Radiation resistance of semiconductor detectors and associated electronics

G. Hall
Blackett Laboratory
Imperial College
London SW7 2AZ, UK

Abstract

A review of the basic damage mechanisms in semiconductor devices is given, with an emphasis on silicon. Some estimates are made of the potential degradation of detectors when operated in an LHC environment.

1. Introduction

In terms of radiation damage, at least, LHC experiments will represent the most challenging environment in which detectors have yet operated. It is now well known that the flux of particles will comprise two important components: neutrons and charged particles. Both of these have important consequences for semiconductor devices and in the case of silicon many of the important mechanisms of damage are well studied[1-4], if not always completely understood. Other potentially interesting materials, such as gallium arsenide, are less well studied and less well known to this author. However some of the damage mechanisms are similar for different materials and it is possible to draw conclusions about likely advantages compared to silicon even if these benefits will require further R&D to realise.

2. Radiation doses

Since the detectors are not yet designed and semiconductor devices, in particular the electronics, will be distributed throughout the entire detector volume it is difficult to generalise about the radiation doses to be encountered. They will depend on the composition, shape and dimensions of the experiment. For example in a spherical lead calorimeter with a 4m diameter internal cavity [5-8] annual neutron fluences near shower maxima are expected to vary from $\sim 10^{12}$ cm^{-2} at $\eta = 0$ to $\sim 10^{17}$ cm^{-2} at large η with corresponding total hadron and gamma doses of ~500 Gray to ~5x 10^6 Gray in the calorimeter. In the central cavity, which will probably be used for tracking detectors, the charged particle dose will depend (as $1/r^2$) on radial distance from the beam while the neutron fluence will be practically isotropic. Here annual neutron fluences of ~10^{13} cm^{-2} will be typical while a charged particle dose of 10^4 -10^5 Gray at 10cm radius may be expected.

Simulations carried out so far are expected to have uncertainties of order 2 [5]. It is also important to note that the fluences depend, at least to factors of 2-3, on the decisions which are made on calorimeter design and thus estimates of the performance of semiconductor detectors, in particular, need to be made using realistic assumptions. It can also be expected that there will be local regions of higher than average doses caused by the finer details of detector construction which need to be taken into account.

The basic damage mechanisms in semiconductors are conveniently separated into two categories [1-3] - bulk effects and surface damage. In general the simplest types of semiconductor detectors, like diodes, are most affected by bulk damage while many important electronic devices in MOS technology are most adversely affected by surface effects. For more complex modern detectors this simple rule may not hold.

3. Bulk damage

To displace an atom from its site in the crystalline lattice requires ~15eV of kinetic recoil energy. This immediately sets a limit to the damage caused by some particles expected to be present, for example electrons and thermal neutrons. Neutrons of the ~1MeV energy typical of nuclear boil-off reactions, and therefore present as a result of hadron collisions in the calorimeter[9], are particularly effective in generating displacement damage. For simple kinematic reasons, it can be estimated that a neutron requires more than ~110 eV to remove an atom from its site. From these considerations and knowledge of neutron-Si cross-sections [10] the relative damage of neutrons as a function of incident energy can be calculated (fig.1); it shows a substantial increase at ~200keV but then remains relatively constant.

There is evidence from studies of electronic devices that displacement damage is proportional to non-ionising energy loss. This can also be calculated and Van Ginneken[11] has extended previous estimates to energy ranges of interest to particle physicists for all particle types (fig.2). Although, as yet, difficult to confront with experimental data this indicates at least that high energy muons and electrons should not be used as the standard with which to measure average ionising particle bulk damage.

An energetic displaced atom initially loses energy by ionisation but towards the end of its range creates multiple further displacements, ultimately leading to ~10^3 displacements in a highly disordered region only a few hundred Angstroms in linear dimensions. The simplest lattice defects are point defects, like vacancies at a lattice site or interstitial atoms located between normal lattice positions. These are normally unstable at room temperature and may migrate from their point of origin - either annihilating, being trapped at a surface or forming a stable defect complex. Since the semiconductor properties depend critically on lattice symmetry both of the latter cases imply adverse consequences for the material since unwanted energy levels in the band gap are formed.

