SILICON DETECTORS

Technology and Applications

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1. Introduction

Silicon detectors have had an enormous impact on the field of high energy physics over the last 15 years. They are usually used to provide high precision tracking information. A relatively recent addition to the standard equipment of high energy physics experiments, they are now crucial for many measurements. This lecture series tries to explain what silicon detectors are, what they can do and what their future might be. No attempt of completeness is made. There are certainly many developments and applications that could or perhaps should be mentioned. However, a selection has to be made and so the author apologizes only half-heartedly. One goal of these lectures is to clarify the terms that are frequently used in connection with silicon detectors. Another goal is to explain the complexity of constructing a real device using silicon detectors and to show that many decisions have to be taken. Some guidelines on how to make the relevant decisions are also given. The intricacies of the design of a real silicon detector and its production are not discussed in full technical detail. Some selected applications are presented instead. At the end, the limitations of silicon and some commonly mentioned alternatives are discussed.

2. What are Silicon Detectors?

In principle, a silicon detector is a solid state ionization chamber. Thus it is a member of the large family of detectors based on ionization. While most of the family members work with ionization in gases, a silicon detector takes advantage of the special electronic structure of a semi-conductor.

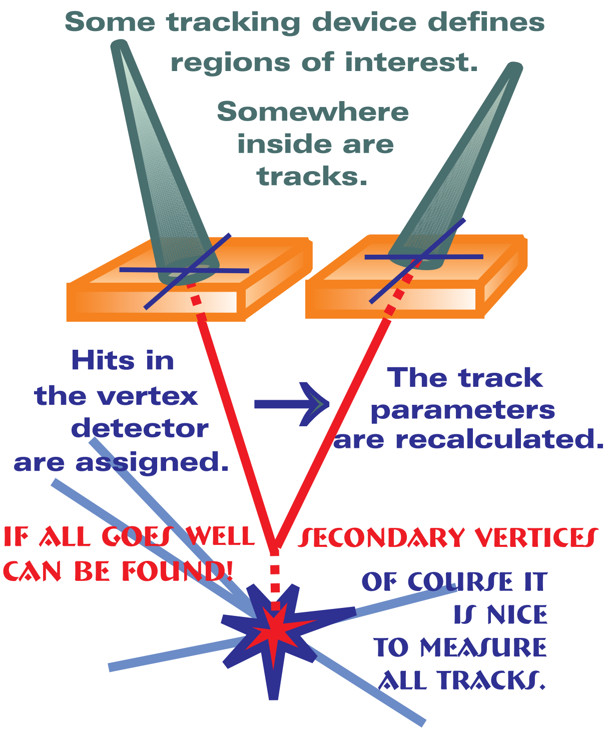

Figure 1. Principle of a vertex detector.

2.1. USAGE AS VERTEX DETECTORS

The most common application of silicon detectors in high energy physics is as active elements of vertex detection systems. Figure 1 illustrates the concept of such systems. Vertex detectors are the detector component positioned closest to the primary interaction point, also called primary vertex. Some tracking device finds tracks and these are extrapolated towards the vertex region. The extrapolations are translated into regions of interest where hits are searched for. These hits are assigned to the tracks and the track parameters are recalculated. By this, the precision is improved such that secondary vertices become distinguishable, hence the name vertex detector. Such secondary vertices are associated with the decay of particles and secondary interactions. Of course there are also tertiary and higher order vertices, all of which should and can, in principle, be identified.

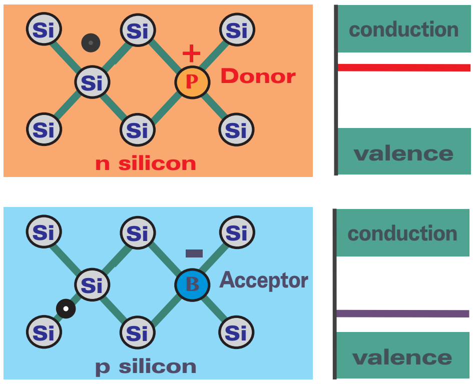

Figure 2. Semiconductor properties of defects in silicon.

2.2. SILICON, THE MATERIAL

For a good introduction into the solid state physics of semiconductors, please have a look at Ref. [1] or Ref. [2]. At room temperatures, the properties of silicon are determined by impurities(see Fig.2). Totally pure silicon would be an interesting material, but is basically unobtainable. It is easier to use the impurities and control them by doping. Silicon has four valence electrons and forms a hexagonal crystal. Defect atoms with 5 valence electrons, like phosphor, act as so called donors, as they donate an electron to the crystal. In the band structure, this electron sits within the band-gap, but close to the conduction band. Silicon with excess donors is called n-type silicon. Defect atoms with three valence atoms, like boron, act as so called acceptors. Here an electron is caught by the boron and it then also sits in the band-gap, but close to the valence band. In this case, somewhere else a hole is created due to the missing electron. Silicon with excess acceptors is called p-type silicon.

2.3. CONSTRUCTING A DIODE

A junction between p- and n-type silicon creates a diode. Figure 3 shows the electron and hole densities as well as the electrostatic potentials in a diode close to the junction. The application of an external potential as shown in Fig. 3 is called reverse biasing. The currents in an ideal diode are also described.

In an unbiased diode there are small and equal generation and recombination currents. Some holes and electrons diffuse through the potential barrier, and as a result there is a certain electron density in the p- and hole

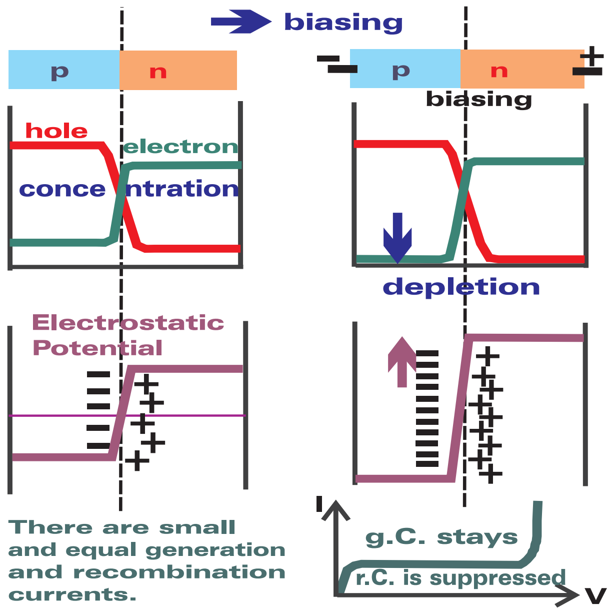

Figure 3. Electron and hole densities[top] and electrostatic potential[center] of unbiased[left] and biased[right] diode close to the junction. The behavior of generation and recombination current is indicated at the bottom.

density in the n-region. When an external potential is applied, the potential barrier becomes higher and the diffusion and thus the recombination current is suppressed. A zone depleted of all carriers forms and starts to grow. The external bias voltage at which the whole diode is depleted is called the full depletion voltage. The generation current in a perfect diode stays constant up to a voltage called break-through voltage, at which the field becomes too high for the internal structure of the diode. This current is referred to as leakage current.

2.4. ELECTRONS AND HOLES

When a charged particle traverses silicon, it produces ionizing and non-ionizing energy loss. The non-ionizing energy loss creates radiation damage(Sec. 2.5.8) and the ionization loss causes the creation of electron-hole pairs which produce the signal (see Fig. 4). The number of pairs created depends on the amount of ionization, and thereby on the absolute value of the charge and momentum of the particle, and on the thickness of the crystal. Silicon has a band gap of 1.12eV at 300°K, and a minimum ionizing particle creates on average 8000 electron-hole pairs in 100μm of silicon crystal.

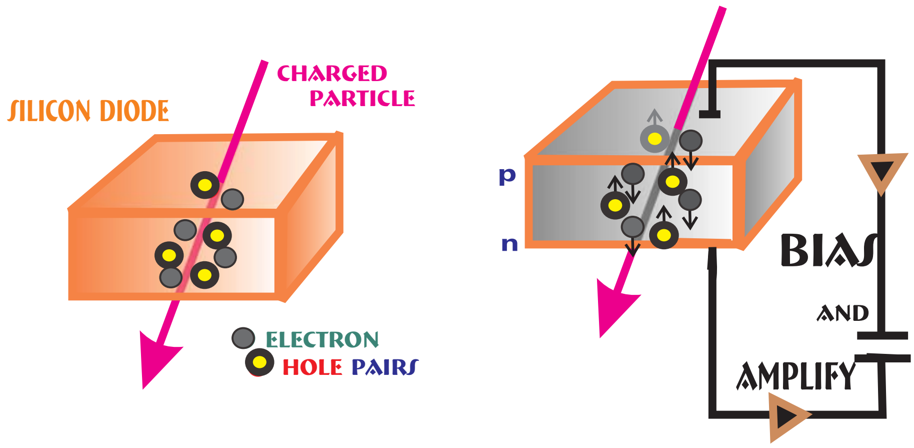

Figure 4. Creation of electron hole pairs and charge collection after biasing.

Figure 5. Side-view of a p on n diode. A typical detector is around 300μm thick. The p-implantation is around 1μm deep.

Once an external bias voltage exceeds the full depletion voltage all the created charge can be collected. The holes drift to the p-side of the diode, the electrons to the n-side.

2.5. DETECTORS

Basically, all silicon detectors are constructed as so called p on n diodes. Nothing else will be discussed In these lectures. Such a diode consists typically of an around 300μm thick n-type bulk, where on one side a layer of p$^+$-doped material of about 1μm thickness is implanted(see Fig. 5). p$^+$ denotes that the defects of the n bulk are over-compensated. Depending on the doping of the n material, a certain electron density is intrinsic before biasing. When the diode is biased, the highest fields occur on the p-side of the diode and the depletion zone grows from the p- towards the n-side.

Detectors are typically made from 4 inch wafers. The necessity to handle the wafers, and the increase of wafer imperfections near the edge, limit the

Figure 6. Side-view of a p on n diode structured to become a single-sided p on n [left], double-sided p on n [center] or a single-sided n on n [right] detector.

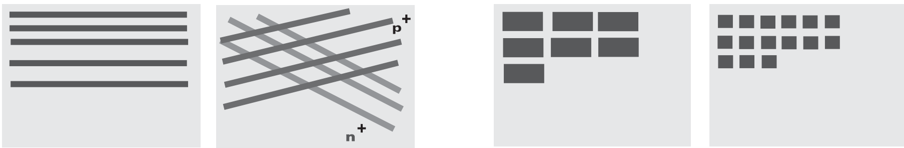

Figure 7. Top view of [from left to right] strips on a single-sided, strips on a double-sided, pads on a single-sided, pixels on a single-sided detector.

possible sizes of the resulting detectors. A maximum size of $6\times6\mathrm{cm}^2$ or $5\times7\mathrm{cm}^2$ is possible, depending whether a square or rectangular shape is needed.

