Multiplication in Silicon p-n Junctions

Moll, John L.

Published in:
PHYSICAL REVIEW

Link to article, DOI:
10.1103/PhysRev.137.A938

Publication date:
1965

Document Version
Publisher's PDF, also known as Version of record

Multiplication in Silicon *p-n* Junctions

JOHN L. MOLL*
The Technical University of Denmark, Lundtofte, Lyngby, Denmark
(Received 17 August 1964)

Multiplication values were measured in the collector junctions of silicon *p-n-p* and *n-p-n* transistors before and after bombardment by 10^{16} neutrons/cm^2. Within experimental error there was no change either in junction fields, as deduced from capacitance measurements, or in multiplication values in any of the transistors. The implication is that the electron and hole ionization rates did not change as a result of the addition of extra scattering centers. This result is in direct contradiction to observations of Lee *et al.* The most likely explanation for the discrepancy is erroneous determination of junction field by Lee *et al.*

IN a recent article, Lee *et al.*[1] present results on carrier ionization rates in silicon that clarify much of the confusion that has existed in the literature on this subject. There is one suggested phenomenon that is raised which is of questionable validity. In particular, it is suggested that some epitaxial *p-n* junctions exhibit a much lower ionization rate than nearly perfect crystals.

We have observed that the conversion of multiplication data into ionization rates on small area *p-n-p* or *n-p-n* transistors tends to result in lower ionization rates than are obtained from large area devices. Careful examination of the small junctions invariably revealed a stain boundary far down on the edge of the mesa or even on the etched silicon surface. Use of the stain boundary to determine junction area in all cases brought the ionization rate into reasonable agreement with the values given by Lee *et al.* for "good" crystals.

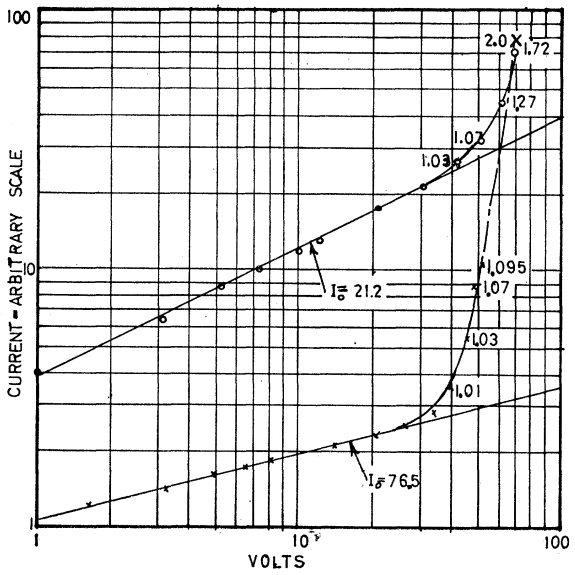

FIG. 1. Logarithmic plot of increment of collector current versus collector voltage. The current that is plotted is $I-I_0$, where I_0 is chosen to make the data points fall on a straight line at low voltages. The data are for a *p-n-p* transistor before and after bombardment. The numbers adjacent the points are values of multiplication. Before bombardment, it was only possible to measure M values up to 1.095, and the point that is marked 2.0 is an extrapolation from known ionization rates and the multiplication at lower voltage.

The epitaxial junctions of Ref. 1 were prepared by diffusion through windows in an oxide mask. If the actual effective diameter of the windows was 12 mil rather than the reported 10 mil, the ionization rates are adjusted back to the values reported for good crystals. These junctions were made before the technology of the use of photoresist on semiconductors reached its present state of exactness.

We have performed some experiments that are in direct contradiction to the assertion that the extra scattering centers in imperfect crystals results in lower ionization rates. The multiplication values and collector junction capacitance of diffused base, diffused emitter *n-p-n* and *p-n-p* silicon transistors were measured before and after bombardment with approximately 10^{16} neutrons/cm^2. Neither the multiplication values nor the junction capacitance of the *p-n-p* changed. There was a fraction of a percent decrease in the collector capacitance and there may have been a slight increase in the multiplication factors in the *n-p-n* transistors. Both of these changes tend to increase the ionization rate at a given electric field.

There is some uncertainty in the interpretation of the multiplication factors since only values close to unity were measured for comparison, and there is a change in collection efficiency with collector voltage in the junction transistor. The latter factor changed somewhat as a result of bombardment. Figure 1 shows the method of accounting for the change in collection efficiency with voltage. The transistor bases showed no tendency towards punch-through. In such a case, it is to be expected that the transport efficiency vary as a fractional power of the collector voltage, or

$$I_c = I_0 + kV^{1/n}, \tag{1}$$

where I_0 is ideally the current that would be collected if the collector junction had zero width. In some simple models, n varies from 2 to 3, and k is just a small constant.