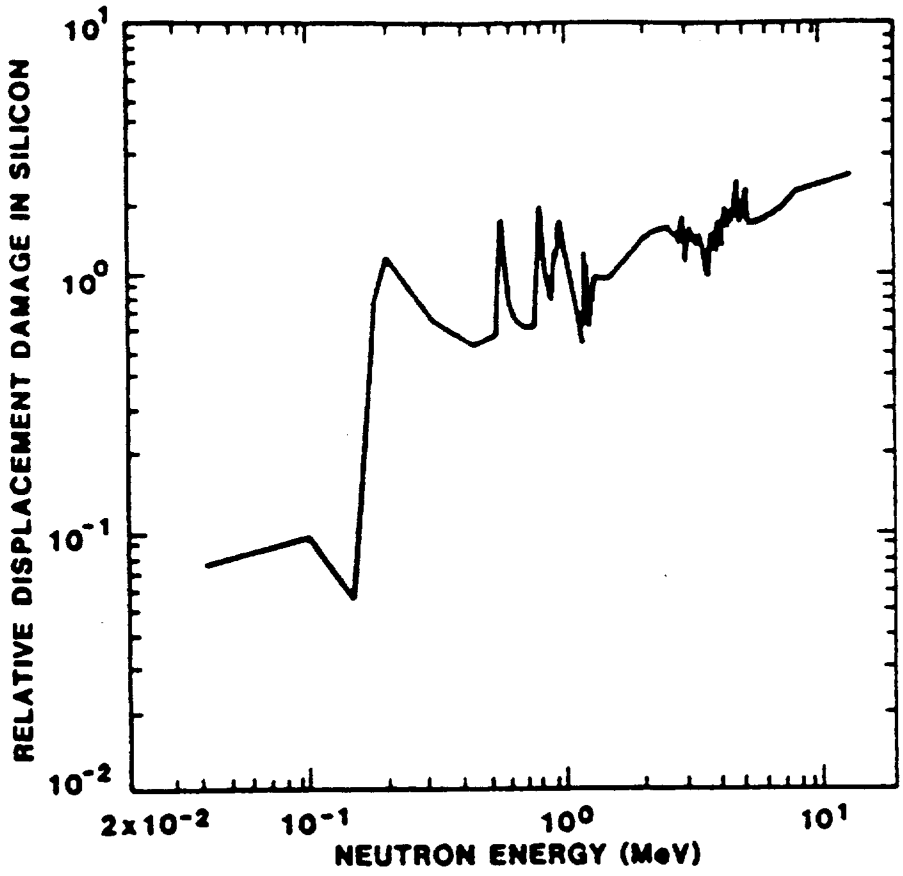

Fig.1 Relative displacement damage by neutrons in silicon [1].

The most well known effect of energy levels in the band gap is an increase in leakage current in depleted detectors since the ease with which a mobile carrier can traverse the gap is greatly enhanced by intermediate levels. There are other important effects however: trapping of carriers can degrade the signal either by incomplete charge collection or by increasing the duration of the signal current pulse. Degradation of minority carrier lifetime is a related effect. An effect of particular concern is compensation of the material by defects which are charged and thus behave effectively as ionised doping atoms; this will change the electric field in the device.

Many of the defect structures present after irradiation have been identified. The complexity of the defects, which can have several charge states as well as energy levels, requires a variety of correlated techniques to characterise them completely[4]. Nevertheless, in the case of silicon, there is some consensus on the most important observations. A vacancy-phosphorus complex has been observed in several studies [4,12,13,19e] and is thought to be responsible for much of the leakage current increase in neutron irradiated detectors [12]; this would also explain the observed temperature dependence of the leakage current[19a,n]. Other complexes which have been identified as important are vacancy-oxygen and vacancy-vacancy in several charge states.

