Semiconductor Tracking Detectors in e^+e^- Vertex Detectors*

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Abstract

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In the last decade substantial progress has been made in the development and the application of solid state detectors. Semiconductor tracking detectors are exploited on a large scale in high energy physics experiments for precise position measurement. In the field of vertex detectors these detectors have proven to be a powerful and reliable tool for physics analysis.

An introduction and an overview of the different detector principles and the implementation of these detectors in large experiments will be given. The current state of the art of vertex detectors will be explained taking the experiments at the Large Electron Positron Collider at CERN as example. Some of the most recent developments in the field of semiconductor detectors will be introduced.

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1 Introduction

When one compares the different layouts of existing and planned experiments in high energy physics one will certainly discover one amazing similarity despite all the differences in the technologies employed. All collider experiments have as the innermost detector device a silicon vertex detector. This is true for hadron colliders at the energy frontier (e.g. Tevatron, LHC) as well as for e^+e^- colliders (LEP and all the planned B-factories). I will try to explain some of the reasons for this fact.

Naturally the choice of the detector layout is driven by physics arguments. In the last decade the study of and search for particles containing heavy quarks (the bottom and the top quark) became the most promising approach to increase our knowledge of the fundamental particles and their interactions. The best way to identify particles containing the bottom quark is to measure the decay length which is a few hundred μm . This method can also serve to tag the top quark, as the dominant decay mode is into bottom quark.

To achieve the required precision in terms of the impact parameter resolution (10–30 μm) one requires a single detector with a resolution of only several μm . This is hardly possible to achieve with gaseous detectors due to the diffusive spread of the liberated electron cloud. This fact leads almost naturally to the choice of solid state devices with much smaller values for the diffusion. But what is the reason for the exclusive use of silicon?

The multibillion dollar industry for silicon chips has provided us with a well developed technology which is now employed in many scientific areas such as high energy physics. This technology allows to build detectors with very fine structures, and, as a consequence, excellent spatial resolution of almost 1 μm can be achieved. The small band gap of silicon results in a large ratio of the signal to the energy loss. The availability of ultrapure silicon, and the fact that silicon is a low Z material with excellent mechanical properties, makes it the ideal choice for vertex detectors.

A limitation of silicon detectors in high energy physics appeared only recently when the design for the next hadron collider with the anticipated high radiation environment started. The radiation damage of silicon vertex layers in some areas close to the beam will be so large that operation for the entire lifetime foreseen for the experiment might not be possible. But one should be careful not to do injustice to the material silicon. Silicon is intrinsically very radiation hard compared to most other materials used for particle detection.

Driven by the problem of radiation damage other materials for solid state detectors such as GaAs, or more recently diamond, are being considered. Detectors made from these materials are still far from achieving comparable performance or the maturity of silicon.

2 Properties of Semiconductor Detectors

To understand the physical properties of semiconductors it is convenient to look at the band model. Gaseous silicon has a typical structure of atomic energy levels, and as silicon condenses in crystalline form these energy levels are merged into energy bands. In these bands the energy levels are essentially continuous. The energy levels which are occupied by the valence electrons develop into the valence band. Between this band and the conduction band, which are the previously unoccupied energy levels, is an energy gap in which no

states are allowed. The characteristics of semiconductors is that this band gap is small (e.g. 0.7 eV in germanium, 1.1 eV in silicon). In insulators this energy gap is much larger (e.g. 9 eV for silicon dioxide) and in conductors the valence band and the conduction band overlap.

The value of the band gap is the essential figure which determines if the material is in principle useful for charged particle detection. A small band gap leads to a large ratio of the signal (ionisation charge) to the energy loss. In silicon with a band gap of 1.1 eV only 3.6 eV of deposited energy is needed to lift an electron from the valence band to the conduction band. An electron in the conduction band will move almost freely and so will the free state (hole) left in the valence band. Thus we speak of the creation of an electron-hole pair. In typical gaseous detectors for comparison one needs about 30 eV to ionise an atom.

