUCTOR IMAGERS IN HIGH ENERGY PARTICLE PHYSICS

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Abstract

Various silicon devices are presently under development to enable the 3-dimensional reconstruction, with a precision of a few μm , of the particle trajectories very close to the interaction point, both for fixed target and collider experiments. The techniques employed are quite similar to those used for X-ray or infrared imaging.

Introduction

The devices used nowadays in high energy particle physics (or in nuclear physics for that matter) are generally not classified as imagers but as detectors. The distinction between imagers and detectors, however, seems to be dictated more by their application than by the devices themselves. Imagers observe a lively scene, whereas detectors observe, and often are part of an empty scene on which the experimenter creates something called "an event". In particle physics such an event features one or two incoming particles and a varying number of outgoing particles around an interaction point, called "vertex". Events of interest may occur at a rate of only one in ten thousand.

As we shall see, most particle detectors provide a one- or two-dimensional projected image of such events, and sometimes also energy-loss ("wavelength") information. With these images the experimenter proceeds to reconstruct the event in space and time. A magnetic field forces a curvature on the swift charged particles, so that their momentum can be calculated. Sometimes a particle may decay in flight into one or several other particles, and this gives rise to a "secondary vertex". The distance travelled by a particle until its decay is a measure for its "mean lifetime" because all high energy particles travel approximately at the speed of light. Recent detector development is greatly influenced by the discovery of the class of "charmed" particles with lifetimes $\sim 10^{-13}$ s, and a trajectory of ≤ 1 mm. These particles have put into evidence the fourth quark "charm" and the fifth quark "bottom" or "beauty". To obtain a satisfactory description of the system of quarks, a sixth quark called "top" is required. A unified description of the electromagnetic force, the weak force and the strong force is attempted and leads to predictions of the existence of other particles and phenomena, some of which were recently discovered at CERN.

Earlier detectors

A full 3-dimensional image of an event can be obtained directly in a thick stack of nuclear (photosensitive) emulsion, which has to be developed after exposure and is scanned under the microscope. Still now, this detector is unsurpassed in precision ($< 1 \mu\text{m}$). A charm event, recorded in emulsion is shown in fig. 1.

Normal photographic film is used to obtain 2-dimensional projections of events in the earlier detectors: cloud chamber, spark chamber or bubble chamber.

Although some people speculated already in 1960 about silicon array detectors [1], the invention of the multiwire proportional chamber [2] provided the real breakthrough towards electronic detectors, enabling real-time triggering and event selection. In a wire chamber the charged particle ionizes the gas and the electrons drift towards a plane of many parallel anode wires, under a high electric field. The original electrons initiate an avalanche towards a single wire and this signals the particle position in one coordinate.

In the seventies the drift chamber, respectively the time projection chamber were developed, in which one coordinate of the particle position is calculated from the drift-time towards a 1- respectively 2-dimensional segmented electrode structure. Great advance was accomplished both on the electronics and the gaseous detectors themselves. Position measurements with a precision of 100-200 μm are routinely done, even in large volumes of many m^3 . In special small detectors one has obtained a precision of $\sim 20 \mu\text{m}$ for charged particles [3] or X-rays [4].

Fig. 1 An interaction of a high energy photon (incoming from the left, not visible) in a nuclear emulsion, illustrating the new particles. The heavy tracks around the interaction point are nuclear fragments of the nucleus on which the interaction took place. The light tracks are caused by elementary charged particles with speed of light. A neutral "charmed" particle (invisible) is coming from the primary vertex point and decays into four charged particles at $\sim 50 \mu\text{m}$ distance. A second, charged, "charmed" particle decays in another charged particle and a neutral particle, which gives a "kink" in the track. This neutral particle has been identified via its decay in another downstream detector (courtesy exp. CERN WA58).