An important side effect of charged defect formation is compensation of the substrate material. It has now been established in several measurements that during irradiation donor removal occurs in n-type detector material which eventually inverts and becomes p-type. The measurements are not yet sufficiently detailed to show if this phenomenon continues indefinitely but at fluences up to about a few x10^{12} n.cm^{-2} there seems to be a roughly linear change of effective doping concentration with fluence. Inversion probably occurs for detector grade material at neutron fluences of ~10^{13} cm^{-2} [19e,n].

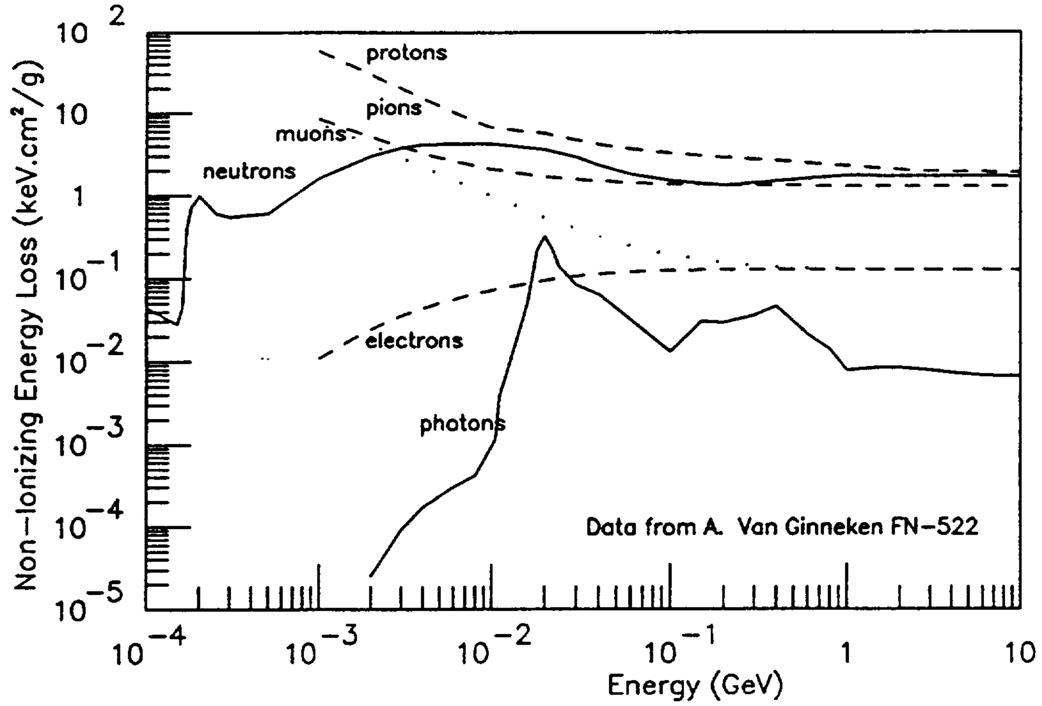

Fig.2 Calculated non-ionising energy loss for different particles [11].

There is a large flux of thermal neutrons expected to be present and it is interesting to note one of their possible effects although, as noted, they cannot directly cause displacement damage. Neutron transmutation doping [14] is a method for obtaining highly uniform n-type silicon for electronics applications. Thermal neutrons undergo capture reactions in silicon but, with the exception of the 3% of ^{30}Si atoms present, the resulting silicon isotopes are stable. ^{31}Si beta decays with a 2.6h half life to ^{31}P which contributes donor dopants. However estimation of the reaction rate demonstrates that fluences of 10^{13} thermal n.cm^{-2} produce only ~10^{9} cm^{-3} phosphorus atoms which is insignificant in comparison to the doping concentration of high resistivity silicon.

4. Surface damage

Surface damage effects are well studied in silicon where the usual oxide-silicon interface plays an important role in the operation of some important electronic devices. During the high temperature oxidation procedure, which is one of the first fabrication steps, charge is unavoidably incorporated into the oxide in several forms. While mobile charges introduced by the presence of sodium are normally avoided by scrupulous cleanliness and gettering techniques several varieties of charges fixed in the oxide are created.