A negative consequence of the small band gap in semiconductors is the large number of intrinsic carriers already excited at room temperature. In a detector device the fluctuations of these carriers correspond to the inherent noise of the system. In intrinsic semiconductors one can calculate the concentration of thermally excited electrons into the conduction band and the concentration of holes in the valence band as

$$n_i = \sqrt{N_C N_V} e^{-\left(\frac{E_g}{2kT}\right)} = AT^{3/2} e^{-\left(\frac{E_g}{2kT}\right)}$$

with N_C , N_V being the effective density of states in the conduction band and the valence band respectively. In silicon at room temperature this value is $n_i = 1.45 \cdot 10^{10} \text{ cm}^{-3}$. In other words 1 in 10^{12} atoms of the silicon lattice is ionised by thermal excitation.

In a silicon detector with a typical element size of 1 cm^2 with $300 \mu\text{m}$ thickness this results in $4.5 \cdot 10^8$ electron-hole pairs. The signal of a high energy charged particle crossing $300 \mu\text{m}$ of silicon can be calculated using the energy loss in silicon of $dE/dx \sim 3.8 \text{ MeV/cm}$ and gives only $3.2 \cdot 10^4$ electron-hole pairs. This is 4 orders of magnitude lower than the number of thermally excited electrons. It is obvious that silicon if it were used in this simple way would be excluded for charged particle detection.

To improve the ratio of signal to noise several concepts are pursued:

- Cooling of the material to decrease the intrinsic carrier concentration. This is done for nuclear physics applications using germanium.
- Using a “better” material with a larger band gap but still small enough to have a reasonably low ionisation energy. This might be the case for diamond with a band gap of 5.5 eV as I will explain in Chapter 7.
- Implementing a clever structure in silicon to remove charged carriers from the sensitive volume. In most high energy physics applications this structure is the p-n junction.

3 Silicon p-n Junction

A silicon p-n junction develops at the interface region of differently doped areas in the silicon bulk. Doping means the replacement of a relative small number of silicon atoms in the lattice by atoms with either 3 or 5 valence electrons in contrast to the 4 in silicon. One obtains a so-called n-type silicon when the dopand is a material with 5 valence electrons

Figure 1: Silicon pn-junction.

such as phosphorous or arsenic (donor atoms). These atoms create energy levels in the band gap very close to the conduction band (see Fig. 1). The electrons in these states are, at room temperature, always excited to the conduction band and thus contribute to the carrier concentration. Doping with a material with 3 valence electrons such as boron or aluminium (acceptor atoms) creates energy levels very close to the valence band (p-type silicon). These originally unoccupied states are filled at room temperature with electrons from the valence band. The remaining holes in the valence band contribute to the hole current in the material. Therefore the excess carriers (majority carriers) in n-type silicon are the electrons and in p-type silicon are the holes.

In the interface region of a p- and n-type material the mobile electrons and holes diffuse in the material of the opposite type and recombine. This leaves positively charged ions in the n-region (exposed donor ions) and negatively charged ions in the p-region (acceptor ions). The consequence of this space charge is an electric field which further prevents the diffusion of electrons and holes into this region and thus stops further recombination. The thickness of this area, usually referred to as the depletion zone, depends on the doping concentration in the p- and n-regions. In the depletion zone all mobile charged carriers are removed making it the perfect sensitive volume for charged particle detection.

If in addition a negative bias voltage is applied to the device (positive potential on the n-side) the additional external field increases the width of the depletion zone by pulling electrons and holes out of the junction region. In a detector the bias voltage should be high enough to deplete the whole detector volume. The width of the depletion zone as a function of the bias voltage can be written as:

$$w = \sqrt{2\epsilon\rho\mu V_B}$$

(simplified formula for a material with one dopand dominating). ϵ is the permittivity of silicon, μ the mobility of the majority carriers, V_B the bias voltage and ρ the resistivity of the doped silicon material. For practical reasons one has to restrict the bias voltage to about 100-200 V, which explains the need for high resistivity silicon ($\rho \geq 3 \text{ k}\Omega\text{cm}$) for these applications.

Figure 2: Basic structure of a silicon strip detector.

Charged particles which traverse the detector volume create electron-hole pairs which drift under the influence of the internal and external field to the electrodes. This drift gives rise to the signal. The dominant noise in such a reversely biased p-n junction comes from thermally generated electron-hole pairs which are also swept out of the depletion region (generation current).