The need for high resolution semiconductor detectors

Events of the type shown in fig. 1 clearly cannot be handled by gaseous detectors, which have a thickness of $\geq 1 \text{ cm}$, wire spacing of $\sim 1 \text{ mm}$ at best, and no multi-hit capability within this spacing. Wire chambers still have their place further downstream in the experimental apparatus, once the particles have been bent far apart by the magnetic field. But in order to obtain images of what happens in the neighbourhood of the primary interaction one needs a new type of "vertex detector". Various suggestions have been made and quite some work was done on high resolution gaseous detectors, on microchannel plates as detectors, on very small bubble chambers and on scintillating fiber targets.

A relatively small effort was needed to show that semiconductor devices, in particular the so-called "silicon microstrip detector" can be used successfully for the study of the short lifetime particles [5,6]. Since one or two years, therefore, the interest in semiconductor particle imagers has increased rapidly. Further development has started in universities and in industry, and various experiments are being planned.

Desired properties of semiconductor particle imagers

It is instructive to note a few important differences between light or X-ray imagers and particle imagers, although some devices could be used equally well for either purpose.

Each event to be imaged is unique and has to be recorded completely, generally within a short time ($10 \text{ ns} - 1 \mu\text{s}$) because other events may follow at a high rate. Optical imagers generally look at a slowly changing scene, which continuously emits photons so that from each part of the scene a large number of photons can be integrated to obtain a sufficient signal. The signal generated by a particle in a semiconductor detector will be discussed in the next section, but it is obtained at once as the event occurs. A scanning mode detector generally cannot be employed, because it is too slow and because little charge is available to activate the memory medium, e.g. a phosphor. However, this solution (using a vidicon) was considered in conjunction with a microchannel plate as the detector medium [7].

If a semiconductor imager is used directly to record particle positions, it should not have any insensitive region. In optical imaging this requirement is becoming of greater interest too as one requires better resolution with smaller area sensors [8].

Although a 100% sensitive area is required, the information actually is sparsely distributed over this area, in contrast with lively imaging where each pixel carries information. In principle, the "event" information could be compacted, neglecting all empty pixels. A similar situation may occur if an imaging device is used for guidance purpose, e.g. in robotics or in navigation instruments.

Usually the detectors are placed themselves in the space where the events occur. Therefore, they have to be thin so that they disturb the particle trajectories as little as possible.

Finally, a considerable area has to be covered with small size elements. Lenses, diaphragms or "light shields" cannot be employed with GeV particles.

Energy deposition in silicon by energetic particles

A charged particle loses energy and creates ionization in matter. In silicon, on the average one electron-hole (e-h) pair is created for an energy loss of 3.62 eV, independent of the type of particle. In suitable semiconductor devices the number of collected electrons and holes is large enough to constitute a measurable signal, so that the passage of the particle can be detected.

Particles of fairly low energy may deposit all of their kinetic energy within the detector volume. For example, a 12 MeV proton can be stopped in 1 mm of Si. The signal in this case is approximately 3.3×10^6 e-h pairs or 0.53 pC.

The specific energy loss decreases for faster particles, as is shown in fig. 2. It is beyond the scope of this article to discuss the energy loss theory and a detailed formulation may be found in the literature [9]. However, it should be noted from fig. 2 that the energy loss of energetic particles reaches a minimum beyond which only a small increase occurs. Hence the terminology: minimum ionizing particles. The average minimum energy loss in silicon is 0.39 MeV mm^{-1} .

Fig. 2 The energy loss ($\text{MeV} \cdot \text{mm}^{-1}$) of muons (pions, protons, etc.) in silicon as a function of the relativistic muon momentum, expressed in $\beta/\sqrt{1-\beta^2}$, with $\beta = v/c$, v is the speed of the particle, c is the speed of light. The different curves indicate:

(a) The energy loss calculated following Bethe-Bloch, without density effect correction.

(b) Idem including density effect correction following Sternheimer.

(c) The restricted energy loss for a thin layer, with a maximum energy transfer of .5 MeV. The measurement points are values of total averaged energy deposition in a 980 μm thick silicon detector.

(d) The most probable energy loss in 1 mm of Si. The measurement points give values found with muons and pions in a 980 μm and a 486 μm thick detector, ref. [9], p. 25.

