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RADIATION DAMAGE: EXPERIENCE WITH SILICON DETECTORS

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IN HIGH ENERGY PARTICLE BEAMS AT CERN

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INTRODUCTION

Silicon detectors are expected to play an important role in future miniaturized high energy physics experiments. They can be used in target telescopes to measure the interaction point and the event multiplicity. Particle localisation with a precision of the order of 10 μm seems possible with the recently developed multi-electrode silicon detector¹ or the silicon microstrip detector², which will enable precise track reconstruction near the vertex. To obtain the high resolution, a possible approach is the charge division between widely spaced strips. This requires a very good noise performance of detector and electronics. In the alternative approach, many closely spaced strips are read out individually, and particles are located with the precision corresponding to the pitch of the strips. Only the presence of a signal needs to be detected, relative to one or two discrimination levels, and digital data treatment can be used.

One major drawback of silicon detectors is the accumulation of radiation damage in the crystal during exposure. This may limit the useful lifetime of a detector to 10^{11} - 10^{14} particles cm^{-2} . Some practical experience with the use of silicon detectors in a high energy radiation environment will be discussed.

RADIATION DAMAGE

The radiation transfers some of its energy to the silicon atoms, which part from their lattice position and leave a defect in the monocrystalline structure. Many different microscopic defects

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can be formed, depending on the kind of radiation, the impurities already present, the temperature during irradiation, ionization density, etc.

Energetic ionizing particles generally create simple defects, like the double vacancy, or the phosphor-vacancy, via the intermediary single vacancy, which is mobile in the lattice above 55°K. Low energy neutrons on the contrary, give rise to disordered regions, which are clusters of extended defects. There exist a number of methods to study these defects on the atomic scale, like Electron Paramagnetic Resonance, Thermally Stimulated Current or Deep Level Transient Spectroscopy. Each type of defect has a characteristic energy level in the forbidden bandgap. These energy levels, additional to the original doping levels, influence the electronic structure of the material, and change the device characteristics. These changes are more dramatic if the original impurity density is low, as is the case for high resistivity silicon (typically 10^{11} - 10^{12} doping atoms cm^{-3}).

On the macroscopic scale, the easiest accessible device parameter, indicating the degree of radiation damage, is the diode reverse current or leakage current. Besides the current, also the diode capacitance may change, the noise increases and finally important charge trapping may occur, as a result of the irradiation.

SILICON DIODE DETECTORS FOR THE MUON FLUX MEASUREMENT

Probably the only large scale, long term application of silicon detectors in high energy physics up to now has been their use for the muon flux measurement in the CERN neutrino beams, both at the PS and since 1976 at the SPS. Prior to the purchase of about 180 detectors for this so-called Neutrino Flux Monitoring (NFM) system³, extensive prototype testing was performed, both on bulk silicon and on complete devices. Information about the type of damage was inferred from the measurement of the Thermally Stimulated Current (TSC) on silicon samples, irradiated in the muon flux, in a cobalt gamma cell and in a controlled neutron flux from a nuclear reactor. The measurements are represented in fig. 1 and it is obvious that comparisons between the various irradiations are difficult to make.

In the muon flux exposure at least one simple defect structure is found to be introduced linearly with the fluence (integrated flux), at a rate of $\sim .2 \text{ cm}^{-3}$ per muon cm^{-2} . This defect most likely is the double vacancy⁴.

Fig. 1 TSC curves obtained on different n-type and p-type silicon samples, after various irradiations.

While the detectors are in operation (about 40 weeks per year), their performance is continuously monitored via the leakage current measurement and by comparing them regularly with a reference detector. In Fig. 2 a difference in the leakage current evolution with muon fluence can be seen for identical detectors 117 and 152. This illustrates the importance of a "hidden" neutron component in the radiation at the PS⁵. Part of the damage in detector 152 anneals with time at room temperature. This is characteristic for the neutron induced damage, as was also observed for the reactor irradiated detectors. Another illustration of the effect of a neutron component is given in table 1. Similar detectors were exposed in this test to electrons of 35, 50 and 80 MeV. In the 80 MeV exposure a considerable degradation is observed, because the threshold for neutron generation is exceeded.

Fig. 2 Current evolution for identical diffused diodes at PS and SPS.

Table 1 Effect of an electron-gamma beam on detector current at MEA linear accelerator in Amsterdam (1978)

Detector	Initial Current μA	Energy dose cm^{-2}	Current after irradiation	Further muon dose cm^{-2}	Current June 1980 μA
133	.054	50 MeV $1. \times 10^{13}$	.134	3×10^{12}	.097
134	.088	35 MeV $.7 \times 10^{13}$	.091	4×10^{12}	.130
123	.112	80 MeV $1. \times 10^{12}$	1.63	7×10^{12}	.770
125	.110	$1. \times 10^{12}$	1.17	6×10^{12}	.830

A number of diffused detectors failed after about 18 months of operation, irrespective of the fluence received. This failure was ascribed to accumulation of charge in the epoxy mounting, and could be repaired by curing the detector for 24 h at 130°C . The same reoccurred for all detectors of this type about two years later, as is shown in fig. 3. The slowly rising straight line gives the true radiation related damage in the silicon.

Fig. 3 Example of detector degradation related to the epoxy mounting.

A typical example of a normal leakage current evolution with muon irradiation is given in fig. 4. This detector has operated for four years up to $4 \times 10^{11} \text{ cm}^{-2}$ and although its current has increased, it is still working well.

Fig. 4 Example of normal detector evolution

A pictorial representation of the radiation history of about two thirds of the detectors used in the muon flux measurement is given in fig. 5. A full line indicates degraded operation, generally at a much reduced bias voltage because of too high leakage current ($> 10 \mu\text{A}$). For the surface barrier detectors (a) the highest resistivity ($\sim 20\,000 \Omega\text{cm}$) is at the top, those at the bottom have $\sim 2000 \Omega\text{cm}$ and these stood 10 to 100 times more flux. For the ion-implanted detectors (category (b)) most failures occurred above a fluence of 10^{12} cm^{-2} . All of the p-type, $3000 \Omega\text{cm}$ diffused detectors in category (c) are still operating well beyond 10^{13} cm^{-2} . From this comparison it becomes obvious that low resistivity, p-type silicon should be preferred for a long radiation lifetime.

Fig. 5 Summary of the behaviour of different types of silicon detectors:

- (a) surface barrier, gold on a n-type silicon
- (b) ion implanted detector (p-n)
- (c) diffused detectors (n-p)

Detectors are ordered from top to bottom by decreasing resistivity, and grouped according to manufacturer.

CONCLUSION

Silicon detectors degrade during operation, both by radiation damage and for other reasons. Background radiation, especially neutrons, may be more destructive than the principal radiation. If radiation damage is anticipated, the detector operation should not depend critically on a low noise performance or a low leakage current. In such a case, localization by charge division may be impractical, and also the usual charge sensitive preamplifier with 20 M Ω bias resistor has to be avoided. If the detector can withstand moderate annealing (150°C), a repair is sometimes possible. The bias voltage required for total depletion should not exceed ~ 200 V. Both technical considerations and physics requirements seem to favour thin silicon detectors, but obviously the need for a good signal to noise ratio imposes the lower limit on thickness.

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