2.5.1. *Single- and Double-sided p on n Detectors*
In order to obtain spatial resolution, the p implantation of a simple p on n diode can be structured(see left of Fig. 6). The result is a so called single-sided p on n detector. It is also possible to add a structured n^+ implantation on the n-side of the diode. The resulting double-sided detector can measure two independent projections(see Fig. 6 and 7). It is also possible to only structure the n-side of the detector, resulting in a n on n single-sided detector. However, the construction of n on n single-sided detectors requires work on the p-side of the diode. Thus, the technology of a double-sided detector is needed and has to be paid for. Figure 7 gives an overview of the most common structures:

Strips are the most common structures used on silicon detectors. They can be equally spaced or not, parallel to the edges or not, and have typical pitches between 25μm and 200μm. In principle, strips could have any form and can wind arbitrarily all over the detector. For some applications, this makes sense. However, straight strips with equal spacing are definitely the most common.

Pads and Pixels are featured on single-sided detectors. A pixel is a small pad. Typical pad sizes are $200\times200\mu\mathrm{m}^2$ to $2\times2\mathrm{mm}^2$. Pixels are typically $50\times\ 50\mu\mathrm{m}^2$ to $200\times200\mu\mathrm{m}^2$. Again, it would be easy to make any shape

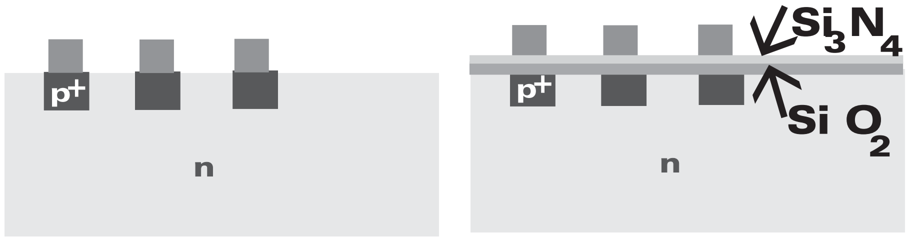

Figure 8. Side view of strips contacted directly [left] or through a SiO_2 and a Si_3N_4 layer [right].

of pad or pixel, but in practice people mostly choose rectangular pads and pixels. A special case of pixel detectors are charged-coupled devices, CCDs (see Ref. [3]).

2.5.2. *Signal Retrieval*

In order to collect a signal from an implanted structure that structure, has to be connected to the outside world(see Fig. 8). The easiest is to just put down a metal strip on top of the implantation. The disadvantage is that any current generated in the diode flows through that contact, and, if no external capacitor is used, right into the amplifier. Many amplifiers don't really like that! Some amplifiers do not mind, but generally this current still creates unwanted noise. Therefore, in most cases, capacitive coupling is chosen. In modern applications, the capacitors are integrated into the detector. This is desirable, as external capacitors are often difficult to fit, and they double the number of contacts. In the following, I will always talk about detectors with internal capacitors. Internal capacitors are built by having an oxide layer separating the implantation and the aluminum strip. Such a layer is about 50nm to 200nm thick. A failure in the oxide is called a pin-hole. Such a failure is very undesirable, as the resulting currents affect more than one strip. An extra layer of silicon nitrite (around 50nm to 100nm) can provide extra security. The resulting capacitors are good for voltage differences of up to 100 Volts(see Sec. 2.5.9). In many applications, the voltage drop across the capacitors is controlled and kept to a few volts during normal operation. For a double-sided detector, that means that the electronics has to be floating on at least one side. Only if a double-sided detector is operated at bias voltages small compared to the break-through voltage of the internal capacitors, can the electronics on both sides work with the same ground.

2.5.3. *Resolution*

The intrinsic resolution of a strip detector depends on the pitch and whether digital or analogue read-out information is used. A simple strip detector with pitch a and digital read-out has an intrinsic resolution of $\sigma = a/\sqrt{12}$.

The intrinsic resolution can be improved with analogue read-out. As the charge created between two implanted strips is linearly divided between the strips, the position of a hit can be reconstructed by calculating the center of gravity of the observed charges. However, if the implantation itself is hit, basically all the charge remains within this strip. Only a small portion is capacitively coupled to the two neighboring strips. In order to optimize the resolution for a given pitch, the implantation width should thus be small. However, that creates large gaps between implantations, where the potential is influenced by the back-side. That can cause the loss of some of the charge. In addition, the field at the point indicated by an arrow in the left picture of Fig. 9 increases. At a certain gap width, the internal p-n-junction breaks before the full depletion voltage is reached and the detector becomes inoperable. Thus the implantation width cannot be very small compared to the pitch. As a result, one has to decrease the read-out pitch in order to achieve better intrinsic resolution, or introduce intermediate strips (see Fig. 9). The pitch cannot be made arbitrarily small, because that increases the input capacitance that the read-out electronics sees, and thereby the noise(see Sec. 2.5.11).

The pitch of the silicon strip detectors for a particular application is usually chosen such, that the intrinsic resolution of the detectors is irrelevantly small. The overall resolution of the system is limited by multiple scattering. Very small pitches are mainly used to separate tracks close to each other. For pattern recognition, it is undesirable to have more than one track hit the same strip.

2.5.4. *Intermediate Strips*

Intermediate strips allow the construction of detectors with improved resolution at fixed read-out pitch.

In general, it is desirable to keep the number of read-out channels as small as possible, because read-out channels are expensive and work intensive. It is also technically difficult to achieve read-out pitches below 50μm, as there is basically no lateral space left for contacts to the outside world. In addition, it is hard to get front-end pre-amplifier chips that have input pitches of less than 50μm.

Detectors with one, two or even three intermediate strips have been used. The signal is capacitively coupled to the 2 nearest read-out strips. That distributes the signal ofr a particle traversing a region between two read-out

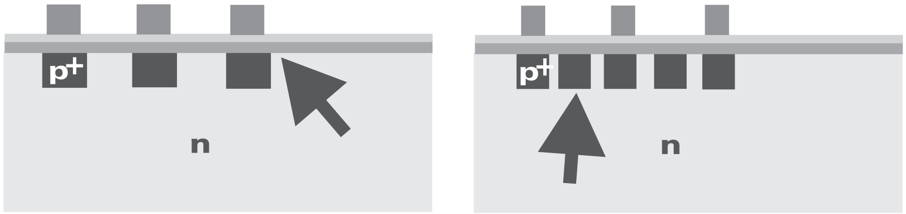

Figure 9. Side view of a detector without [left] and with [right] intermediate strips.

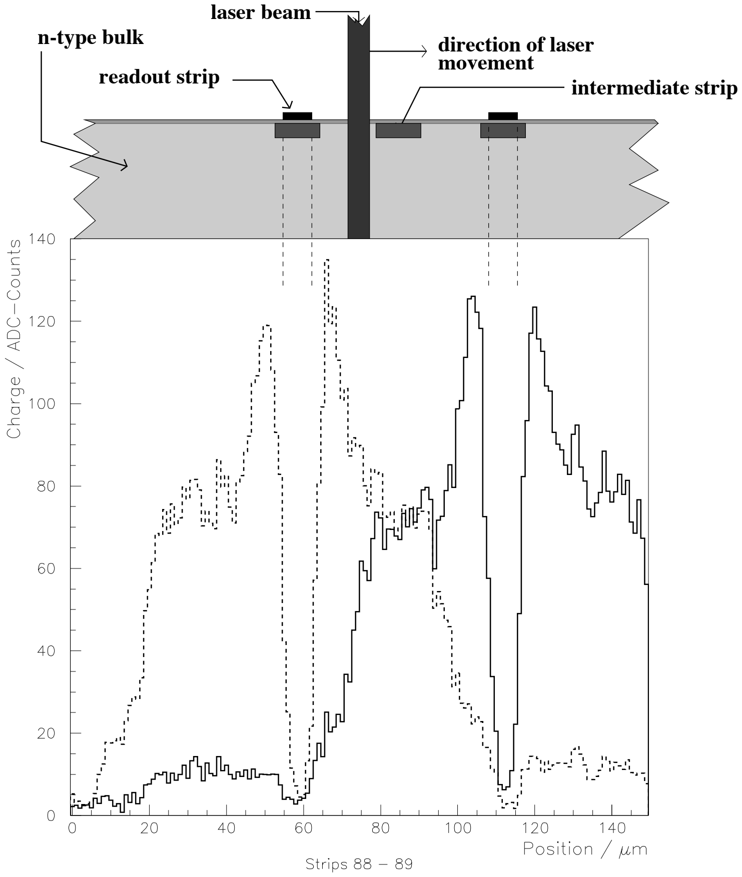

Figure 10. Measured charged division in a detector with one intermediate strip. The schematic of the detector is shown on top. A laser beam is moved across the detector. The dashed line is the charge seen by the strip on the left [#88]. The full line is the charge seen by the strip on the right [#89]. The x axis is the position of the laser beam. The deep minima right on the read-out strips result from the reflection of the laser light from the aluminum read-out strip.

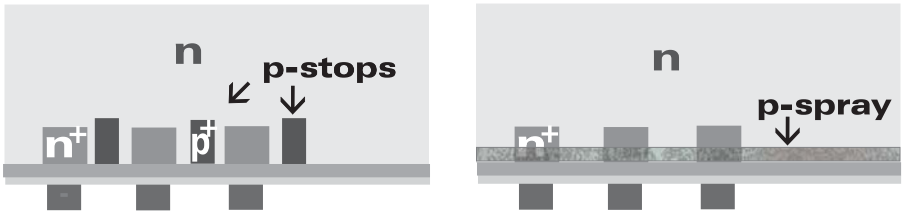

Figure 11. Side view of a "realistic" detector with structured n-side. On the left, so called p-stops isolate the n^+ strips. On the right side a p-spray implantation does the same job.

strips more evenly than a wide read-out strip geometry would. Figure 10 shows the measured charge division in a detector with one intermediate strip [4]. For the measurement, a laser-beam with a wavelength of 963nm was moved across the detector in 1μm steps. The strip pitch is 55μm. Shown are the collected charges of two adjacent read-out strips while the laser-beam was moved across. Clearly distinguishable are the positions where the laser beam gets reflected by the aluminum strips. Between implantations, the linear dependence between position and charge sharing is well realized. When the intermediate strip is hit, the charge is shared equally between the two neighboring read-out strips. In this case there is no information for where the hit occured within the intermediate strip.