The energetic particle loses energy through successive encounters with close or distant electrons in the material. This is a stochastic process so that the actual energy loss for a particle traversing a thin layer of material has to be described by a probability distribution, the so-called Landau distribution (fig. 3). A small number of particles undergo a large energy loss (represented by the tail of the distribution). Most particles lose an energy around 0.30 MeV mm^{-1} in a 1 mm Si layer (curve (d) in fig. 2). Note that the specific energy loss decreases for decreasing layer thickness: it is only $\sim 0.25 \text{ MeV mm}^{-1}$ in a 0.1 mm thick Si layer. A recent discussion of energy loss in thin Si layers has been presented by Bichsel [10].

The signal generated by minimum ionizing particles then consists of $\sim 80\,000$ charges (12.8 fC) per mm of Si.

Fig. 3 A measured pulseheight spectrum of 280 GeV muons passing through a 980 μm thick silicon detector. The x-axis shows the channel number, corresponding to the energy deposited in the silicon. The y-axis shows the number of counts of particles within a certain energy channel. Most particles loose an energy of $.30 \text{ MeV mm}^{-1}$, here corresponding to $\sim$ channel 290. The full curve is the theoretical distribution, calculated following Landau. The discrepancy is partly due to noise and partly due to shortfailing approximations in the Landau theory, as explained e.g. by Bichsel [10]. The "hump" around channel 550 is ascribed to accompanying secondary ("delta") electrons.

Particle detection in silicon devices

Given the amount of charge generated by the particle (~ 80 e-h pairs per μm of Si), it is principally the pixel capacitance together with the readout amplifier which determines if the particle can indeed be observed. For example, if a typical CCD pixel has a capacitance of 10 fF, and if one can measure a 10 mV signal, then the detectable charge $Q = C.V = 620 \text{ e}^-$, which can be generated by the particle in $\sim 8 \mu\text{m}$ of Si.

If one uses a digital device, e.g. a Random Access Memory (RAM) for particle detection, the charge needed to change the state of a memory cell might be as high as $\sim 3 \times 10^6 \text{ e}^-$, taking the cell capacitance .1 pF and $\Delta V = 5 \text{ V}$. Obviously, such a digital device is optimized for not detecting particles.

Currently available discrete amplifiers for large capacitance (1-50 pF) silicon detectors have noise levels of 400-1500 e^- r.m.s. in the appropriate frequency region of 10-100 MHz. Therefore, silicon diode structures with a depletion thickness of 100-300 μm should be used (signals of 8000-24000 e^-).

The electric field present in the diode depletion region causes all charge to be collected in 5-15 ns. If there is an undepleted region, additional charge may be collected by slow diffusion.

Because of the high critical charge and because of the insensitive area, occupied by the addressing circuitry, RAM devices in their present form are not particularly suitable for high energy particle detection.

Among the various types of CCD, the scanned devices and the interline transfer devices cannot be used either, but frame transfer devices are particularly useful, as will be shown in detail by Damerell et al. [11], in one of the following papers. One aspect of the use of frame transfer CCD is the superposition of "out-of-time" events on top of the "interesting" event. By using several CCD, and transferring the images in different directions, one is able to reconstruct the "in-time" event and reject the "out-of-time" information. In this way one achieves a 4-dimensional reconstruction in space and time.

The Position Sensitive particle Detector (PSD), based on resistive charge division between two or four electrodes and used in various optical systems cannot be applied for particle imaging, because several particles will be incident at the same time, often quite close together.

A solution, which can be described as a zero-phase CCD, consists in drifting the charged packets created by simultaneous particles along a potential "gutter" towards a single electrode, and use the time of arrival for position measurement. Becker et al. [12] will describe this so-called "silicon drift detector" in detail.

Use of high resistivity silicon

The thickness of the diode depletion region is dictated by the signal-to-noise ratio of the total system. In a low capacitance detector like a CCD a depleted thickness of $\sim 10 \mu\text{m}$ is sufficient. This can be obtained with a 15 V potential on a MOS capacitor on p-type silicon with $60 \Omega\text{cm}$ resistivity.