Close to the interface [15] resides the positive fixed charge which results from the transition from silicon to silicon dioxide over atomic layer dimensions; typical densities are 10^{10}-10^{12} cm^{-2}. Interface states, which represent surface mid-gap energy levels, are also formed; these are mobile and play an important role in surface leakage currents. Bulk fixed trapped charge can be present from defects in the bulk oxide. All of these are enhanced by irradiation, most importantly by ionising particles.

Typically, after mobile charges are generated by ionisation a certain fraction rapidly recombines. Electrons then diffuse or migrate in any oxide field to a surface while holes, which are several orders of magnitude less mobile, move slowly in the opposite direction. In many cases this can be the oxide-silicon interface and holes are trapped there, enhancing the fixed charge or the interface states. The dynamics of this process are quite complicated [16] and the mobility of defects created by ionisation appears to depend strongly on processing conditions, for example the presence of hydrogen. An enormous research effort has been devoted to developing radiation hard oxides for MOS electronics with considerable success and some of this information is in the public domain, for example the well known dependence of gate voltage threshold shifts on oxide thickness[1,2].

Typical consequences of oxide damage are therefore increased surface leakage currents, and decreased carrier mobility, as a result of carrier scattering from traps. Gate voltage threshold shifts in MOS transistors are caused by the need to compensate extra charge accumulated at the Si-SiO_2 interface before inducing carriers in the channel for device conduction. Another potentially important effect is the creation of conducting surface channels by inversion layers. In p-type silicon additional positive oxide charge at the oxide interface causes a high density of negative charge to be accumulated there; n-type regions can therefore be connected together by low resistance paths produced by electron layers.

In the electronics industry many years of research have been repaid with the ability to control most of these effects by special processing and careful design; fabrication of detectors is a relatively primitive technology in comparison.

5. Consequences of radiation damage for detectors

Some of the effects caused by radiation damage have already been mentioned. Here they are summarised, along with important side effects. Most silicon detectors are operated at room temperature but it should be noted that the effects of damage may be different at lower temperatures. Annealing effects on detector leakage currents have only been studied carefully under ambient conditions and different defect complexes are likely to be stable at reduced temperatures. Certainly, less annealing is expected although bulk leakage currents have an exponential dependence on temperature and will be reduced substantially by cooling. The consequences for compensation and trapping are less clear. It is also well known[15] that hole mobility in the oxide is substantially reduced at low temperature and thus a different distribution of oxide charge, compared to room temperature, may result.