4 Silicon Strip Detectors

4.1 Basic structure

The basic structure of a silicon detector for position measurement looks as follows. The initial silicon material is an n-type silicon with a donor concentration on the order of $5 \cdot 10^{12} \text{ cm}^{-3}$ and a thickness of about $300 \text{ } \mu\text{m}$. The pn-junction is realised by implanting acceptor atoms on one side with a concentration of about 10^{15} cm^{-3} . The layout of these implants is defined by photolithography. Fig. 2 shows a sketch of such a simple detector where the implants are strips. The SiO_2 layer between the implants and the aluminium on top of the strips serves as the insulator for the integrated coupling capacitors (ac coupling). The process for producing such detectors is the so-called planar technology developed originally for electronic chip production.

Most of the detectors used at present are ac coupled devices. These detectors require an integrated biasing structure to supply each strip with the bias voltage. One solution is to use on-chip polysilicon resistors to connect each strip with a common bias line. A second approach is to use a so-called reach through structure [1] or FOXFET structure [2]. These are narrow $\text{p}^+\text{n}\text{p}^+$ -junctions between the strips and a common bias line which holds the strips at a potential a few volts from the bias line. On the back side of the silicon detector a highly n^+ -doped layer provides good ohmic contact.

The use of photolithography allows to define very fine structures with narrow strips and narrow strip distances. In the simple detector shown in Fig. 2 the position resolution is clearly dominated by the distance of the strips. In most detectors not only the position of the strip closest to the particle track is determined, but also the signal height on this and the neighbouring strips is measured (analogue read out). This allows to interpolate between strips and thus to improve the spatial resolution significantly, which depends on the signal to noise ratio of the detector.

Practical limitations of the spatial resolution, other than the detector geometry, are restrictions coming from the read out electronics. Even with the well established VLSI technology it is difficult to connect and read out strips with a distance of less than $50\text{ }\mu\text{m}$. Further limitations in a large scale detector are the number of electronic channels and the power dissipation.

A method to improve the spatial resolution of strip detectors beyond the limitation of the read out distance is the implementation of intermediate strips, i.e. strip implants which are not connected to the read out electronics. The signal generated below these strips is transferred to the read out strips via the capacitance between the strips inherent to the detector.

The ultimate limitation of the spatial resolution, however, is δ -electrons which produce large charge clusters which may be far away from the original particle track. This causes a shift of the centre of gravity of the charge cloud and thus an error in the position measurement. Although silicon detectors are very thin the probability of δ -electrons is not negligible. The best performing strip detector to my knowledge [3] achieved a spatial resolution of about $1.25\text{ }\mu\text{m}$ and it was shown very nicely that events with large energy depositions (δ -electrons) are limiting the spatial resolution.

4.2 Measurement of the second co-ordinate

The first generation of LEP vertex detectors had only $r\phi$ strips. The strips were running parallel to the beam at different radii thus measuring the ϕ co-ordinate at different r . The physics capabilities of a vertex detector, however increases when in addition the z co-ordinate, even with less precision, can be determined. Therefore very soon all experiments upgraded their detectors to measure rz as well.

At the LEP experiments two approaches were used. The first and the straightforward solution is to glue two standard detectors with orthogonal strip orientation back to back. This was chosen by the experiment OPAL [4] and in some parts of the DELPHI vertex detector [5].

The second approach was developed by ALEPH and DELPHI and is the so-called double-sided detector. The basic idea of a double-sided detector is to segment not only the p-junction but also the backside n^+ -implantation. If both sides of the detector are segmented into strips with orthogonal orientation, one obtains devices capable of measuring 2 co-ordinates. The advantages are obvious: with the same material thickness twice the information is obtained, the alignment of these detectors is easier and charge correlation between p- and n-side may be used to reduce ambiguities.

There is one fundamental problem. The SiO_2 layer on top of the silicon, which is used to passivate the detector and in most detectors is serving as the insulator for the integrated coupling capacitors, has inherent positively charged ions. The positive charges close to the SiO_2 -Si interface on the n-side are compensated by a thin electron accumulation layer of mobile electrons in the silicon which shortens the n^+ -strips and makes a position determination impossible. Two solutions have been developed:

The first method is to implement p^+ -lines (p^+ -stops, Fig. 3 a) around the n^+ -strips (see ALEPH [6], L3 [7]). These implants interrupt the accumulation layer and isolate the n^+ -strips.

The second method is the use of field plates (Fig. 3 b) developed by DELPHI [8]. The aluminium read out lines extend sideways beyond the n^+ -implants and by applying a

Figure 3: Isolation of n^+ -strips for double-sided detectors. a. p^+ -stops. b. field plates.

negative potential to these lines with respect to the bulk the electrons in the accumulation layer are repelled, and the n^+ -strips are isolated from each other.