To obtain a depleted layer of $300 \mu\text{m}$ thick with an applied voltage of 100 V, one has to use silicon with a resistivity in excess of $3300 \Omega\text{cm}$.

Manufacturers of detectors for nuclear applications are not so much guided by the signal/noise criterium but more by the total stopping power of the detector. They aim for very thick detectors (1-3 mm) and use routinely $\geq 20 \text{ k}\Omega$ silicon, or they make a compensated volume by the lithium drift process. Very pure silicon is needed, with a long minority carrier lifetime. Therefore, one always uses float-zoned silicon, most often with $\langle 111 \rangle$ orientation. Most manufacturers used the surface barrier technique, because they found that high temperature processes would kill the carrier lifetime and decrease the silicon resistivity.

Using very clean processing, Kemmer [13] showed that diode structures with very low reverse currents can be made, with long minority carrier lifetime and high resistivity. He reported a reverse current of $2 \text{ nA}\cdot\text{cm}^{-2}$ for a $300 \mu\text{m}$ thick diode ($70 \text{ nA}\cdot\text{cm}^{-2}$).

There seems still fairly little known about the processing of high resistivity silicon with the VLSI techniques [14]. In fig. 4 the high frequency C-V curves of 2 MOS capacitors are shown, made on $\langle 111 \rangle$ $5000 \Omega\text{cm}$ and $\langle 100 \rangle$ $1200 \Omega\text{cm}$ silicon. The oxides were grown at 1050°C and have a thickness of $\sim 100 \text{ nm}$ respectively 80 nm . The capacitance values are strongly dependent on the applied frequency, making quantitative analysis hazardous.

Silicon microstrip detectors

The idea of segmented detectors dates back to 1963 when Hofker et al. constructed the "checker-board" detector [15]. Although in 1980 the first "microstrip detectors" (with a pitch of $200 \mu\text{m}$) also were made by the surface barrier technique, it was the intention from the beginning to employ standard silicon processing technology to obtain small, well defined patterns [5].

The parallel segments, or "strips" are realized as separate diodes by B^+ ion-implantation in a high resistivity n-type substrate, after oxidation and creating the wafer-scale pattern with a photomask. The rear side of the substrate is also implanted (with As^+ ions) to obtain a common ohmic contact for all diodes.

Sometimes, an "inverted" structure is made, with an undivided rectifying contact and a segmented ohmic contact on the rear side of the wafer. This requires a double-sided polished substrate.

Fig. 4 High frequency C-V curves for 2 MOS capacitors. The resistivity of the $\langle 100 \rangle$ substrate is $\sim 1200 \Omega\text{cm}$ and that of the $\langle 111 \rangle$ substrate is $\sim 5000 \Omega\text{cm}$. The oxide thickness is ~ 80 respectively 100 nm . It was grown at 1050°C .

The detector size often approaches that of a complete wafer, 2" or 3" in diameter. An example of a silicon microstrip detector is shown in fig. 5. It has 520 parallel strips of 26 mm length and $50 \mu\text{m}$ pitch. The implantation is $30 \mu\text{m}$ wide, with $20 \mu\text{m}$ of silicon dioxide between the diodes. The resistance between elements is of the order of $1 \text{ G}\Omega$ in a good detector, if totally depleted. The chip of $30 \times 30 \text{ mm}^2$ is mounted in a hole in the $100 \times 100 \text{ mm}^2$ ceramic plate, which carries the fanout. Ultrasonic bonding with $25 \mu\text{m}$ Al-wire is used to connect 512 strips to the corresponding lines on the ceramic plate. The pitch of the bonding in this case is $100 \mu\text{m}$, but a smaller pitch is feasible.

using bonding in two or three concentric levels. The ceramic plate is connected to the electronics via flexible kapton foils, which are glued to the ceramic, using a thick film process (300 μm pitch of contacts).

Fig. 5 A silicon microstrip detector with 520 elements, and a sensitive area of $26 \times 26 \text{ mm}^2$. The chip measures $30 \times 30 \text{ mm}^2$ and is mounted on a $100 \times 100 \text{ mm}^2$ ceramic plate. Kapton foils enable connection to 512 amplifiers, realized as 4-channel hybrids on $1" \times 1"$ ceramic substrates. 32 of these (128 channels together) fit into a single box of $90 \times 35 \times 35 \text{ mm}^3$.