2.5.5. *n-sides: p-stops and p-spray*

A closer look at the n-side of a detector reveals that as simple a device as described above cannot work. There would be charges induced in the oxide layer that would short out the n^+ implantations. There are two commonly used ways to prevent this(see Fig. 11). In each case, a p implantation insulates the n^+-strips. In the p-stop version, separate implantations are used. That basically doubles the number of structures to be made. Especially with intermediate strips, that can get very crowded. In the p-spray option the whole area is implanted. This option has the principle advantage of not introducing more structures, and it has the lower internal fields. However, the doping in p-stops is easier to control during manufacturing, and at this point in time p-stops are more common than p-sprays.

2.5.6. *Biasing*

A detector has to be fully depleted in order to deliver the full signal. The full depletion voltage depends on the resistivity of the material used. It is typically between 30 Volts and 120 Volts. It is advisable to run at least 10 to 20 Volts above full depletion voltage, because a higher field speeds up the signal, which is very important for applications with fast electronics [peaking times of less than 100ns].

The individual strips are taken to the desired potential through bias resistors. This resembles any bus system used to distribute voltages. The voltage is brought from the external world to a bias structure, usually a ring, from which it is internally distributed. There are three different choices on the market: polysilicon resistors, punch-through structures and implanted resistors. Table 1 lists advantages and disadvantages of the three options.

Biasing Choice	Advantages	Disadvantages
Polysilicon	radiation hard	takes space
	easy to operate	expensive
Punch-Through	cheap	not radiation hard
		difficult to operate
Implantation	cheap	works only on p-side
	radiation hard	⇒ single-sided detectors only

TABLE 1. Advantages and disadvantages of different bias methods.

The choice of biasing method really depends on the application and on the budget available. One of the main inputs to the decision is the radiation dose that the detector is most likely to see.

2.5.7. *I-V Characteristics*

Ever since the beginning of Sec. 2.5, I claimed that a silicon detector is basically a structured diode. Therefore, the leakage current it draws versus the bias voltage should show the typical diode behavior(see Sec. 2.3). In practice, most detectors are not perfect. And this is reflected in their IV-curves. Figure 12 shows IV-curves for three double-sided detectors. Each one has a break-through voltage much higher than the full depletion voltage. A "perfect" detector shows a small rise in current at the beginning and then a long plateau up to the break-through voltage. The small rise at the beginning is connected to the oxide charges. Some imperfections can cause the current to rise with voltage. Quite often, these rises are linear, i.e., resistive behavior is observed. Imperfections on the p-side are immediately visible, while n-side imperfections only take effect after the detector is fully depleted. Some imperfections only take effect at voltages much higher than

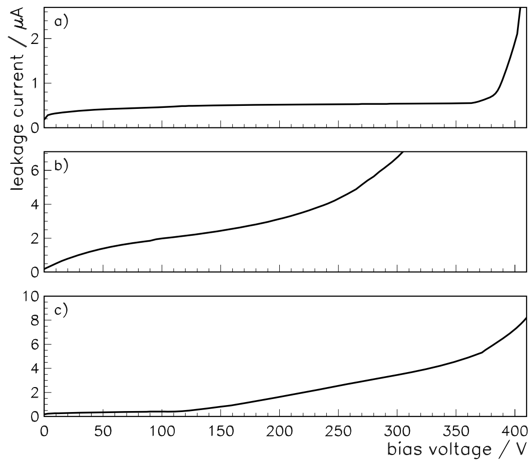

Figure 12. Typical IV-curves for silicon detectors: The curves shown are those of $5 \times 7 \text{cm}^2$ double-sided detectors designed for the HERA-B experiment(Sec. 3.2.2). All three detectors are fully depleted at around 110V. Detector a) is as close to a diode as they come. Detector b) has an imperfection on the p-side, reflected in a steady rise of current even before it is fully depleted. Detector c) has an imperfection on the n-side, which becomes visible as soon as the depletion zone reaches it.

full depletion voltage. Such imperfections are irrelevant for detectors that are not subjected to irradiation.

2.5.8. *Radiation Damage and Full Depletion Voltage*

Silicon detectors are damaged by charged and neutral particles. The damage is caused by non-ionizing energy loss. Charged particles mainly damage the bulk material. Neutral particles, especially soft ones, also damage the surface structures.

For strip detectors, the bulk damage is the more important effect. The crystal itself is damaged such that donors are removed and acceptors are created. This happens through the dislocation of lattice atoms. A damaged crystal has some self-healing ability called annealing. However, on a longer time-scale it also gets even sicker. This is called anti-annealing. Annealing can be quite well understood and is connected to diffusion. There are several models for anti-annealing. However, none of them is quite complete or convincing.

The operational consequence of radiation damage is that at any fixed voltage the leakage current goes up as $\text{I}=\text{I}_0+\text{I}_d \cdot \Phi$, where soon the original current I_0 becomes totally negligible. The size of I_d depends on many factors, but, even after a moderate radiation dose Φ, the resulting leakage current I

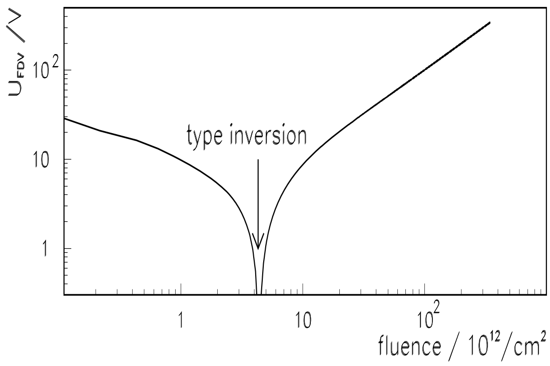

Figure 13. Development of the full depletion voltage with integrated radiation dose, here given as the number of minimum ionizing particles per cm^2.

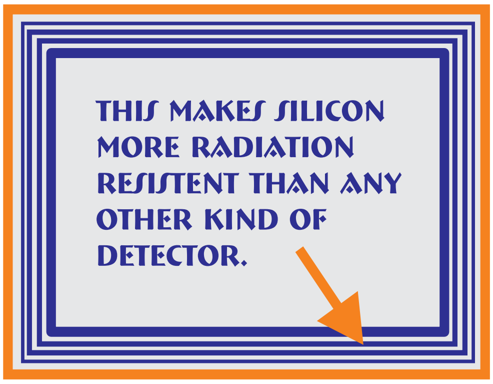

Figure 14. Multiple guard-rings gradually take down the voltage between the active area and the edge.

can easily increase by a factor of 100. In addition, the full depletion voltage changes. Figure 13 shows that the full depletion voltage first decreases and then, after a point called type inversion, increases. In order to still fully deplete the device, higher and higher voltages have to be applied. As real detectors are usually not perfect diodes(see Sec. 2.5.7), the leakage current increases accordingly. By how much, depends on the quality of the device. The full depletion voltage after a severe radiation dose, lets say 5×10^{14} minimum ionizing particles, can be 500 Volts or more. Detectors are made to be able to work at that kind of voltage by guard-rings that shield the active area from the voltage drop around the edge. The voltage is taken down gradually from one ring to the next. Figure 14 is a sketch of such a guard-ring structure. Design engineers have very strong opinions about the number and width of the guard-rings. Details are important, but there is more than one solution.

It is very important to remember that there is no such thing as "radiation hard" silicon. Silicon is always damaged when exposed to radiation. The trick is to design the detectors such that it still works even though damaged. Well designed silicon detectors can survive longer than any other ionization devices currently available at mass production levels.

2.5.9. *Radiation Bursts and Pin-Holes*

In some applications, silicon detectors are periodically exposed to bursts of radiation. In accelerators, this is often related to beam losses. Such bursts can create an enormous amount of charge inside the detector. This charge can dissipate only through the resistive bias structure. The time constants involved can temporarily cause a large voltage drop across the silicon-oxide and nitrite layers, which might then locally break. This creates so called pin-holes. Therefore, the internal capacitors are built to withstand relatively high voltage drops of up to 100V. External capacitors break down at far smaller voltages.

2.5.10. *Read-Out*

Some remarks about retrieving the signal were already made in Sections 2.5.2 and 2.5.4. The general goal is to get the resolution needed with the fewest read-out channels possible. Most applications, but by far not all, are best served with a capacitively coupled silicon detector and a charge integrating pre-amplifier. Depending on the technological choices and the needed resolution, a detector may have intermediate strips or not. However, quite often a read-out pitch of around 50μm or 100μm turns out to be optimal. The pre-amplifiers are usually packaged in custom made chips. The peaking time has to match the repetition rate of the experiment. The faster the pre-amplifiers have to be, the more difficult they are to get. Modern chips have typically 64 or 128 channels. Some chips have integrated pipelines that store the data for a while. This is needed for high frequency experiments where the silicon is read out only after a first level trigger has decided that the event under consideration is worth it.

The silicon detectors that are right now being conceived, or already in use, usually involve quite large systems. A double-sided detector can have 2000 or more channels, and a complete system has often more than 100 [LHC more than 1000] detectors. This creates hundreds of thousands of channels, all of which have to be connected to pre-amplifier chips, which then have to be connected to the outside world. The connections between detector and chip is made by wire bonding, often through a fan-out. A fan-out doubles the number of wire bonds, but it allows for pitch adjustment, which is sometimes necessary. Even though chips are custom made for high energy physics, and very often for a specific experiment, they are used under slightly different geometrical conditions. In most applications, there is very little space available for the pre-amplification electronics, which adds to the fun of designing a complete system.

The connections to the outside world also have to be considered carefully, especially in 4π detectors. Here the cables have to be threaded through the outer shells of the detector. The cables create holes in the acceptance and can add material in front of the outer shells. It is therefore desirable to multiplex the signals before routing them to the outside world. An intrinsic multiplexing is done for the pixels in a CCD. But CCDs are quite slow. In all applications with tight timing conditions, the speed of the link, has to increase with the number of multiplexed channels. The higher the speed of a link the more difficult it becomes. A reasonable compromise has to be made depending on the constraints of the application.

A fundamental decision to be made for any detector system is whether to read out the analogue information, and, if so, to what accuracy. In principle, the digital information "hit" or "no hit" would be enough for most applications. However, in practice a phenomenon called "common mode" makes digital read-out often unusable. When real silicon detectors are connected to real amplifier chips, the baseline of the chips can jump for some events. These jumps can be higher than the signal from a minimum-ionizing particle. This makes it impossible to adjust a single threshold for digital read-out. The reason for common mode is not well understood. The ground of the detector couples in one way or another to the ground of the chips, and the whole assembly acts as an antenna or signal generator. It is believed that the problem is best controlled by "perfect" grounds. There is no firm belief, let alone knowledge, on how to achieve these "perfect" grounds in an experimental hall. If a sufficient number of bits is read out, usually 8 is fine, it is possible to monitor the common mode and subtract it online.

