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RADIATION DAMAGE IN SILICON SURFACE BARRIER DETECTORS*

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September 1980

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Abstract

Radiation damage can be a limiting effect on the usefulness of silicon detectors in high energy physics. Damage effects including resolution and leakage current degradation have been studied in two transmission mounted commercial surface barrier detectors placed near a production target at the AGS. Fast neutrons in the radiation field are suggested to be the major factor in producing increased leakage current and conversion to p-type base material. Both detectors experienced over 10^{14} fast n/cm² and more than 10^{16} thermal neutrons/cm² and exhibited severe hole trapping.

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Introduction

High energy protons and associated heavy particles including neutrons are expected to be the major cause of radiation damage in silicon detectors considered for use in high energy physics experiments. Device effects to be expected are energy resolution degradation due to carrier trapping by radiation introduced defects and leakage current increase from increased generation-regeneration of carriers through the defect levels.

Van Lint et al.¹ have summarized the status of the degradation of carrier lifetime by various radiations. The empirical effect on lifetime τ is linearly formulated with a "damage" constant related to lifetime K_τ where ϕ is the radiation fluence:

$$1/\tau = 1/\tau_0 + K_\tau \phi$$

For high energy protons, we extrapolate K to be $5 \times 10^{-6} \left(\frac{\text{cm}^2}{\text{sec}} \right)$ and estimate the effect of trapping by the effect on carrier drift length. Unfortunately this result does not predict a clear decision for the use (or not) of silicon detectors in an environment of high energy charged particles.

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Another deleterious electronic effect of the introduction of deep levels within the band gap by radiation-caused defects is that they are generation centers for leakage current. Neglecting edges, the leakage current in a reverse biased junction (depletion depth) has also been described by a damage constant K_g (to be compared with K_r as the inverse). Srour et al.² predict the increase of leakage current density to be

$$\Delta J_g = \frac{q n_i x_d \phi}{2K_g}$$

where q is the electronic charge, n_i the intrinsic carrier concentration, x_d the depletion depth, ϕ the fluence and K_g the damage constant which we will take for fast (fission) neutrons (shown to be important later) to be 7×10^6 n-sec/cm².

Experimental Conditions and Results

Two silicon surface barrier detectors were purchased from Ortec, Inc. in a transmission mount which allows access to both contact areas of the detector for an alpha source which can verify depletion voltage, material type and carrier type trapping. The "front" side is the p+ Au layer from which the depletion depth proceeds to the "rear" or "back" contact on the n-type material, evaporated aluminum. The detector areas were $\sim 50 \text{ mm}^2$ and the total silicon thickness nominally 560 and 500 μ . The detector serial numbers were 837 and 903 (to distinguish them) and were made from 6.1 and 14 K Ω on material, respectively, which required a depletion voltage of 200 and 65 V, respectively.

Detector 903 was mounted about 40 inches downstream from the production target in the test beam turned at approximately 15° from the beam axis in the forward direction. Detector 837 was mounted further, 150 inches downstream from the target at about the same forward angle. A ^{241}Am alpha source was placed about 3 mm (in air) from the gold, front contact to continuously monitor resolution degradation during the course of the run. The preamplifiers were ac-coupled with a total of 20 M Ω bias load resistors. The preamps were cabled out $\sim$ 100 ft. to linear amplifiers outside the beam cave.

The proton fluence from the production target in beam line B-4 was monitored with a scintillation detector and secondary emission detector (BSEC) whose outputs were recorded on scalers during the run. Detector 903 (close) was kept in position for $\sim$ 45 hours (31.2×10^{16} protons on target) and detector 837 (far) was positioned for the duration of the beam cycle, $\sim$ 13 days and 302×10^{16} protons on target.