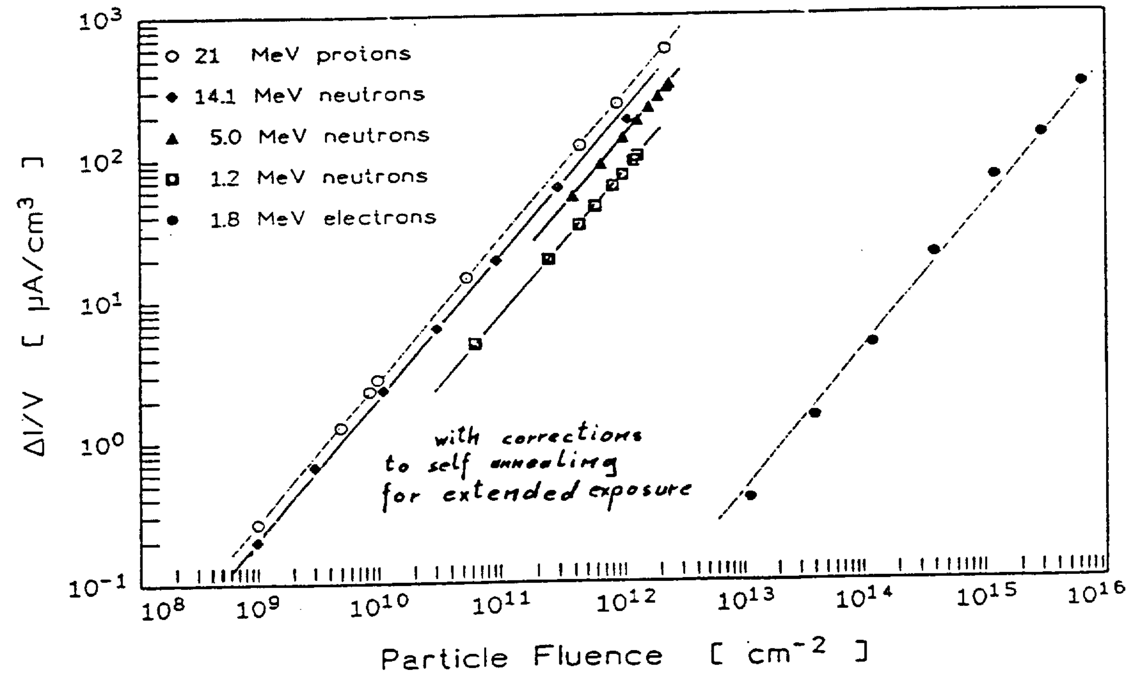

Fig.3. Change of leakage current density after irradiation [19e].

5.1 Increased leakage currents.

These lead to increased electronic noise and increased power consumption, neither of which will be trivial for any silicon detector operating in the LHC environment. Gallium arsenide detectors show a much lower increase in leakage current after extremely large neutron fluences[17]. This is probably because the substrate material is of relatively poor quality compared to silicon and the band gap is already heavily populated with intermediate levels. However since the initial leakage current is comparable with good quality silicon devices gallium arsenide is a promising material for LHC applications provided large area detectors with uniform (even if incomplete), high speed charge collection can be produced.

More systematic studies (a good example is that of ref [19e]) are still needed but for silicon it is well established that the increase in current density is proportional to particle fluence: $\Delta J = \alpha \phi$ (fig.3). The damage constant is not well defined for all types of particle and most of the available data, acquired under a range of conditions[1], are shown in Table 1. From these it is possible to extract damage constants for neutrons and charged particles[2]. I estimate [18] $6.9x10^{-17}$ A.cm^{-1} for neutrons and $2.9x10^{-17}$ A.cm^{-1} for charged particles. Given these it is possible to calculate the leakage current increase for a given detector configuration at LHC .

Table 1 **Leakage current damage constant**

Experimenters	**Irradiation**	**α (nA/cm)**	**Ref**
NA32	200 GeV hadrons	1.3 10^{-8}	19a
Nakamura	800 GeV p	2.9 10^{-8}	19b
Lindström	14 MeV n	15 10^{-8}	19d
Lindström	21 MeV p	21 10^{-8}	19d
Lindström	1.2 MeV n	7.9 10^{-8}	19d
Lindström	5 MeV n	14 10^{-8}	19d
Lindström	1.8 MeV e	4 10^{-11}	19d
Vismara	^{252}Cf n	4.5 10^{-8}	19e
Borgeaud	hadrons	9.1 10^{-8}	19f
NFM	reactor n	15 10^{-8}	19c,d
NFM	GeV μ + shower	0.6-9 10^{-8}	19c,d
NFM	GeV μ + shower	0.18 10^{-8}	19c,d
Korde	^{252}Cf n	5.8 10^{-8}	19g
Ohsugi	12 GeV p	3.0 10^{-8}	19h
Hasegawa	reactor n	6.6 10^{-8}	19i
Djikstra	β electrons	~0.5 10^{-9}	19j
Chilingarov	1.5 MeV e^- ,~10keV γ	0.8-7.0 10^{-9}	19k
Mishra	0.8 GeV p	1.8 10^{-8}	19e
Ziock	800MeV p	3.9-4.4 10^{-8}	19m
Edwards	~1MeV n	>3.1 10^{-8}	19n

As an example I consider a detector consisting of cylindrical layers of 300μm thickness silicon in the inner cavity of a uranium-scintillator calorimeter

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[1] Few of these are dedicated experiments and most extract the damage constant from a single measurement.