2.5.11. *Signal to Noise*

The distribution of the size of the signals in a 300μm silicon detector corresponds to a Landau distribution with a mean of 24000 electrons.

The electron-equivalent noise as seen by the pre-amplifier has several components: white series, white parallel and 1/f:

$$ENC^2 = a_1 \frac{C_{inp}^2}{T_p} + a_2 I_L T_p + a_3 C_{inp}^2$$

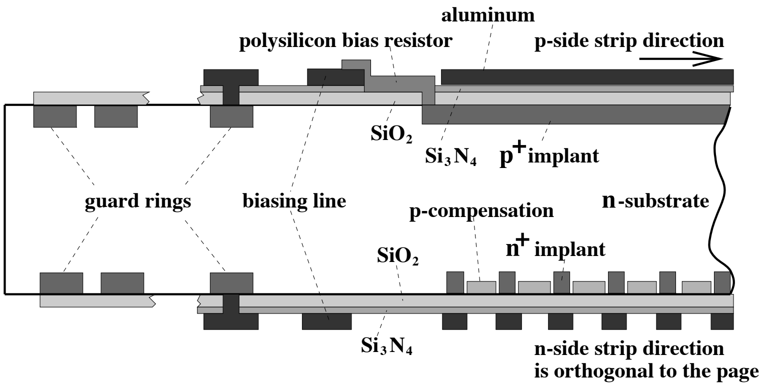

Figure 15. Cross section of a double-sided detector with polysilicon bias resistors

C_{inp} is the input capacitance, and determined by the layout of the detector and fan-out. T_p is the peaking time of the pre-amplifier; it has to be chosen to match the repetition rate of the experiment. The constants a_i are dependent on the technology of the amplifier chip. The only parameter that can be tuned during operation is I_L, the leakage current. At room temperature the leakage current through the bulk is reduced by roughly a factor 2 by cooling down by 7°C. This becomes important after irradiation.

Typically, the systems are configured such that at room temperature the signal to noise ratio for an undamaged detector comes out to 15 to 20 for fast [$T_p \approx 50$ns], and 50 to 100 for slow, electronics.

2.5.12. *Detector Production and Prices*

The production of silicon detectors is not your typical "do it yourself job". For a small scale production of a medium-complicated device, you need a $\mathcal{O}$($15M) silicon laboratory and a lot of expertise. Even though the principles of a silicon detector are relatively straightforward, the details are very involved. Figure 15 is a drawing showing a little more technical detail. In reality, it is even more complicated, and small changes in layer thicknesses, distances between structures, doses or process temperatures, result in catastrophic failures.

There are quite reliable commercial suppliers like Hamamatsu, CSEM or Sintef [this list is incomplete by definition]. There are also unreliable suppliers which will not be listed, because my legal insurance leaves a lot to be desired. The price of a detector varies widely, depending on size and requirements. For maximum area detectors from 4 inch wafers, the following numbers are a very loose guideline. single-sided p on n detectors are between $500 and $2000. Double-sided p on n detectors are between $1000 and

\$4000. single-sided n on n detectors are almost as expensive as double-sided detectors, as both sides of the wafer have to be worked on. The set-up costs for a new line of detectors is significant. A double-sided detector requires 10 or even more layers, and for each layer a so-called mask is required. Each mask, depending on the needed accuracy, can cost more than $\mathcal{O}(\$2000)$. Total set-up charges of more than \$30,000 are not unheard of. It is clear that a large silicon system is not inexpensive. Single detectors, however, are per cm^2 even more expensive due to the set-up charge.

2.5.13. *System Costs*

In the last section it became clear that silicon costs money. But pieces of silicon don't make a detector system. In addition, a mechanical support structure and a control and read-out system is required. That also costs money.

Mechanical support structures are made out of low-Z materials, preferably with thermal expansion coefficients close to silicon and a lot of strength. Carbon fiber and graphite constructions are common. Beryllium supports are also often used. All these materials have in common the fact that they are expensive. Detector cooling is often difficult and involved. The resulting systems also have a tendency to cost a lot of money.

The read-out systems consist of pre-amplifiers, perhaps with pipelines, pitch adaptors, optical links or twisted pair cables, A/D converters, plenty of control electronics, and probably fast processors to deal with the raw data. The detectors need power-supplies, and so does all the read-out electronics. All this has to be controlled and monitored.

It can easily happen that the silicon itself does not dominate the system cost. In the case of the HERA-B silicon vertex detector system, for example(see Sec. 3.2.2), the total cost is around \$3M, while the actual silicon detectors only cost \$300k.

2.5.14. *Choices*

In the previous sections words like "typically" and "usually" were not uncommon. When building a silicon detector system, there are plenty of choices. In many cases, there is no clear "best choice". But there are usually some very bad choices. In large collaborations it can take longer to make the choices than to actually build the device. Figure 16 can be used as a guideline on how to choose the "correct" piece of silicon. It should certainly enable the reader to hold his/her own in any collaboration or other such meeting.

The standard solution is to use silicon strip detectors with a read-out pitch adjusted to the resolution requirement of the application. If the track density or the radiation level are too high, the prescribed cure is to go for

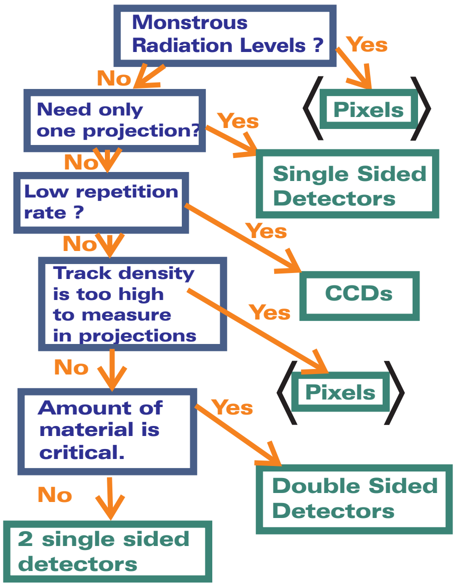

Figure 16. Decision Flow Chart. This is an extreme simplification.

pixels. It has to be noted, however, that, at the moment, no totally functional read-out scheme for pixel detectors other than CCDs exits. CCDs can only be used if the read-out rate is sufficiently low. In such a case of low read-out rate, it is always worth to explore the CCD option. The measurement of space-points is very attractive, and it makes track reconstruction easier and more efficient. Even with perfect hits in two projections, false assignments occur that can be prevented by measuring space-points(see Fig. 17).

The evaluation of different solutions involving strip detectors very often focuses on double sided versus single-sided. Many people are afraid of double-sided detectors because their operation demands a little more care and thought. Some suppliers also have problems making double-sided detectors while they are more successful with single-sided devices. Nevertheless, if multiple scattering limits the overall performance of the envisioned system, double-sided detectors should clearly be the choice.

3. Applications

Looking outside our field, the range of applications of silicon detectors is quite large. CCDs, in particular, are used in many scientific and commercial detection devices or cameras. This ranges from video cameras to X-ray detectors in satellites [5]. A review of charge-coupled devices as particle

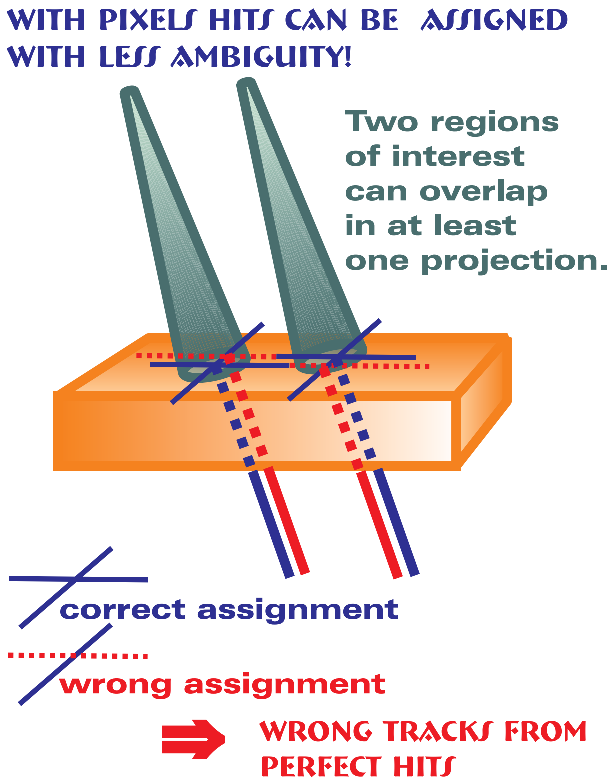

Figure 17. The advantage of measuring space-points. A hit, even perfectly measured in projections, has a higher probability of being assigned to the wrong track than a hit measured as a space-point.

tracking detectors is given in [3]. Strip detectors are not widely used in industry, but they are much more common in high energy physics. Basically, every modern high energy physics experiment has a silicon based component, an exception being neutrino detectors. Silicon is used mostly to satisfy the requirements of high precision tracking close to the interaction point, and as the active material in high density calorimeters.

3.1. SOME HISTORY

Silicon detectors are a relatively recent invention. Their development went in parallel to the development of integrated circuits. Without the revolutionary progress made in the last 15 years in the packaging of pre-amplifiers, the wide spread usage of silicon detectors would not have been possible.

3.1.1. *Fluxes*

In "historical" times, as in the early eighties, silicon detectors were used to measure particle fluxes. In Ref. [6], the use of silicon detectors at CERN is described in detail. When a large number of charged particles traverse a silicon diode, the induced charges create a sizable current that can be measured. The current depends on the energy and angular distribution of the particles, as well as on their charge. For a beam with a well known energy and momentum spread, it is possible to calculate the flux from the generated current, once the leakage current of the diode (that has to be subtracted) is known.

This principle was, for instance, used to calibrate neutrino fluxes. Here, the incident protons interact in a beryllium target to produce pions and kaons. The mesons decay in flight, and produce a neutrino beam. The accompanying muons have to be stopped in a shield. Measuring the muon flux in the shield is a way to measure the neutrino flux. Therefore, at the CERN neutrino beam facility, silicon diodes, at that time called solid state detectors, were positioned inside the shield and provided that flux measurement. However, a cross-calibration with nuclear emulsions was necessary, as the angular distribution of the beam could not be calculated well enough from Monte Carlo(see Ref. [7]). The accuracy achieved for the neutrino flux was about 3%.

Silicon diodes are still used as warning devices. Many experiments place diodes close to the beam-pipe and monitor their currents. Either the long-term dose is deduced from the increased leakage current, or sudden increases in current are used as an early warning against special problems such as beam-losses.