At present, silicon microstrip detectors are commercially available, with sizes between $1 \times 1 \text{ cm}^2$ and $5 \times 5 \text{ cm}^2$, with a pitch of 20 μm , 50 μm , 100 μm , and above. The large number of elements to be read out imposes a miniaturized electronics.

Characteristics of charge collection in a microstrip detector

If a microstrip detector is placed perpendicularly in a parallel beam of energetic particles, the projected position of each particle along one coordinate is found with a precision of the pitch of the strips, if only a single element responds. In practice it was found that a certain proportion of the particles cause two or three elements to respond: the so-called double or triple hits. The proportion of double hits is only ~ 5% for devices with high resistance between elements, and is then determined by the beam divergence and the carrier diffusion during the charge collection. For devices with low interstrip resistance, the number of double hits may be as high as 30%. If the interstrip resistance becomes comparable to the input impedance of the amplifiers, no localization is possible anymore. It has been verified that all charge is collected on one or several adjacent elements, by comparing signals for 45° and perpendicular incidence as shown in fig. 6. No insensitive region remains between the segments, under condition of total or even partial depletion. This was also checked by measuring the detector efficiency, i.e. the proportion of particles detected by the device in a well-defined beam. It was found to be practically 100%.

SILICON SURFACE BARRIER MICROSTRIP DETECTOR

Fig. 6 A silicon microstrip detector with totally depleted strips of $200 \mu\text{m} \times 400 \mu\text{m}$ cross section. Particles which cross at 45° deposit $\sqrt{2}$ times more total energy than particles which are perpendicular to the detector. A particle (a) causes a double hit, particles like (b) cause triple hits. The signal in the central element of a triple hit is just $1/\sqrt{2}$ times the signal of particles which are perpendicular.

Charge division between two adjacent elements can be used to improve the precision of localization by determining the centre of gravity. One approach has been the capacitive charge division, by introducing several floating strips between the read-out strips. A precision of $4\text{ }\mu\text{m}$ has been achieved in this way, with a pitch of $20\text{ }\mu\text{m}$ and a readout every $60\text{ }\mu\text{m}$ [16].

The ultimate precision obtainable with silicon detectors depends on the lateral diffusion of the charge carriers during their collection, and on the occurrence of energetic knock-on delectrons ("delta-electrons") which mask the real position of the particle. Triple hits are mostly attributed to such delta electrons, travelling a long distance away from the original track. The thinner the detector, the lower the probability for a delta electron to occur, and therefore the better the precision.

The carrier diffusion has been studied by Belau et al. [17]. Using the homogeneous distribution of particles incident on two adjacent strips of $20\text{ }\mu\text{m}$ wide, the diffusion may be calculated from the relative signal heights in double hits. They report a charge distribution of $6\text{ }\mu\text{m}$ wide for a collecting drift field of $4300\text{ V}\cdot\text{cm}^{-1}$. The application of a magnetic field causes an asymmetric charge carrier distribution, but does not prevent charge collection. The width of the charge distribution becomes then $\sim 10\text{--}15\text{ }\mu\text{m}$.

Silicon Microstrip detectors in fixed target experiments

Microstrip detectors have to be used in doublets or triplets to enable 2-dimensional image reconstruction. Even so, there are always ambiguities caused by closely coincident particles. A true 2-dimensional detector like an image CCD is preferable, but is too small to cover a significant area, and needs a long readout time. Damerell et al. [11] will show the possibility of using CCD very close to the target.

Most experiments use several doublets or triplets, like the one shown in figs 7 and 8. An event reconstruction [18] is shown in fig. 9. The signals in the strips are displayed along the detector planes, and the tracks are fitted to the positions derived from these signals.

So far, five experiments at CERN and two at Fermilab have employed a complete silicon microstrip vertex detector, and they are producing now the first physics results.

