Presented at:
2nd Pisa Meeting on Advanced Detectors,
Grosetto, Italy, June 3-7, 1983

BNL 33692

CONF - 8306110 - 3

RADIATION DAMAGE IN SILICON DETECTORS*

BNL--33692

DE84 001460

H. W. Kraner
Brookhaven National Laboratory
Upton, New York 11973

August 1973

---

* This research was supported by the U. S. Department of Energy: Contract No. DE-AC02-76CH00016.

DISCLAIMER

RADIATION DAMAGE IN SILICON DETECTORS*

H. W. Kraner, Brookhaven National Laboratory, Upton, New York 11973

ABSTRACT

A review is presented of the effects of radiation damage on silicon detectors which are being considered for high energy physics applications. The main degradation in performance is an increase in leakage current, which can be well characterized by an empirical damage constant for many radiations. A summary of data on damage constants is given. A brief discussion of annealing effects in terms of band gap level changes is included.

I DAMAGE EFFECTS

Effects of radiations encountered in the environments of high energy physics experiments on semiconductor detectors are becoming better understood as their use increases and as the applicability of the general literature on this subject becomes better appreciated. Silicon junction detectors of large areas but relatively thin depletion depths (≈300 μm) are the detector types which deserve most consideration[1,2,3], although germanium detectors with much larger depletion depths or charge collection distances have also been used as active targets[4,5]. Effects to be expected from radiation-

---

* This research was supported by the U. S. Department of Energy: Contract No. DE-AC02-76CH00016.

EHB

produced defects include: (a) increased leakage currents as the defects act as centers to increase the generation-regeneration bulk current; (b) degraded energy resolution since the defects are trapping centers which remove charge from the "observed pulse" within the amplifier shaping time; (c) an increase in output pulse rise times or charge collection times which are caused by detrapping, from (b), or reduction in carrier mobility and (d) actual material type change, from N to P as introduced defects tend to act as acceptors. Of these effects, (a) is dominant for thin junction devices of interest whereas (b) is significant for high resolution germanium gamma ray spectrometers.

The increase of leakage current observed in several experimental situations[7,8,9] can be related to the minority carrier lifetime of the material if recombination is dominated by "mid-band" levels[10] caused by defects. Other leakage current effects (surfaces, coatings, etc.[6]) will not be considered. The current density J for a junction having depletion depth w is:

$$J = \frac{q\ n_i\ w}{2\tau} \qquad (1)$$

where n_i is the intrinsic carrier concentration, $1.5\times10^{10}/\mathrm{cm}^3$ for silicon, q is the electron charge and τ is the minority carrier lifetime.

The relationship of the minority carrier lifetime τ (or the change in τ if the initial value is very large) to a particular radiation fluence has been the subject of many studies[11] and has been applied to the effect of high energy environments on silicon detectors by Kraner, et al[7]. If the carrier recombination probability increases linearly with defect introduction or fluence, a proportionality constant K, i.e. the damage constant, may be defined:

$$1/\tau = 1/\tau_o + K\phi \qquad (2)$$

The damage constant K is sometimes defined as $1/K_g$[17] or K_τ[11], that K related to lifetime reduction. For large decreases in lifetime, compared with the initial lifetime τ_o, $\tau \approx 1/K\phi$ and the leakage current increase can be predicted for a given radiation (K) and fluence ϕ. It is indeed necessary to predict expected leakage currents over the projected lifetime of the device because they dictate the parameters of the readout electronics including amplifier noise and bias load resistance.

To give an example of the use of (1) and (2) with particular damage constants, one might choose to limit the leakage current of a 300 μm deep device to less than 10 μa/cm^2. From (1) it is found that $\tau \leq 3.6$ μsec, a value somewhat less than that expected from junction detectors as initially processed (although detectors from many suppliers are often not measured). The planar technology methods described by Kemmer[13] do produce high initial lifetime devices as do the low temperature processes of surface barrier technology. With this lifetime limit, one can estimate the tolerance to fast, 1 MeV neutrons using $K = 1 \times 10^{-5}$ cm^2/sec as well as minimum ionizing particles having $K \approx 4 \times 10^{-8}$ cm^2/sec to give an interesting comparison. This example does presuppose that these damage constants are well known and accurate, a premise which is to be examined later. Equation (2) yields a limit for fast neutrons of 3×10^{10} n/cm^2 and 7×10^{12} n/cm^2 for minimum ionizing particles. These values reflect again the well known fact that fast neutrons are much more damaging than other particles anticipated in high energy experiments.