We found that before bombardment, $n=3$ and after bombardment when the α_{ce} was reduced from about

* Permanent address: Stanford University, Stanford, California.
[1] C. A. Lee, R. A. Logan, R. L. Batdorf, J. J. Kleimack, and W. W. Wiegmann, Phys. Rev. **134**, A761 (1964).

0.98 to about 0.05 that $n=2$. The multiplication was taken as the ratio of the actual collector current to the value obtained by extrapolating (1) into the multiplication range. As can be seen in the particular example shown, there is little change in M before and after bombardment.

It is well known that bombardment by 10^{16} neutrons/cm^2 produces a very pronounced decrease in mobility as well as recombination time.[2] Lee *et al.* indicate almost a 50% increase in the field at which a given ionization rate is obtained in some epitaxial material. In a graded collector, a 50% increase in field requires an increase of about 60% in collector voltage. Thus a change in ionization rate tends to be slightly magnified on the voltage scale in the resulting multiplication versus voltage. A change of 10% in the field at which a given ionization rate is obtained will be readily seen in our experiment.

We must conclude either that the experiments of Lee *et al.* were erroneous—possibly with respect to determination of area, or else the scattering centers in their crystals have an effect on hot-electron scattering that is not exhibited by neutron damage. It seems that the former explanation must be given serious consideration: particularly since the theory of scattering of charge carriers by charged centers shows that the scattering cross section decreases as the fourth power of the electron or hole velocity.

The possibility that ionization rates are different in different crystals of the same substance must certainly be recognized. There is the possibility that the ionization rates are either greater or less than in the perfect crystal and any instance that is well documented is of interest.

[2] J. W. Cleland and J. H. Crawford, J. Appl. Phys. **29**, 149 (1958).

PHYSICAL REVIEW VOLUME 137, NUMBER 3A 1 FEBRUARY 1965

Temperature Dependence of Positron Mean Lives in Polymers*

B. C. Groseclose† and G. D. Loper‡§
Department of Physics, Oklahoma State University, Stillwater, Oklahoma
(Received 11 September 1964)

The mean lives and intensities of positrons decaying by the pickoff mechanism in polystyrene, Lucite, and polyethylene (Marlex 50) have been measured in the temperature interval −200 to +150°C. The mean-life variation with temperature in both polystyrene and Lucite has the same general shape as the specific-volume variation of these materials and may be interpreted as a free-volume effect. However, an observed sharp drop of τ_2 with decreasing temperature below −20°C in Marlex 50 does not correspond to the smooth change in volume of this material in that temperature range.

I. INTRODUCTION

THE decay of positrons in molecular materials is complex, consisting of a short lifetime of the order of 10^{-10} sec due to annihilations from the free state and the bound state of singlet positronium, and a longer lifetime of the order of 10^{-9} sec due to pickoff annihilation from the bound state of ortho-positronium.[1] This latter mean-life component, called τ_2, depends on the amount of positron-lattice electron wave function overlap, and may be expected to give some information about internal structure. The τ_2 component is temperature-dependent, the lifetime increasing with increasing temperature.[2] This effect has been qualitatively explained by saying that greater molecular motion and molecular separations provide more room for the positronium atoms and make pickoff annihilation less likely.[3] A theoretical expression for τ_2 as a function of free volume has been derived and has had some success in fitting experimental data.[4] Most of the pertinent results have been summarized in a review article by Wallace.[5] The purpose of this investigation was to measure τ_2 and the intensity of this component I_2 in the polymers polystyrene, Lucite, and Marlex 50 in the temperature interval −200 to +150°C, and to correlate this behavior with known changes in other physical properties.

II. EXPERIMENTAL PROCEDURE

The measurements were carried out with typical fast-slow coincidence apparatus, including Nuclear Enterprises NE 102 plastic phosphors, Amperex 56AVP

* Research supported in part by the U. S. Army Research Office, Durham.
† Present address: Lawrence Radiation Laboratory, University of California, Livermore, California.
‡ This paper is part of a thesis submitted as partial fulfillment of requirements for Ph.D. in physics at Oklahoma State University, Stillwater, Oklahoma.
§ Present address: Wichita State University, Wichita, Kansas.
[1] R. A. Ferrell, Rev. Mod. Phys. **28**, 308 (1956).
[2] R. E. Bell and R. L. Graham, Phys. Rev. **90**, 644 (1953).
[3] P. R. Wallace, Phys. Rev. **100**, 738 (1955).
[4] W. Brandt, S. Berko, and W. W. Walker, Phys. Rev. **120**, 1289 (1960).
[5] P. R. Wallace, *Solid State Physics*, edited by F. Seitz and D. Turnbull (Academic Press Inc., New York, 1960), Vol. 10, p. 1.