[2] The reader is invited to form his own opinion as to the merit, or otherwise,of the values I have chosen.

with 2m inner radius[3]. The three inner layers could be part of a microstrip tracker; the outer layer could be one part of a pre-shower detector (not necessarily simultaneously present).

For a luminosity of $2\mathrm{x}10^{34}$ $\mathrm{cm}^{-2}.\mathrm{s}^{-1}$ and $10^7\mathrm{s.yr}^{-1}$ the fluences are $\approx 4\mathrm{x}10^{16}/R^2$ minimum ionising particles.cm^{-2} and $\approx 3\mathrm{x}10^{13}$ n.cm^{-2}[5,8]. The annual rate of increase of leakage current, assuming room temperature operation, can be written

$$\Delta I = 62 + 3.5\ 10^4/R^2\ (\mu\mathrm{A.cm}^{-2})$$

The results for layers at different radii, including the extra power need to sustain the increased leakage current, are shown in Table 2.

Table 2 **Annual rate of leakage current increase for L = 2 x 10 ^{34} $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$**

Layer	R(cm)	L(cm)	$\Delta I(\mu A cm^{-2})$	$\Delta I_{layer}(A)$	$\Delta P(kW)$ (at 100V)
1	10	50	410	1.3	0.13
2	30	130	100	2.5	0.25
3	50	200	75	4.7	0.47
4	200	400	63	32	3.2

Electronic noise depends on detector segmentation. As an example consider a microstrip 25µm x 9cm (or a pad 1.5mm x 1.5mm) in each layer. After five years of operation, assuming CR-RC shaping with a 15nsec time constant, the strip or pad currents and shot noise are given in Table 3. Increased noise at these levels may just be tolerable for the outer layers but for the inner layers increased segmentation is surely required to ensure a reasonable lifetime for detection of minimum ionising particle signals of ~25000 electrons, often shared between strips.

Table 3 **Microstrip leakage currents and shot noise contribution after 5 years operation**

Layer	ΔI_{strip} (µA)	ENC_{shot} (e)
1	46	2900
2	11.3	1430
3	8.4	1230
4	7.1	1130

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[3] U-scintillator is a median case; other materials change the neutron fluence up or down by a factor 2-3 [5]. More optimistic or pessimistic assumptions regarding several factors could be made; those chosen are not claimed to be optimal, merely realistic.

It is clear that leakage currents alone represent a significant heat load and need to be allowed for - in addition to the 1-2mW/channel required for front end electronics. For detectors at larger distances from the beam it would clearly be advantageous to reduce significantly the neutron flux if this can be achieved, by the use of moderating material at the calorimeter face for example. Unfortunately there are potentially even more serious problems.

5.2 Change of effective doping concentration

As n-type material gradually becomes intrinsic and then inverts to p-type the electric field in the detector changes. This will have the effect of changing the speed at which the carriers are collected and thus the time development of the signal current pulse. It has already been stressed [22] that it is important to operate the detectors well over-depleted to ensure that the full signal is observed within the electronic shaping time; otherwise further signal to noise degradation occurs. This will become more important after inversion of the substrate. Then the junction side, where the electric field is maximum, moves from the p-type surface to the n-type surface. Holes will then be collected more slowly, probably leading to extended tails on the signal pulse.

A second effect, not so far observed, is the likely interconnection of p-type regions after the substrate becomes inverted. In double sided strip detectors a considerable effort has been devoted to solving the problem of isolation of n-type strips on n-type silicon. It is not yet clear how serious a problem this will be for p-type areas on p-type silicon. It should be noted that it applies to multi-pad detectors as well as microstrips.

For microstrip detectors the change in electric field within the detector is likely to lead to degradation in position resolution, especially if the radiation is significantly non-uniform. Such an effect was observed already in the NA32 experiment[19a] where field distortions caused carrier trajectories to be non-normal to the wafer surface.