The literature on radiation effects on semicaonductor devices yields much information on damage constants. However very little is relevant to radiation detectors which are made from very pure material and operate with very low currents. These results must be empirical as they combine a great many variables that affect a materials radiation "hardness." Table I summarizes much of the relevant work for silicon devices.

Some values listed, such as those derived from Srour and van Lint, are derived from silicon devices other than detectors and are taken for the lowest injection levels available; leakage currents should not be large enough to affect the level population. One difference between values for N-and P-type silicon can be explained by noting the assumptions inherent in Eq. (1) which condenses levels near band edges to effective levels near the mid band. Clearly, the effect of levels

Table 1

RADIATION DAMAGE CONSTANT SUMMARY

PARTICLE	DAMAGE CONSTANT K (cm^2/sec)		REFERENCE
	N-Type	P-Type	
Electrons			
3 Mev	$2-10\text{x}10^{-8}$	$3\text{x}10^{-9}$	van Lint[11,14]
4.5 MeV	$1.2-3.7\text{x}10^{-8}$	$1.1\text{x}10^{-8}$	Bielle-Daspet[15]
Muons			
GeV	$\approx 10^{-8}$		Heijne[6]
Neutrons			
Fission	$0.5\text{x}10^{-5}$	$2.5\text{x}10^{-6}$	Srour[16,17]
1 MeV	$1\text{x}10^{-5}$	$2.5\text{x}10^{-6}$	van Lint[11,14]
14 MeV	$2\text{x}10^{-6}$	$0.7\text{x}10^{-6}$	Srour[16,17]
	$1.5\text{x}10^{-6}$	$0.8\text{x}10^{-6}$	Bielle-Daspet[15]
Protons			
20 MeV	$2-10\text{x}10^{-5}$	$1.3\text{x}10^{-5}$	van Lint[11,14]
207 MeV	$5\text{x}10^{-6}$	$2\text{x}10^{-6}$	Bielle-Daspet[15]
590 MeV	$1.2\text{x}10^{-6}$	$0.9\text{x}10^{-6}$	Bielle-Daspet[15]
3 GeV	10^{-6}		Bielle-Daspet[18]
GeV	$\approx 10^{-8}$		Menzione[9]
24 GeV	$3.8\text{x}10^{-8}$		Borgeaud[8]
2 MeV	$2\text{x}10^{-8}$		Grube[19]

which inject or accept charge does depend on their placement in the band gap and therefore a type dependence (at least) should be expected. Also some defect structures are complexes of a physical defect (e.g. vacancy) with a substitutional impurity (e.g. phosphorus) and the resulting effect on lifetime is therefore type-dependent.

Without going into detailed description of the nature of defects from all radiations, it is sufficient to mention that heavy charged particles, neutrons and protons, can impart a large recoil energy to silicon to the extent that the recoil ("primary knock-on") will itself cause many closely-spaced displacements creating "clusters" of damage (as well as some isolated single defects). A cluster is particularly effective in introducing a continuum of mid band levels that are effective for both charge trapping and generation-regeneration current increase. Lightly ionizing particles, electrons and minimum-ionizing particles, cause mainly isolated single defects. The radiations listed in Table I clearly group around damage constants of ≈ 10^{-6} for heavy charged particles and damage constants in the 10^{-8} range for minimum ionizing particles, which illustrates the basic difference in energy transfers and level creation. Variation of the damage constant as a function of particle energy for both protons and neutrons up to 590 MeV, reflect the variation in cross section (which decreases rapidly) times energy transfer (which rises linearly). The value for protons at 2 MeV derived from the data of Grube et al [19] is an apparent anomaly compared with other proton data from several sources which appear to be consistent. The data of Bielle-Daspet[15] is extremely applicable because its source and energy are of direct interest and quite representative. However, only a few float-zone crystals akin to detector grade material were used in this study.