Silicon detectors in colliding beam experiments

The sensitive area in a colliding beam experiment is several orders of magnitude larger than in a fixed target experiment: $1\text{--}100\text{ m}^2$ instead of $10\text{--}25\text{ cm}^2$ for a single detector in a fixed target telescope.

A project for the use of CCD in the new Stanford collider will be presented by Damerell et al. [11]. They profit from the extreme focalization in this machine.

The UA2 experiment at CERN is presently building a silicon array of fairly coarse elements. It will consist of 432 detectors, $6.1 \times 4\text{ cm}^2$, each with 7 segments. The total number of segments is then 3024 and is mainly limited by the space available for electronics. The detectors are arranged on one side of a sword-like fiberglass board, the electronics is placed on the other side, as shown in fig. 10. The aim of this detector is mainly to reject certain undesirable events where an outgoing electron is accompanied by a positron: this will cause a signal in the silicon segment twice as high as in the case of a single electron. The silicon has been chosen in this case because of its compactness and because it was easy to obtain detecting elements of the desired shape and dimension.

Electronics developments for silicon detectors

The progress in the use of silicon detectors for particle imaging is closely related to the availability of compact, cheap electronics. This is obvious if one remembers that a typical experiment now may have 10000 or more electronic channels, each connected to an analog-to-digital converter (ADC). Such parallel processing has been customary in high energy physics experiments because of the high event rate of $10^5\text{--}10^6$ per second. A reduction of the number of ADC channels by parallel-serial multiplexing is possible if event information can be buffered in a pipe-line for a time, long enough to make a "useful-event" selection. This selection, or "trigger", must be based on quickly available data from a small subset of detectors. A hardwired first level trigger may be obtained in $\sim 100\text{ ns}$, a microprocessor evaluation takes several μs .

Fig. 7 Two silicon microstrip detectors are assembled into a sandwich, enabling two perpendicular projections of the particle positions on an area of $26 \times 26 \text{ mm}^2$.

Fig. 8 The assembled sandwich on its mounting. Shown with two of the eight amplifier boxes. The thickness of the whole assembly is less than 40 mm, enabling close staking of these modules.

Fig. 9 An event reconstruction using three microstrip detector planes. In (b) the target region is enlarged, and a secondary vertex is clearly found. [18].

Fig. 10 One of the 48 sword-like elements which surround the UA2 inner region, at 14 cm radius. The electronics side of the sword is shown, the other side has 9 detectors, of which one is shown besides the sword. Multiplexer and line driver are coupled to the right.

Efforts are under way to produce integrated circuits in NMOS or CMOS which incorporate a preamplifier, a sample/hold circuit and a multiplexer for 60 or 128 inputs. A different approach is the use of a signal processing CCD with 20 parallel inputs and one serial output [19].

The initial approach has been, however, one of brute force, just connecting all imaging elements, as shown in fig. 8. This proved to be possible by using a simple preamplifier, manufactured in thick film hybrid technology [20]. The amplifier noise is $\sim 1500 e^-$ r.m.s. The amplifier cost per channel is only a few dollars. The space occupied by 128 channels could be reduced to a volume of $90 \times 35 \times 35 \text{ mm}^3$.

The lower the noise of the preamplifier, the thinner the silicon detector can be, and consequently lower resistivity silicon could be used. With lower electronic noise also the possibilities of interpolation read-out become more attractive.

Also reduction of the power consumption of the electronics is important, as one should not release too much heat in the neighbourhood of the silicon detectors. This would increase their diode reverse current, and thereby the noise.

Conclusion

Recent developments of silicon devices for high energy particle event reconstruction enable the observation of particles with 10^{-12} s lifetime. Various other applications of CCD and silicon detectors are envisaged, e.g. in the future collider experiments.

The complete integration of particle detector and signal processing electronics is a still remote goal. However, in imaging CCD it has proved to be feasible by adjusting individual parts to the overall system requirements. Ultimately, it may not be necessary for particle detection to continue using extremely high resistivity silicon, if a fast readout can be conceived for a large number of low capacitance detector pixels.

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