3.1.2. *Dawn of the Age of Silicon: Charm Lifetimes*

The first true silicon vertex detector was constructed in 1983 for ACCMOR [NA11], an experiment at CERN designed to measure charm lifetimes [8]. The experiment used 8 single-sided detectors with 20μm strip pitch. At that time, the read-out was a major problem. It was basically not possible to work with such a pitch in the external world. Therefore, only every third strip was read out actively. These detectors, with their analogue read-out actually achieved a spatial resolution of 5μm. Thus, from the very beginning, the point resolution of the devices was not the limiting factor for the overall performance. Figure 18 gives a schematic view of the NA11 setup, while Fig. 19 shows an event and the reconstructed charm decay. It should be noted that another part of the same collaboration pioneered the usage of CCDs as tracking detectors [9].

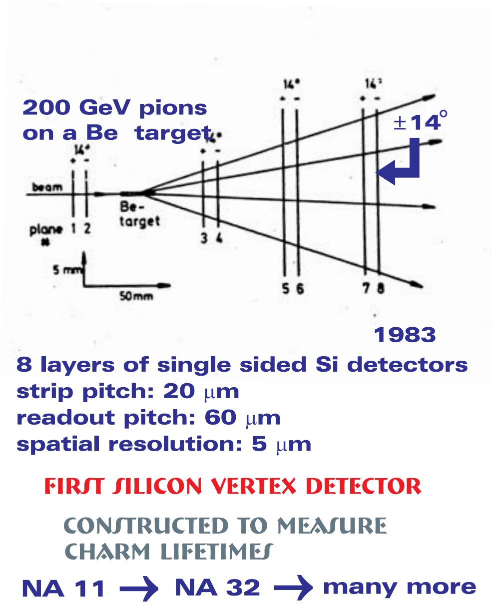

Figure 18. Schematic of the vertex region of the NA11 detector.

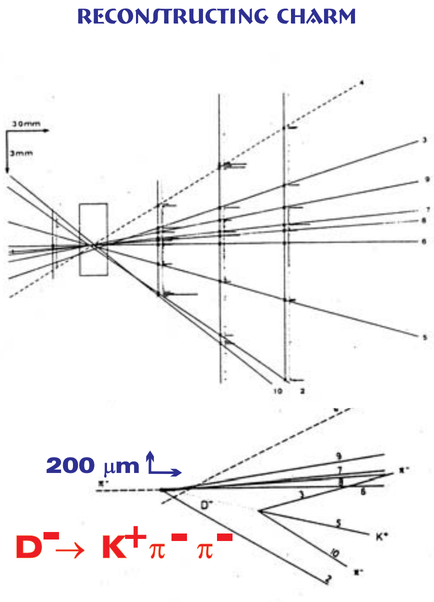

Figure 19. Display of an NA11 event and its reconstructed charm decay.

3.1.3. *Silicon goes 4π: B-lifetimes*

The immediate success of silicon in fixed-target detectors was followed by their usage in 4π detectors. The main problem in 4π detectors is to find space for the read-out electronics, which in addition should not introduce too much material into the acceptance. Without the rapid development in integrated circuits, silicon detectors could not have been used in a 4π geometry. Integrated circuits have revolutionized the construction of all detectors, not just silicon detectors. It should never be forgotten that the electronics is as important as the detector itself. For simplicity, at the beginning most experiments used single-sided detectors. The first 4π experiment with a vertex detector constructed from double-sided silicon was ALEPH [10] at LEP. The barrel shaped detector was constructed out of 27 faces deployed in two layers(see Fig. 20). Each face carried 4 detectors, each with an area of $5\times5\text{cm}^2$. The detectors had a strip pitch of 25μm on both sides. The read-out pitch was 50μm in the $r-\phi$ and 100μm in the z-direction. The intrinsic resolution was 12μm and 17μm, respectively. Again, the overall performance of the detector was limited by multiple scattering. For muons, residuals of 20μm in $r-\phi$ and 40μm in z were achieved. A special chip, the CAMEX64 [11] was developed for the read-out.

All of the LEP detectors, as well as all 4π detectors everywhere, were eventually upgraded to have a large silicon vertex detector system. These systems were a huge success, and established themselves very quickly as the standard technology for vertexing. The field of b-physics was revolutionized. The improvement of the quality of B lifetime measurements can be seen in Fig. 21 [12]. It should be noted that the old measurements are all systematically low. It looks like the systematic errors were underestimated. The first group of measurements coming from LEP is a very tight cluster, where every error bar overlaps with the old average. Only after really understanding their vertex detectors, did the LEP groups dare to measure a longer B lifetime. Such historical developments are unfortunately not uncommon. However, any more along this line would belong in an entirely different lecture.

3.2. SELECTED EXAMPLES

The selected examples are in no way representative. They are rather extreme cases where one particular choice of technology is pursued almost to the limit. There are many other interesting and challenging systems in operation, production, or in design. Just pick up any proposal or detector paper for a LEP, B-factory, LHC, or a Tevatron detector!

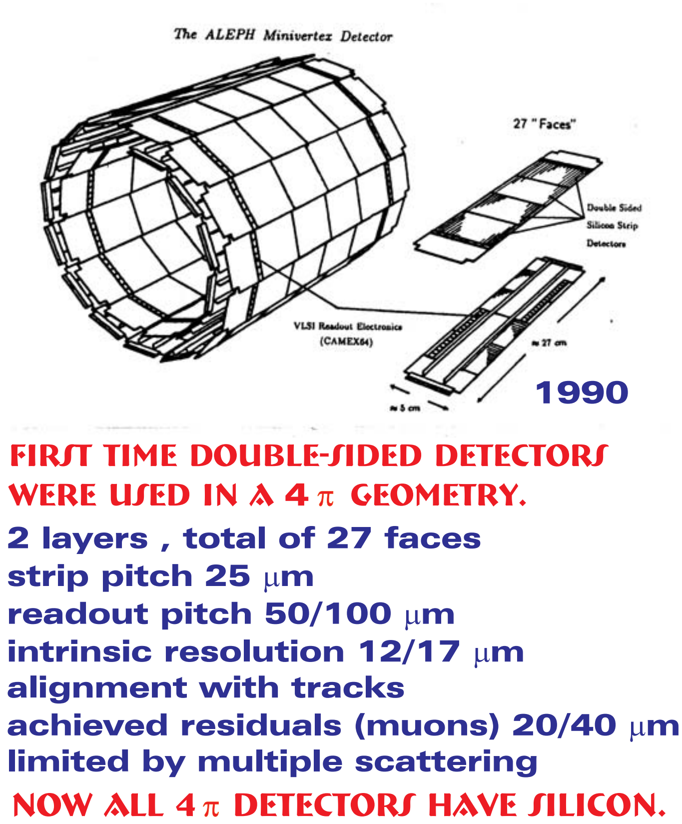

Figure 20. Schematic view of the first ALEPH vertex detector.

3.2.1. *SLD*

The SLD [Stanford Linear Detector] operates at the SLC [Stanford Linear Collider] at the Stanford Linear Accelerator Center [SLAC]. SLD is designed to operate at the Z^0 resonance, which determines its size, and at SLC, which determines its overall timing. The SLC has a low, repetition rate of 120Hz. As, in addition, the occupancy per beam crossing is very low and thus hits from 26 beam crossings can be sorted out later, a CCD system that takes more than 200ms to read out can be used. A full description of the SLD vertex detector system can be found in Ref. [13]. The first complete system called VXD2 started to take data in early 1992, and was a 120 Mpixel device. Since 1996, the upgraded version, VXD3, a 307 Mpixel device, is in use. Its point resolution is of the order of 4μm. The SLD vertex detector upgrade(see Fig. 22) is similar to many other upgrades at 4π detectors, for example, at LEP. The 4 detectors operating at LEP at CERN were

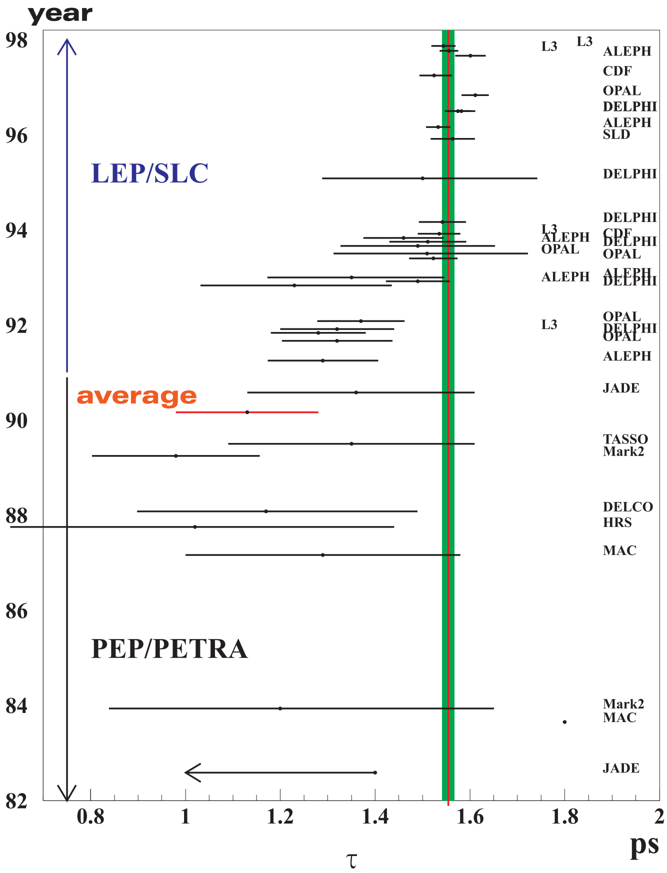

Figure 21. Development of B lifetime measurements: Measurements without silicon detectors dated before 1990 are averaged separately. Silicon detectors significantly reduced the error bars.

also designed for Z^0 physics. All these detectors look very similar in design. Some technical choices are different, but the principle layers of the onion are equivalent. All LEP detectors also have vertex detectors, tracking devices, particle identification devices, calorimeters and muon chambers. And the first vertex detector built for all of them turned out to be too short. As many interesting physics phenomena occur predominantly in forward-backward direction, a large angular coverage, i.e., a long barrel, is desirable. The parameters achieved in the second version of a detector become often only possible through the experience gathered while building the first detector.