Indications of damage constants for electrons of ≈ 3 MeV are indeed in the low 10^{-8} or high 10^{-9} cm^2/sec range whereas Borgeaud reports[8] data which yield a damage constant of 3.8×10^{-8} cm^2/sec for 24 GeV/c protons. It is of interest that Borgeaud estimates that they may have had a ≈ 1% fast neutron contribution to the flux. Although this K value is not greatly above 1×10^{-8} cm^2/sec it may belie the effect of a fast neutron contribution to the radiation field. It is important to recognize that the radiation field should be well characterized. It may be that other results for minimum ionizing radiation are influenced by an unknown component having very large damage constant. Calculations are underway[20] to consider the neutron albedo from GeV pions impinging on iron and uranium in order to gain an appreciation of the residual fast neutron background in representative geometries.

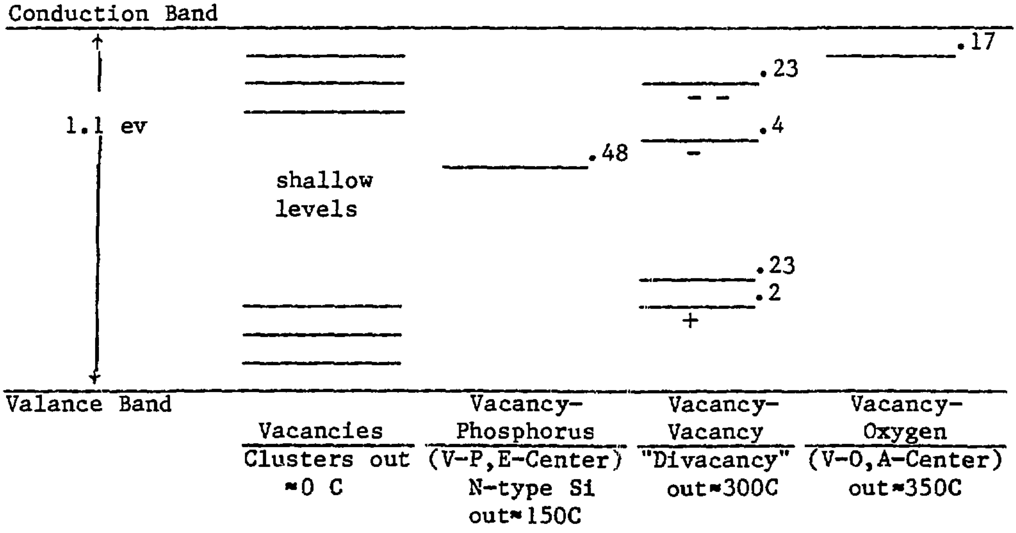
II. ANNEALING

Detectors made with implanted or diffused contacts may withstand elevated temperature cycles which will anneal some defects or damage structures. It may therefore be worthwhile to summarize some annealing properties, which relate to individual level behavior. Surface barrier detectors can not be heated successfully.

Heavy charged particle and fast neutron irradiations produce vacancy clusters which are not completely stable at room temperature but "decay" or migrate to smaller vacancy aggregates, specifically vacancies or single defects[cf 23]. Other structures which can result from a source of vacancies including vacancy (and interstitial) complexes with impurities of inate oxygen or carbon also appear with time after irradiation and more profoundly after a modest heating cycle above room temperature. The appearance of new defects (as well as the disappearance of others) following a heating cycle is often referred to as "reverse" annealing but it is nonetheless a distinct step in the annealing process. Many variations of reverse annealing have been observed which are dependent on the specific material and radiation type.

Irradiation with minimum or lightly ionizing particles produce single isolated defects directly which have less pronounced reverse annealing effects. To illustrate the several single defect levels in the band gap and relative annealing data for which a concensus exists the following level diagram is presented[21,22,23].

SINGLE DEFECT LEVELS



The + and - symbols used on the divacancy levels indicate the charge state of the level when electrically active. All levels participate electrically as traps when ionized or as generation or recombination centers centers when neutral. The annealing effects as a function of temperature are ordered from left to right with clusters annealing first at 0C and vacancy-oxygen structures being among the last to disappear. Divacancies, which are expected to be predominant in pure, float-zone refined, detector-grade material, require at least a 300C anneal. Complexes with oxygen are not expected to be as important in float-zoned materials as they would be in the Czochralski material (which may contain as much as two orders of magnitude more oxygen) of which which many other devices are made. Several of these levels have been identified in the effects reported by several workers including Heijne[6] and Bielle-Daspet[15].