Detector 903 showed evidence of charge collection degradation as early as $\sim$ 4 hours after beam start up and the possibility of an extraordinary fast neutron flux was postulated. Therefore, on removal, 903 was replaced by a 1 gm titanium rod which is an activation sample for fast neutrons above 1 MeV by the $^{47}\text{Ti}(n,p)^{47}\text{Sc}$ reaction (80 mb, to 3.43d ^{47}Sc which emits a 160 keV γ -ray).

The Ti rod was exposed for 31.9×10^{16} protons on the target nearly equal to that of detector 903. When counted with

a calibrated HPGe detector, we found that 903 received 3.6×10^{14} fast n/cm^2 and by extrapolation 837, $2.4 \times 10^{14} \text{ n/cm}^2$.

A production calculation³ for the given 903 detector geometry and angle estimates a fluence of all hadrons ($\pi^+, \text{n}, \text{p} > 300 \text{ MeV/c}$) at $10^9/\text{cm}^2$ per 10^{12} protons on that target. Neutrons of all energies are estimated to comprise between 20 and 50% of all hadrons and would therefore amount to 31.9×10^{16} protons $\times 10^{-3}$ hadrons/proton $\times .5$ neutron/all hadrons or $1.6 \times 10^{14} \text{ n/cm}^2$ in agreement with that measured by the Ti sample. The use of the higher figure for neutrons/hadrons (0.5) is justified in that it would help include the many other indirect sources of fast ($> 1 \text{ MeV}$) neutrons.

Additionally, both detectors were found to be somewhat radioactive with ^{198}Au , a standard activation source for thermal neutrons. By measuring the intensity of the 411 keV gamma ray following the irradiation and considering that each 50 mm^2 detector contained $\sim 1 \text{ cm}^2$ of $40 \text{ } \mu\text{g/cm}^2$ gold on the surface barrier, we find that 903, for example, experienced $\sim 10^{16}$ thermal n/cm^2 . The thermal fluence estimated from the ^{198}Au measurement for 837 was about 10 times higher than this as expected by its position.

After only 40 hours from the start of the run, (27.9×10^{16} protons on target or $2.2 \times 10^{13} \text{ n/cm}^2$ in 903) the alpha pulse in 837 was observed to have a rise time degraded to the order of $10 \text{ } \mu\text{sec}$ and a considerable increase in leakage current was also observed. Current measurements for both 903 and 837 at that time showed a leakage current limited only

by the 20 M Ω bias load resistors in each case (e.g., 15 μ a at 300 V), which was in part responsible for the apparent poor charge collection. Charge collection in 903 had continued to deteriorate between 4 and 40 hours and was removed at 45 hours.

Both detectors retained high leakage current following their removal from the beam cave. Figure 1 shows the pre and post leakage currents of the detectors measured in dark conditions. Capacitance or detector function could not be measured at these leakage currents but were studied after cooling by $\sim 40^{\circ}\text{C}$.

Capacitance measurements were made in a three terminal configuration with a Boonton 74-C bridge and yielded a flat capacitance versus applied bias curve with values of 26 and 27 pf for 837 and 903, respectively, independent of applied bias. These values may be taken to be the geometrical capacitance of the devices which results when the base material (undepleted region) resistivity has been sufficiently raised to "unshort" the high base capacitance which then appears in series with the depletion depth capacitance. The series combination of depleted and undepleted region capacitances must yield the geometrical capacitance of the device independent of bias. This observation has been made with neutron damaged germanium detectors⁴ and was previously explained by Haller, et al.⁵ The marked increase in base material resistivity can be due to the effect on carrier mobility of large damage clusters either producing scattering or carrier removal. The series resistance also results in an additional R-C

component on the pulse rise time observed at the preamp output shown in Figs. 2a,b. One should note that with the apparent resistivity increase, the depletion depth itself becomes less well defined. Grube et al.⁶ contend that increases in pulse rise time in 2 MeV proton damaged material may be due to field-assisted, (field-dependent) detrapping effects.