The power of the SLD vertex detector is demonstrated in Fig. 23. Tracks are shown as reconstructed with the central drift chamber, as well as with

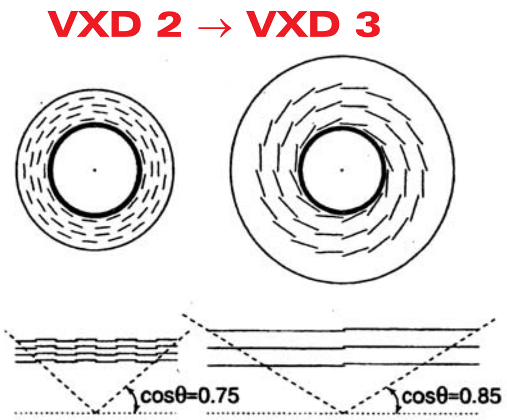

Figure 22. Layout of the VXD2 and VXD3 SLD Vertex Detectors. VXD3 is longer than VXD2, thus increasing angular coverage. In addition, the placement of layers is improved.

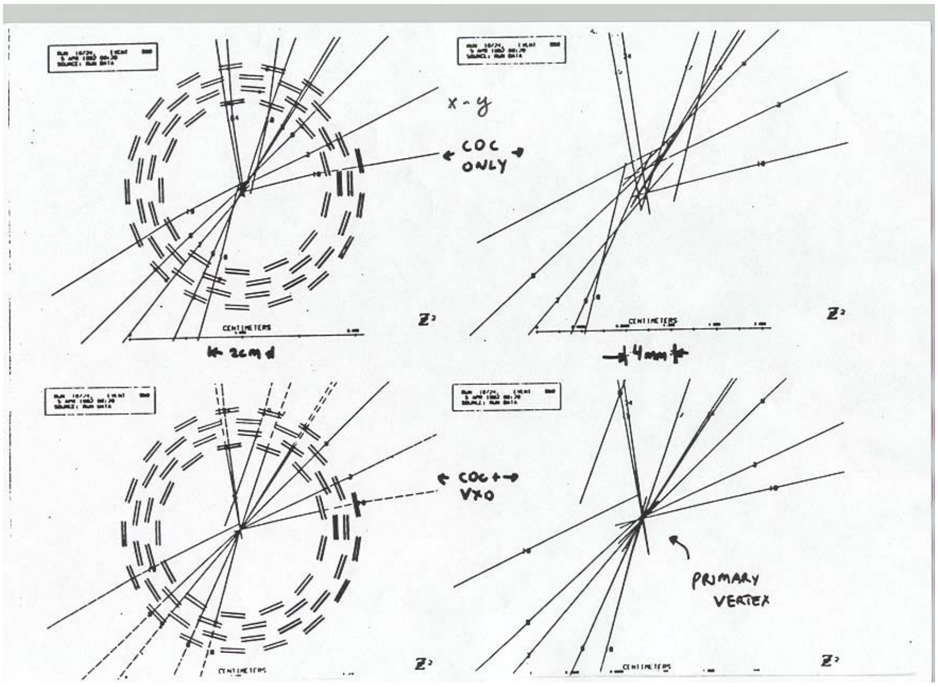

Figure 23. Demonstration of the power of the SLD VXD2 system: On the left are the tracks as they penetrate the layers. On the right, a close up of the interaction region is seen. The x-y projection is displayed. The top pictures show the tracks as reconstructed with the central drift chamber, while the bottom ones depict them as reconstructed with the help of the vertex detector.

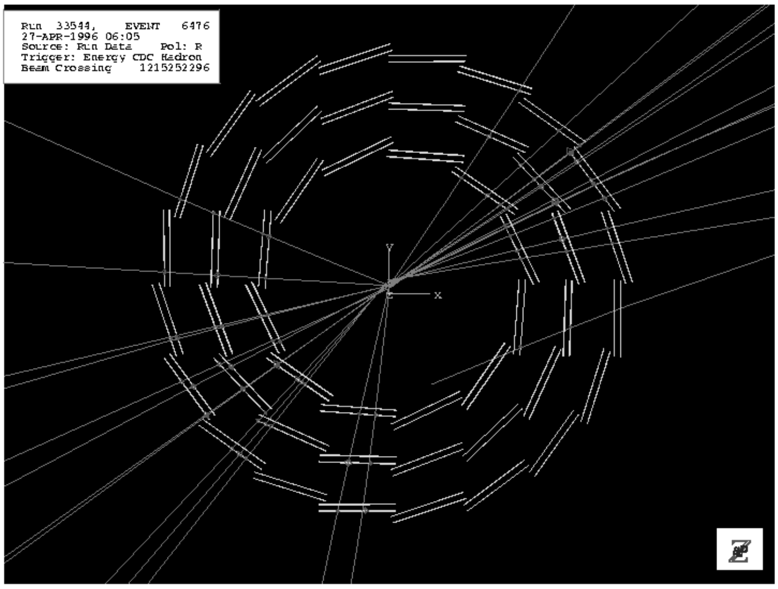

Figure 24. Event as seen by the VXD 3 detector.

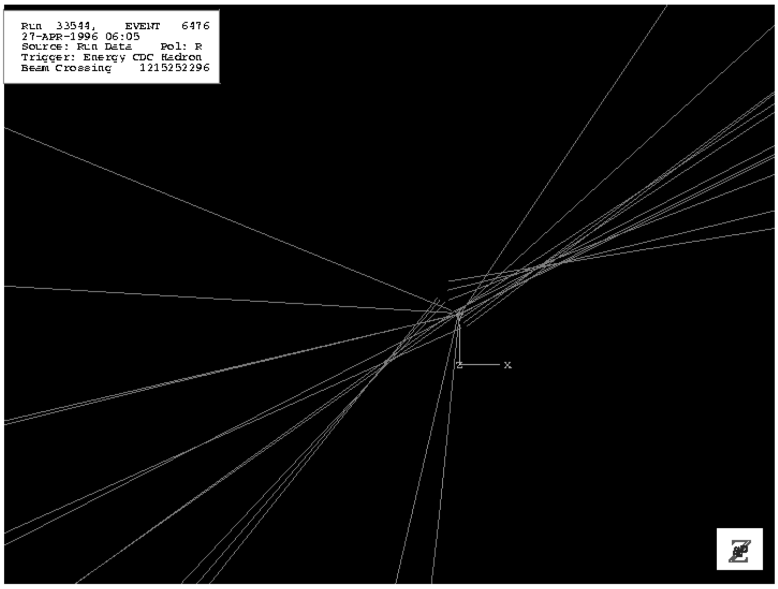

Figure 25. Revealing secondary vertices: In both event hemispheres, the secondary vertices can be seen clearly.

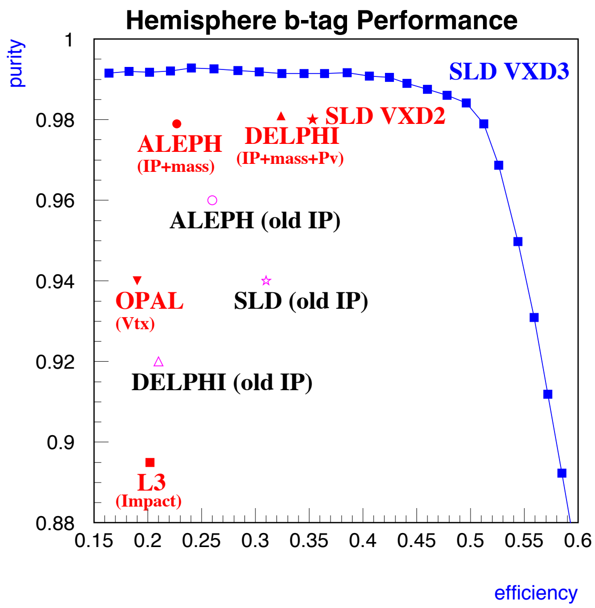

Figure 26. Comparison of b-tag performance: The purity versus efficiency for the SLD VXD3 detector is compared with results from VXD2 and the 4 LEP detectors.

the improved track reconstruction after inclusion of the information from the vertex detector [VXD2]. Figure 24 and Fig. 25 show the x-y projection of an event as seen by VXD3. The close-up in Fig. 25 clearly reveals secondary vertices.

The ability to identify secondary vertices opens up a wide field of b-quark physics. The events containing b-quarks are identified[tagged] using the visible decay length associated with B-mesons and b-baryons. All 4 LEP detectors, as well as SLD, have widely explored that possibility. In the tagging of b-quarks, it is also where SLD's pixels pay off. Figure 26 gives a comparison between different LEP results and SLD [14]. In all tagging efforts there is a trade-off between purity and efficiency. As the c-quark also has a significant lifetime, any b-quark sample is threatened by c-quark contamination. With its VXD3 detector, SLD achieves excellent purity for up to almost 50% efficiency. However, it should also be noted that SLD has the additional advantage of small initial beam spots and a small distance(28mm), between the beam axis and the first layer of CCDs. Good b-tags translate into good results on measurements such as R_b and R_c, the fractions of Z decays into b- or c- quarks, respectively. Some comparisons can be found in [14].

The SLD vertex detector has the largest number of channels of any high energy physics detector I know. 307 million pixels have to be dealt with. For the many technical details, such as mechanical support, cooling and read-out, which are quite involved, please have a look at Ref. [13]. It is the only application of CCDs in a collider experiment. The detector was operated very successfully, and helped SLD to overcome the disadvantage of having lower statistics than the competing LEP experiments. CCDs are an extremely attractive possibility for a vertex detector, if the experiment can allow read-out times that are in the hundreds or perhaps tens of milliseconds, and the radiation encountered is moderate.

3.2.2. *HERA-B*

The HERA-B detector is a forward spectrometer currently operating at DESY in Hamburg. It is designed to study CP violation in B-meson decays. The B-mesons are produced by proton interactions in wires placed within the beam-pipe of the HERA proton ring. As at LEP, a silicon vertex detector is used to identify the B-mesons through their visible decay lengths, which at HERA-B are about 1cm.