4.3 Routing of z lines

The implementation of detectors with $r\phi$ and rz read out in complex vertex detectors led to a new problem. The electronic chips bonded to the $r\phi$ strips are placed outside the acceptance of the vertex detector. However if one places the electronics for the rz strips at the end of the strips as well, the electronic components will be inside the acceptance. This additional material, very inhomogenously distributed, increases multiple scattering and therefore worsens the achievable position resolution of the detector. The upgraded vertex detector of ALEPH in 1991 was built that way [6].

The experiments L3 and OPAL use kapton foils and glass plates respectively with printed lines to route the signals from the rz strips to the side where the electronics is placed. Clearly one needs additional bondings to and from these fanout structures and again additional material is introduced in the detector. A further drawback is that the final detector modules may become quite complicated to assemble and to handle.

A very ambitious development was initiated by DELPHI. The fanout lines of the rz strips were integrated in the detector using a double metal layer [8]. This additional layer is placed on top of a thick isolation layer ($4-5 \mu\text{m}$ SiO_2 or Polyimide) and has lines running orthogonal to the rz strips (Fig. 4). Each line has a connection to the appropriate strip to connect the strip to the fanout line and to the read out channel of the chip. These ultimate double-sided double metal strip detectors give a maximum of information with a minimum of material. The construction of such detectors requires 12 to 15 photolithographic masks compared to 5 necessary to produce a single-sided detector. The large number of production steps is responsible for the significantly higher cost of these detectors.

5 Hybrid Pixel Detectors

In spite of all the effort which is put into the development of double-sided strip detectors one major disadvantage is unavoidable. If more than one charged particle traverses a detector plaquette at the same time this will lead to irreducible ambiguities (ghosts). Pixel detectors where the segmentation is into pixels rather than strips are detectors with a genuine two dimensional read out and avoid this problem.

Figure 4: Cross sectional view of a double sided double metal detector.

Figure 5: Schematic drawing of a hybrid pixel detector.

Up to now only hybrid pixel detectors have reached the status of being employed in high energy experiments [9]. The name hybrid means that the detector elements are built on high resistivity silicon and the read out electronics is built on low resistivity silicon (see Fig. 5). This avoids the incompatibilities between the two production processes. The area of one electronic channel is equal to or smaller than the pixel area. An electrical connection has to be made between each pixel and the corresponding electronic channel. This connection is usually done by a method called bump bonding [10]. The number of channels scales quadratically with the detector size and so does the number of connections. The production of this tremendous number of bond connections with a reasonable small failure rate is the key problem of hybrid pixel detectors. The large number of pixels makes additional electronics on the chips necessary for extracting the relevant information on-line (e.g. sparse data scan). The DELPHI experiment is at present (spring 1996) upgrading their vertex detector with a forward pixel system. The pixel size is $330 \times 330 \mu\text{m}^2$ and in total 1.2 million pixels are foreseen [11].

6 Vertex Detectors at LEP

At the large electron positron collider (LEP) at CERN four large experiments are installed (ALEPH, DELPHI, L3, OPAL) and are taking data since 1989. At the start-up none of the experiments had a vertex detector. In 1990/91 ALEPH, DELPHI and OPAL installed their first silicon vertex detectors, which had essentially 2 layers of $r\phi$ strips only. Since then a

Detector	ALEPH	DELPHI ^a	L3	OPAL
layers	2	3+4	2	2
coverage $\pm\theta$ [deg]	18	10	25	23
type of detector	ds strips	ss, ds strips pixels	ds strips	ss strips (back to back)
bias method	p ⁺ reach through n ⁺ accum. layer	polysilicon FOXFET	p ⁺ reach through n ⁺ accum. layer	FOXFET
interruption of n ⁺ accum. layer	p ⁺ strips	field plates	p ⁺ strips	
z fan out	electr. on z side ^b kapton foil ^c	double metal	kapton foil	glass plate
impact parameter resolution $r\phi$ [μm]	23	20	25	18
impact parameter resolution rz [μm]	28	28	under study	23

^ainstalled in May 1996

^b1991–1995

^c1995

Table 1: Comparison of silicon vertex detectors at LEP.

continuous upgrading of these vertex detectors took place. First rz strips were installed to measure the z co-ordinate as well, and more recently (1995/96) all experiments upgraded their vertex detectors to increase the angular coverage. This increase in coverage was necessary to prepare the detectors for LEP operating at higher energies (LEP200). The physics objectives at LEP200 (e.g. search for the Higgs boson and for supersymmetric particles) require maximal acceptance and an improved hermeticity. The experiment L3 installed the vertex detector in 1993 and proved with a very short design and construction time that silicon detectors are a well established and mature technique.