5.3 Surface damage

Many microstrip detectors presently in use now incorporate integrated capacitors and resistors. Some of these, for example polysilicon resistors and capacitors, are quite clearly radiation hard[19n]. Others, such as punch-through and accumulation layer resistors[20] may be radiation tolerant but, for operation, depend strongly on conditions at the surface of the silicon. The magnitude of resistor values is known to change with leakage currents drawn by the detectors and measurements are required to demonstrate that this can be tolerated at LHC. Interstrip isolation is also dependent on surface fields in some designs [21] and needs evaluation.

6. Consequences of radiation damage for electronics

Summarising the radiation resistance of electronics is made difficult by the range of technologies available. In practice hardness depends on choice of technology, details of design and processing, and fabrication techniques specially aimed at very high radiation hardness specifications have been developed for military and space applications.

Table 4 **Selected hardness levels of LSI circuits (after Dressendorfer)**

Technology	Total dose (rads (Si))	Neutrons (n/cm^2)
NMOS	$10^3 - 10^4$	$>10^{15}$
CMOS		
Commercial	$10^3 - 10^4$	$>10^{15}$
Hardened	$10^5 - 10^6$	
CMOS/SOS		
Commercial	$10^3 - 10^4$	$>10^{15}$
Hardened	$10^5 - 10^6$	$> 10^{15}$
Bipolar		
Older technologies	$10^6 - 10^7$	$10^{14} - 10^{15}$
Newer technologies	$10^4 - 10^5$	$10^{14} - 10^{15}$

Two of the most interesting technologies for general HEP and, specifically, LHC requirements are CMOS and bipolar. Variations on simple hardened CMOS processing include silicon on insulator (SOI) [26,27] technologies and demonstrations have recently been provided of circuits hardened to 1MGray levels using SIMOX processes [23-25]. The radiation resistances achieved have been summarised by Dressendorfer [29] (Table 4) and the principal requirements to achieve radiation hardening are explained below.

6.1 MOS technologies

The main cause of damage is from ionisation within the oxide which leads to accumulation of charge and traps at the oxide interface; thus total dose is of greater concern than neutron fluence. The most important parameters changed are gate voltage thresholds and carrier mobility in the conducting channel of the transistors. Bulk damage is of much less importance but leads to increased leakage currents, decreased minority carrier lifetimes and reduced mobility. In CCDs bulk effects reduce charge transfer inefficiencies but surface damage dominates in non-hardened devices.

An example of a radiation hard bulk CMOS process is that of UTMC [27] where the technical description guarantees that circuits in a 1.2μm process will meet specifications to 10^6 rads and at least $5x10^{14}$ n.cm^{-2} and function to doses greater than 10^7 rads. Measurements have confirmed the small expected threshold changes [19m]. What is not yet clear, and is of great interest to analogue designers, is the noise behaviour of the transistors.

6.2 Bipolar technologies

In contrast to MOS devices, bulk damage is of great importance in bipolar transistors. Enhanced carrier recombination in the base due to displacement damage effects is an important cause of gain degradation since transistor gain is determined by the fraction of carriers which traverse the base from emitter to collector. Leakage currents also increase because of bulk damage. Surface effects are most important for relatively low doses but a general statement of the hardness of bipolar circuits depends on details of the technology and design of the devices. Certainly useful analogue electronics can be designed to accommodate significant changes in transistor gain so reduction need not be fatal.

7. Conclusions

Estimates can already be made of the radiation tolerance of detectors in an LHC environment and potential weak points can be identified. It is still possible to imagine the use of silicon strips or pixels in regions even quite close to the beam but close attention needs to be paid to charge collection speed, total leakage current and shot noise to ensure adequate detector lifetimes. Gallium arsenide detectors could be a promising alternative to simple silicon diodes in some circumstances to avoid these problems if better quality detectors can be developed in the near future.

The consequences of damage induced compensation of bulk silicon are a serious concern and further investigations are certainly required. Complex microstrip detectors with integrated components need further development and evaluation of the different technologies available to ensure sufficient radiation tolerance.

Radiation hard electronics technologies based on silicon appear to be commercially available with adequate levels of radiation resistance to read out signals from semiconductor detectors at LHC. There are important questions concerning noise and performance which will only be answered by detailed evaluation of circuits produced for high energy physics applications.

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