All particles are boosted into the extreme forward direction. Therefore, the HERA-B vertex system takes the so-called "Roman pot" design to an extreme. Figure 27 illustrates the idea. When a particle leaves the beam-pipe at a small angle, it traverses a lot of material. The amount of matter traversed is reduced by inserting pots into the beam-pipe. That also provides a way to get closer to the beam axis. The HERA-B silicon detectors are operated as close as 1cm to the beam axis. Unfortunately, the HERA proton beam moves around during injection and acceleration, and therefore the Roman pots have to be movable. The resulting mechanical system is quite involved. A 2.5m long vessel carries the Roman pots and manipulators for 32 silicon detector modules(see Fig. 28 for a schematic and Fig. 29 for a picture). In order to further reduce the material in front of the silicon detectors, the aluminum walls of the Roman pots are reduced to 150μm. As 150μm thick aluminum cannot withstand atmospheric pressure, this requires a secondary vacuum inside the pots. The engineering of the modules themselves is also not at all trivial. They have to fit into the very limited space inside the pots and, due to the vacuum, they have to be cooled through their support structures. As the electronics produces much more heat than the silicon detectors do, different cooling paths for electronics and detectors have to be provided. Everything has to be made out of carbon fiber and kapton because the system is still limited by multiple scattering. The resulting construction is depicted in Fig. 30. A picture of a mounted module, ready to be inserted

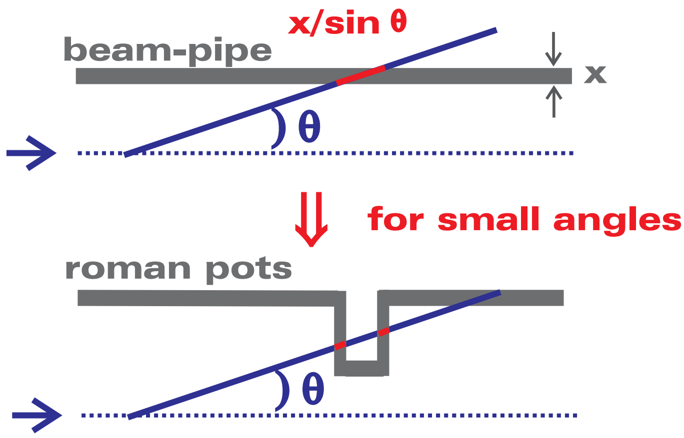

Figure 27. Schematics of a Roman pot: Particles produced at small angles θ relative to the beam axis have to traverse too much material to be tracked by normal detectors placed outside of a beam-pipe. Roman pots are inserted into the aperture to circumvent this problem.

into its pot, is shown in Fig. 31. Each module has two silicon detectors and has more than 10,000 wire bonds. It costs about $12,000. The actual silicon detectors, when purchased commercially make up about 30% of that cost. The total system cost is such that the silicon contributes only about 10% to the total. And it should be recognized thatthese silicon detectors are very expensive and very complicated devices for mass production runs.

The silicon detectors for HERA-B are pushed to the limit in radiation resistance. The expected dose at 1cm distance to the beam axis is 10 Mrad per year, mainly caused by a flux of $\approx 3\times10^{14}/\text{cm}^2$ minimum ionizing particles. This is about the limit of what is feasible with current technology. The signal to noise will be reduced to almost the limit of usability, depending on the ability to reduce the leakage current through cooling(see Sec. 4.3). It is not feasible to cool the silicon to optimum values. It is therefore foreseen to replace the silicon every year. Even if it were possible to cool the silicon to its optimum operational temperature of about -10°C, it would not survive more than two years, as the full depletion voltage would increase to unmanageable values. For more information check Ref. [15].

3.2.3. *Silicon Drift Detector in CERES*

As mentioned before, all kinds of structures are possible on a silicon wafer. It is also possible to construct a real drift detector, where the time of arrival of the charge is used to measure one of the coordinates. Figure 32 shows a circular detector [16] constructed for the CERES[NA45] experiment at

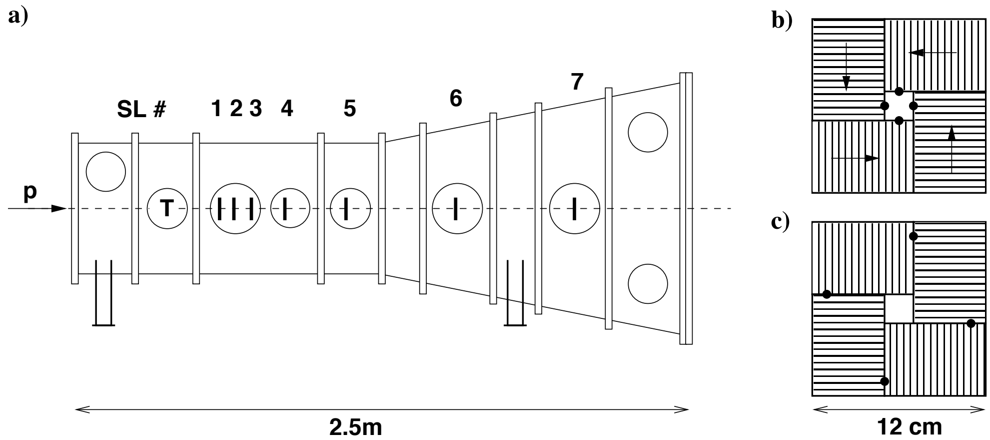

Figure 28. a) Schematic of the VDS vessel with the positions of the wire targets (T) and the VDS super-layers (SL 1-7). b,c) Arrangement of the detectors around the beam axis. The detectors are switched between positions b and c, so that the point of highest irradiation [black dots] on the detector is changed regularly.

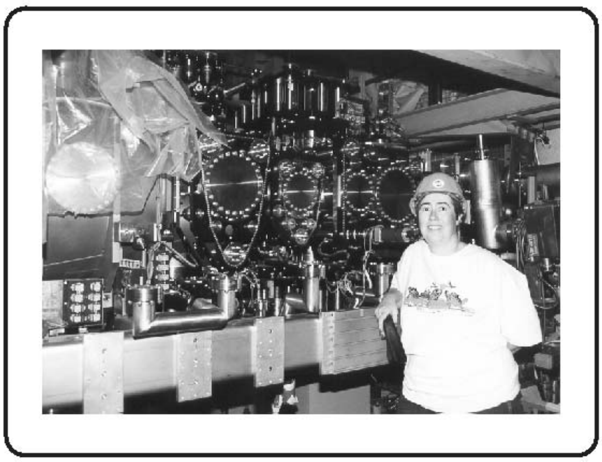

Figure 29. Picture of the HERA-B vertex vessel.

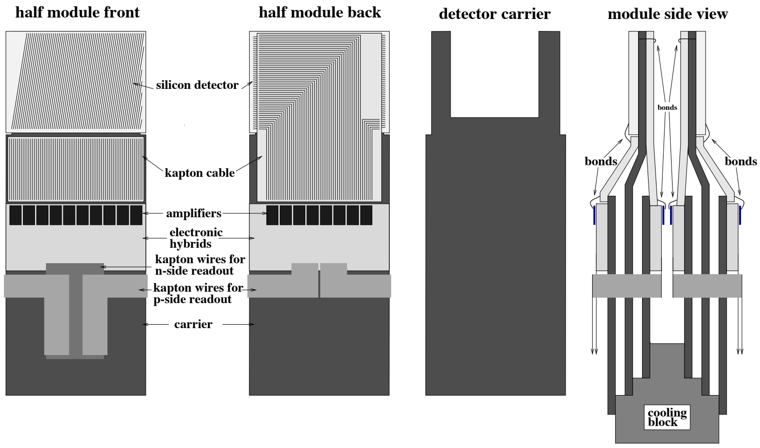

Figure 30. Schematic of the HERA-B silicon vertex detector module: Two half-modules are mounted together in one Roman pot.

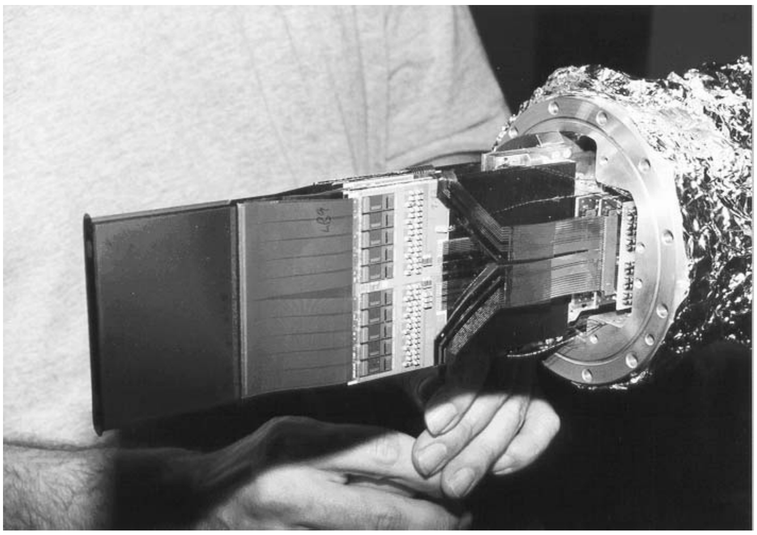

Figure 31. Picture of a mounted module to be inserted into its Roman pot.

CERN. In this experiment, the beam passes through the hole in the middle of the silicon detector. The radius and the angle Φ is measured for scattered particles hitting the detector. The charge is pulled to the edge of the detector by the field induced by 240 circular field electrodes. The resolution in Φ is given through 360 signal anodes. The resolution in R is given by the drift

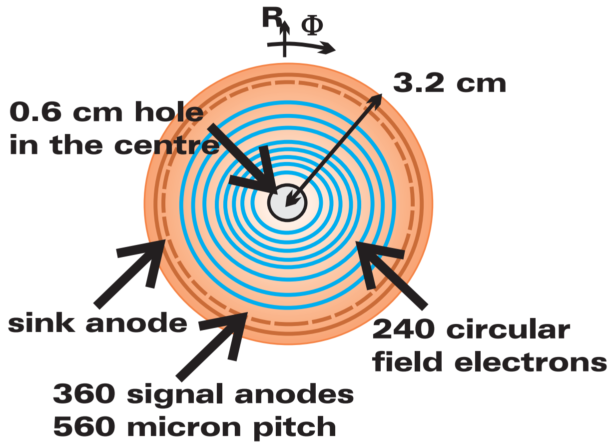

Figure 32. Schematic of the silicon drift detector used in the CERES experiment.

time measurement. The nominal drift field is 500 Volts/cm resulting in a maximum drift time of 4μs. The resolution is less than 20μm in R and Φ. The special trick in the design are the sink anodes. Without them, the current would flow into the signal anodes and cause too high a level of noise.

The big advantage of silicon drift detectors is that a relatively large area can be covered with very few read-out channels. The big disadvantage is that such a device is necessarily rather slow.

Very specialized designs, such as the one presented here, can be very efficient. However, they don't come cheap, and can usually never be used for anything else.

3.2.4. *Silicon-Tungsten Calorimeters*

Related to the historical flux measurements are the modern calorimetric applications of silicon. Wherever there is little space and/or a lot of radiation, calorimeters made of dense materials, with silicon as the active element, can be considered. The dense material is usually tungsten. The silicon detectors usually feature pads. Such calorimeters are often used to measure the luminosity of an electron ring by looking for electrons scattered at small angles. Consequently, they can be found for instance at LEP,SLC and HERA. The standard geometry depicted in Fig. 33 is only one possibility. Wedge shaped objects forming rings, and other more exotic constructions, can be used.