Table 1 gives an overview of the silicon vertex detectors of the four LEP experiments. In the table the different techniques chosen and the final performances achieved (1995) are listed. Details of the four vertex detectors can be found in [6, 8, 7, 4]. The DELPHI vertex detector as it will be installed in 1996 is by far the largest one of all LEP experiments (and probably the largest in the world) with 888 detector plaquettes summing up to a total of about 1.5 m² of silicon. It consists of 3 concentric layers in the barrel region ($\theta \geq 21^\circ$) and 4 layers of endcap detectors. The overall coverage is $\theta \geq 10^\circ$. For the first time in a collider experiment hybrid pixel detectors are used for two of the endcap layers.

7 Future Detectors

In future experiments, especially at the LHC-collider but also at HERA-B, the vertex detectors will be installed in a very high radiation environment. One expects that during the lifetime of the LHC experiments the detectors of the inner vertex layers will receive an ionisation radiation dose of ~ 10 Mrad and particle fluxes exceeding 10^{14} particles/cm² (neutron, pions). To cope with this conditions is an enormous challenge for any detector technology and has triggered many groups to study radiation damage of silicon detectors. A large and very successful effort went into the understanding of the mechanism respons-

ible for the damage (see for example [12]). The outcome of these studies are new detector designs (e.g. multi guard ring structures) and a good understanding of how to operate silicon detectors in high radiation environments (e.g. optimised ambient temperature). It is now generally believed that one knows how to build and operate silicon strip detectors for most parts of the planned vertex detectors at LHC, and there is no doubt that the major part of all vertex detectors will consist of silicon strip detectors similar to those described in this paper. For the innermost layers one foresees the use of silicon hybrid pixel devices.

However in the innermost layers of the barrel and in the forward discs of present designs it is very likely that silicon detectors will not survive the whole lifetime of the experiment. And in addition there are some very good physics arguments (e.g. improved B tagging) to install detectors even closer to the beam in places where silicon is excluded. Driven by these concerns and challenges several groups are trying to develop detectors made of GaAs or diamond. Both materials are expected to be more radiation hard than silicon.

The most recent results of GaAs detectors including radiation tests can be found in [13]. I would like to give some information about the activities concerning diamond detectors. In diamond the band gap between the valence band and the conduction band is about 5.5 eV. This results in a very low intrinsic carrier density ($<10^3 \text{ cm}^{-3}$), and as a consequence no special structure like the pn-junction is necessary to deplete the detector. The basic structure is a CVD (chemical vapour deposition) diamond film with metalisation on both sides to form ohmic contacts. The metalisation may be segmented into strips or pixels. The simplicity of a diamond detector is certainly very appealing. The largest drawback of diamond detectors is also a consequence of the large band gap. To create an electron-hole pair 13 eV are required, which means that the average number of electron-hole pairs created by a high energy charged particle in $100 \mu\text{m}$ is only 3600. Unfortunately due to the finite charge collection distance also part of this signal is lost. The RD42 collaboration [14] has already built several diamond strip prototypes to prove the feasibility of these detectors.

The radiation hardness of diamond on the other hand has been shown to be exceptional. Detector grade diamond samples have been irradiated with 10 Mrad photons, $5 \cdot 10^{13} \text{ protons/cm}^2$ and $8 \cdot 10^{13} \text{ pions/cm}^2$ with no measurable degradation found [15]. These are radiation doses where all other materials have developed severe macroscopic signs of radiation damage such as a dramatic increase in leakage current or losses in the charge collection efficiency. Further irradiations are in progress with particle rates equivalent to 10 years of LHC running.

Vertex detectors at future experiments will certainly continue to play an important role for physics analysis. The detectors will be more diverse than the present ones. There will be a mixture of different layouts like strips and pixels, and furthermore one can expect that silicon will no more be the exclusive material for vertex detectors.

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