III CONCLUSION

This discussion is an attempt to impart an appreciation for the dominant effects of radiation damage in silicon detectors applicable to high energy physics and to consider the prospects for their anneal. The increase in leakage current often reported can be characterized by a damage constant and adequate data exist to make realisitic predictions of detector behavior if the radiation field is known.

IV ACKNOWLEDGEMENTS

It is a pleasure to thank E. H. M. Heijne, T. W. Ludlam and A. J. Stevens for stimulating discussions and reviews of the subject.

VI REFERENCES

[1] E. Heijne, L. Hubbeling, B. Hyams, P. Jarron, P. Lazeyras, F. Piuz, J. Vermeulen and A. Wylie, Nucl. Inst. & Meth. 178, (1980) 331.

[2] B. Hyams, V. Koetz, E. Belau, R. Klanner, G. Lutz, E. Neugebauer, A. Wylie and J. Kemmer, Nucl. Inst. & Meth. 205, (1983) 99.

[3] S. R. Amendola, et al, Nucl. Inst. & Meth. 176, (1980) 457.

[4] S. R. Amendola, et al, IEEE Trans. Nucl. Sci., NS-30, (1983) 98.

[5] M. Giorgi, this volume.

[6] E. Heijne, Miniaturization of High-Energy Physics Detectors, A. Stefanini, ed., Plenum Press, New York (1983).

[7] H. W. Kraner, T. Ludlam, D. Kraus and J. Renardy, Miniaturizatin of High-Energy Physics Detectors, A. Stefanini, ed., Plenum Press, New York (1983).

[8] P. Borgeaud, J. G. McEwen, P. G. Rancoita and A. Seidman, Nucl. Inst. & Meth., 211 (1983) 363.

[9] A. Menzione in "Silicon Detectors for High Energy Physics," Workshop at Fermilab, T. Ferbel, ed., Oct. 15-16, 1981.

[10] A. S. Grove, Physics and Technology of Semiconductor Devices, John Wiley & Sons, Inc., New York (1967).

[11] V. A. J. van Lint, T. M. Flanagan, R. E. Leadon, J. A. Naber and V. C. Rogers, Mechanisms of Radiation Effects in Electronic Materials, Vol. 1, John Wiley & Sons, New York (1980)

[12] J. R. Srour, S. C. Chen, S. Othmer and R. A. Hartmann, IEEE Trans. Nucl. Sci. NS-26 (1979) 4784.

[13] J. Kemmer, Nucl. Inst. & Meth. 169 (1980) 499.

[14] V. A. J. van Lint, G. Gigas and J. Barengolitz, IEEE Trans., NS-22 (1975) 2663.

[15] D. Bielle-Daspet, Radiation and Damage Defects in Semiconductors, The Institute of Physica Conference Series, No. 16 (1972) London & Bristol, U.K., 129.

[16] J. R. Srour, S. C. Chen, S. Othmer and R. A. Hartmann, IEEE Trans., NS-26 (1979) 4784.

[17] J. R. Srour, IEEE Trans., NS-20 (1973) 190.

[18] D. Bielle-Daspet, Solid State Electronics, 16 (1973) 1102.

[19] R. Grube, E. Fretwurst and G. Lindstrom, Nucl. Inst. & Meth., 101 (1972) 97.

[20] I am indebted to T. A. Gabriel of ORNL for performing the albedo calculations for representative background-producing particles such as 1 and 5 GeV pions incident on iron and uranium. A previous and somewhat similar calculation is available as T. A. Gabriel and R. T. Santoro, ORNL-TM-3437, August 27, (1971).

[21] V. S. Vavilov, B. N. Mukashev and A. V. Spitsyn, in Defects in Semiconductors, Inst. Physics Conf. Series No. 16, Bristol, U.K. (1972).

[22] L. C. Kimerling, in Radiation Effects in Semiconductors, 1976, Inst. Physics Conf. Series No. 31, Bristol, U.K. (1977).

[23] I. D. Konozenko, A. K. Semenyuk and V. I. Khivrich, Radiation Effects in Semiconductors, J. W. Corbett and G. D. Watkins, eds., Gordon & Breach, London (1971).