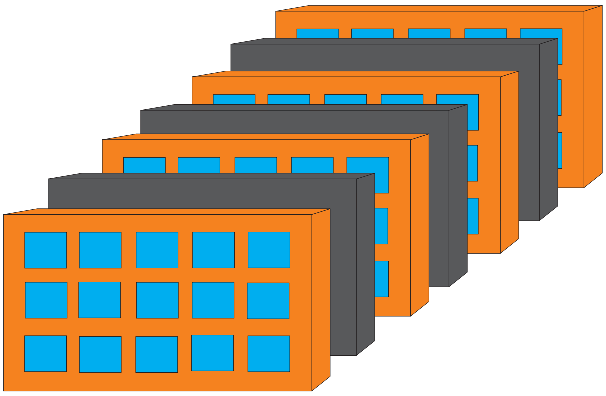

Figure 33. Schematic of a standard silicon-tungsten calorimeter: Layers of tungsten and silicon pad detectors form a sampling calorimeter.

4. Limitations of Silicon Detectors

4.1. BASIC PARAMETERS

4.1.1. *Speed*

The speed of silicon detectors will start to become an issue if event rates will continue to rise. The speed depends on the drift field and thus on the bias voltage, but, at normal operational parameters, electrons take about 3ns to traverse 100μs, while holes need about 8ns for the same distance. Thus, 25ns is the minimum time needed when the p-side is read out, and the full signal is required for a detector is that is 300μm thick. In cases of very low occupancy, several events can be read out together. Hits from different events are then separated through additiona; information. This option has rarely been used, but it should be looked into more often.

4.1.2. *Size*

Many applications call for very large areas of silicon. Square-meters of silicon are planned for LHC, and this trend will continue. Very often the segmentation into small individual wafers causes problems. Basically, all detectors today are manufactured from 4 inch [10cm] wafers. However, 6 inch wafers have been used to produce detectors, and there is no physical law preventing 10 inch wafers. However, the over-all properties of a detector can be ruined by a single defect. The probability for a defect is at least proportional to the area of the device. It will be very difficult to have a good yield for very large detectors, and that will most likely result in forbidding costs per cm^2.

4.1.3. *Resolution and Material Budget*

As far as resolution is concerned, the limit is about 1μm. That has been achieved for strip detectors [17] and could be done with pixels. The corresponding structures on the silicon are of the order 10μm, and pose no real problem to good manufacturers. However, the actual resolution of a silicon system is usually not limited by the intrinsic resolution of the detectors. The main limitation of vertex detectors come from the material needed for the beam pipe and the detector itself. This is why Roman pot systems(see Fig. 27) become increasingly popular, and some experiments try to use thinner silicon detectors. Extremely important is the amount of material a track has to traverse before its first hit can be recorded. The corresponding contribution to the impact paramter resolution can be written as:

$$\sigma_{ms} = 13.6 \frac{MeV}{c} \frac{1}{p} D \sqrt{\frac{X}{X_0}}$$

where p is the particle momentum, D the distance from the interaction point, X/X_0 the fraction of a radiation length traversed, and ms is a reminder that multiple scattering is responsible. For somewhat normal values like D =20cm and p =30$\times$10^{3}MeV/c, and a detector with 10μm intrinsic resolution, multiple scattering starts to dominate at X/X_0 of 0.012. That translates into about 1mm of aluminum.

Material pile-up is quite a problem. A typical system has more than one layer, and following layers are affected by the first layers. Therefore, all mechanical support structures, the read-out electronics close to the detectors, and cooling devices, have to have as little material as possible. Many designs start out being based on beryllium [100μm $\approx$ 0.03% X_0] and beryllium oxide [100μm $\approx$ 0.09% X_0]. However, both materials are difficult to handle and are very expensive. So most people use carbon fiber or graphite support structures. Typical values for those are $\approx$ 0.3% X_0 for a thickness of $\approx$ 700μm. For a 300μm detector, the silicon itself adds 0.3% X_0 In principle, thinner detectors can be made, however, they are too fragile for mass production, and thus cannot be used for large systems. In addition, the size of the signal is proportional to the thickness of the detector. 300μm is usually a good choice. Generally, it can be argued that anything less than 1% of a radiation length per layer is very good.

4.2. RADIATION DAMAGE

4.2.1. *Integral Dose*

The amount of integral radiation a silicon detector can digest and still function is its serious limitation. As explained in Sec. 2.5.8, a detector can in principle function as long as it can hold the voltage necessary to fully deplete it. The well designed guard ring structures can certainly be made to hold 1kV or more. However, a single defect on the n-side can cause a single strip to cause a break-through. Thus, perfect n-sides are needed in addition to good guard structures. Unfortunately, it is basically impossible to conclusively test the n-sides before type inversion. There are indications for n-side defects in the IV-curves(see Sec. 2.5.7). However, it is impossible to predict whether and at what voltage the device will fail. However, we should not forget that silicon detectors are by far the most radiation resistant detectors we have in large-scale production right now. The current generation of experiments expect to be able to use their silicon after a dose of up to $3 \times 10^{14}/\mathrm{cm}^2$ minimum ionizing particles or 10Mrad.

4.2.2. *Radiation Bursts*

As explained in Sec. 2.5.9, radiation bursts can create pin-holes. The internal capacitors cannot be made to withstand significantly more than 100V without creating other problems. Thus, a detector will get destroyed if it gets exposed to strong bursts creating voltage drops larger than 100V. The system usually tolerates a couple of pin-holes, but at a certain point the detector becomes unusable. It is necessary to control the environment such that bursts do not become a habit.

4.3. COOLING

As mentioned before(see Sec. 2.5.11), the current generated in the bulk of a silicon detector at room temperature can be reduced by a factor of 2 through cooling by 7°C. This is important after a detector is damaged by irradiation and the increased leakage current reduces the signal to noise ratio. Unfortunately, the geometrical and mechanical realities of a detector system, as well as the heat produced by the read-out electronics, can limit the ability to cool the silicon. The cooling capacity thus can limit the results that can be achieved for the signal to noise ratio.

Cooling also suppresses anti-annealing(see Sec. 2.5.8). That is beneficial. However, it also suppresses annealing, which is bad. Fortunately, the two effects occur on different time scales, days for annealing, months for anti-annealing. Thus, it is useful to slightly warm up detectors from time to time to let them anneal, and cool them down again before they can anti-anneal. It is also useful to adjust the operation temperature such that annealing is not totally suppressed. The optimum temperature turns out to be around -10°C. This is in many cases below the temperature achievable with a reasonable and affordable technical effort.

5. The Future of Silicon Detectors

5.1. SHORT-TERM FUTURE

Almost all of the next generation of experiments have a silicon detector component. Some silicon systems are pure vertex detectors, where other systems define tracks, and hits in the silicon are attached to these tracks. Others are trackers in their own right. They have many layers, and they are used for stand-alone tracking. Many designs feature the classical strips, some call for pads, and some for pixels. Some of the trackers will use several square meters of silicon, and some vertex detectors will use the most refined pieces of silicon ever made. Collider experiments generally want huge silicon trackers. These many-layer designs are generally built because a drift chamber could not operate in the environment at hand. Their resolution is totally dominated by multiple scattering, and the silicon technology itself can be rather crude.

A true vertex detector is used only when some other component already finds the tracks, and the information from the silicon is used only to refine the track parameters. Such a detector is designed with minimal material and optimized silicon detectors. The most delicate silicon detector designs can be found in fixed-target applications, where a single detector can be placed at a very special location.

Unfortunately, the design of many of the devices currently under construction is not very well motivated. The systems are hybrids between trackers and vertex detectors. Quite often they are built before anybody had the time to clearly specify what is needed or wanted. In some collaborations, especially the very large ones, decisions may be more influenced by political than by technical and physics considerations. This is not only true for silicon detectors, but it is a clear trend in detector contruction that should be reversed as soon as possible!

5.2. LONG-TERM FUTURE

DISCLAIMER:
Any prediction the author made in the past turned out to be wrong!

Silicon is actually not cheap, requires some expertise, and is not easy to handle. Therefore, lots of people would like to replace it with something else. However, there is no well developed something-technology at hand. On top of this, all the technologies that are at the moment considered as alternatives(see below) are also expensive and difficult. Therefore, I predict that silicon detectors are going to stay, no matter what. Even in 50 years they will have a wide range of applications in high energy physics, if there will be high energy physics in 50 years.

The question remains whether a mode of operation can be found for silicon detectors that allows their usage after radiation doses equivalent to more than $10^{15}/\mathrm{cm}^2$ minimum ionizing particles. Irradiated silicon at nitrogen temperatures could be the way. At low temperatures, silicon itself becomes an insulator with a small band-gap. The original defects in the material are compensated by radiation defects. The resulting material is something new. The research is ongoing [18] and we will have to see what comes of it.

5.3. ALTERNATIVES

The first two of the following "alternatives" are listed only because the discussion about them resurfaces every time a silicon detector seems to be too expensive or too difficult. The other two technologies are not ready to be used for the construction of a large device. However, they show some promise.

5.3.1. *GaAs*

IThis was advertised as the technology of the future. As far as detectors are concerned, it is now a technology of the past. It was supposed to be radiation hard. However, that is only true for neutral irradiation. It is worse than silicon under charged irradiation. Another draw-back of GaAs is that the signal is small to start with. The average number of electron-hole pairs is 3000 for each 0.1% of a radiation length instead of 8000. Everything considered, GaAs cannot any longer be counted as an alternative to silicon.

5.3.2. *Scintillating Fibers*

Scintillating fibers are used in tracking devices, for instance, in the D0 upgrade [19]. However, they cannot achieve the resolution wanted for vertex detectors. They are also hard to read out, and they are not radiation hard. So while they can be useful in a particular tracking device I do not consider them an alternative to silicon.

5.3.3. *Scintillating Capillaries*

There is an impressive number of technological problems yet to be solved. Most importantly, there is no clear scheme how to read them out efficiently. However, it might work one day.

5.3.4. *Diamonds*

The small size of the signal remains a problem, because the total thickness of the substrate cannot contribute to it. However, the thickness of the layer contributing is being constantly improved. There are still a number of technical problems to be solved before a large system can be designed. However, diamond seems the most promising alternative at the moment [20].

6. Conclusions

Silicon detectors are an extremely powerful, tool widely used in high energy physics. Over the last ten years, they have become a standard piece of equipment and they will continue to be so over the next ten years. I risk the prediction that, as long as particles are tracked, there always will be a place for silicon. At the moment, silicon detectors are the most radiation resistant detectors that are available for large scale projects. That may remain so for quite some time to come. Anybody designing a detector should study diligently what requirements the vertex detector has to fulfill. In order to get the best possible detector, all choices have to be made carefully. That is only possible when the requirements are known and clearly stated.

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