When α 's were incident on the gold "front" contact, neither detector collected even as much as 0.1 of the expected charge at low bias. However, both detectors collected at least half the expected charge (electrons), observed as a quick portion of the preamplifier rise time when irradiated from the back n^+ aluminum contact at low biases. Trapping aside for the moment, the material has apparently been converted to p-type so that depletion now proceeds from the n^+ aluminum contact into the now p-type base, presumably by the deep acceptors responsible for the still predominant hole trapping.⁷ This type conversion even compensated the transmutation doping effect of the $\sim 10^{16} \text{ cm}^{-2}$ thermal neutrons ($^{30}\text{Si}(n,\gamma)^{31}\text{Si} \rightarrow ^{31}\text{P}$). Meese et al.⁸ use a conversion coefficient of 3.36 ppb of ^{31}P per 10^{18} n/cm^2 . Thus 903 which was initially n-type, 14 k Ω -cm, would become further doped to 2.5 k Ω -cm.

Using the previously mentioned damage constant for fast neutron-produced leakage effects, we find that $10^{14} \text{ fast n/cm}^2$ yields $\Delta J = 170 \text{ } \mu\text{A/cm}^2$ for a representative 100 μm depletion depth, or 85 μA for the 50 mm^2 device irradiated. This value is in agreement with that observed (Fig. 1) lending some credence to the damage constant formulations.

Given that reliable damage constants may exist for several radiation types, considerable stress should therefore be placed on characterizing the radiation field in an experimental situation.

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Figure Captions

- Fig. 1 Leakage current versus applied bias for each detector before and after irradiation.
- Fig. 2a. Preamplifier output pulse shape of Detector 837 after irradiation at several biases. ^{241}Am alpha particles were incident on the aluminum "back" contact.
- Fig. 2b. Preamplifier output pulse shape of Detector 903 after irradiation at several biases (top trace). ^{241}Am alpha particles were incident on the aluminum "back" contact and a pulser pulse is shown to illustrate the system response. The lower trace is the output of the linear amplifier.

REFERENCES

1. V. A. J. Van Lint, G. Gigas and J. Barengoltz, IEEE Trans. Nuc. Sci. NS-22, (1975) 2662.
2. J. R. Srour, S. C. Chen, S. Othmer and R. A. Hartman, IEEE Trans. Nuc. Sci. NS-26 (1979) 4784.
3. A. J. Stevens, Brookhaven National Laboratory, performed these calculations.
4. H. W. Kraner, R. H. Pehl and E. E. Haller, IEEE Trans. Nuc. Sci. NS-22, 1, (1975) 149.
5. E. E. Haller, W. L. Hansen and F. S. Goulding, IEEE Trans. Nuc. Sci. NS-19, 3, (1972) 271.
6. R. Grube, E. Fretwurst and G. Lindstrom, Nucl. Instr. & Meth. 101, (1972) 97.
7. E. H. M. Heijne, et al., CERN/EF/BEAM 80-6, submitted to Nucl. Instr. & Meth. (1980).
8. J. M. Meese, D. L. Cowan and M. Chandrasekar, IEEE Trans. Nuc. Sci. NS-26, 6, (1979) 4858.

FIGURE 1

DETECTOR 837
 POST IRRADIATION
 ^{241}Am α ON ALUMINUM BACK CONTACT
 (FULL ENERGY IN CHANNEL 3276)

30V BIAS
 PEAK CHANNEL 500

150V BIAS
 PEAK CHANNEL 1285

250V BIAS
 PEAK CHANNEL 1658

FIGURE 2 a.

DETECTOR 903
 POST IRRADIATION
 ^{241}Am α ON ALUMINUM CONTACT
 (FULL ENERGY IN CHANNEL 3276)

30V BIAS
 PEAK 1068

70V BIAS
 PEAK 1624

150V BIAS
 PEAK 2329

250V BIAS
 PEAK 2653

FIGURE 2 b.