GAMMA IRRADIATION OF LITHIUM DRIFTED *p-i-n* JUNCTIONS IN SILICON

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p-i-n JUNCTIONS

In the present experiment the effects of gamma irradiation on silicon were studied using lithium drifted *p-i-n* junctions.

The initial material [2] is float zoned single crystal silicon, which is *p*-type, boron doped, with a resitivity of (100 ± 25) Ωcm. The minority carrier lifetime of the silicon is at least 200 µsec ; the concentration of oxygen [3] is below 6×10^{15} atoms. cm^{-3}, while the etch pit density [4] was found to be $(30\,000 \pm 5\,000)$ cm^{-2}.

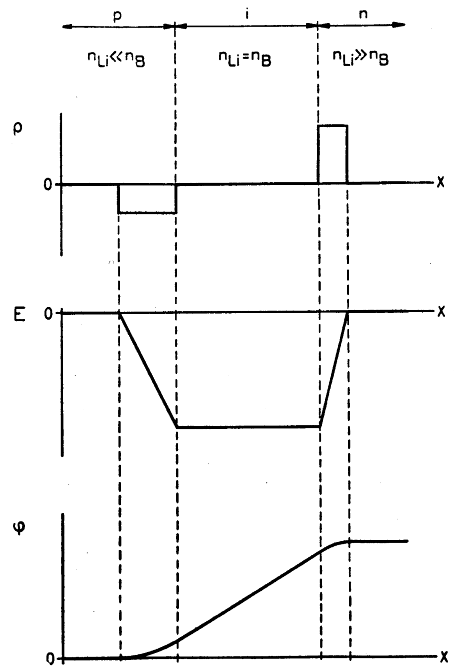

FIG. 1. — Space charge ρ, electric field E and potential φ against position x in a reverse biased *p-i-n* junction. n_{Li} = lithium concentration, n_B = boron concentration.

From this material cylindrical shaped slices are cut, with a diameter of 23 mm and a thickness of 2.5 mm, parallel to a { 111 } plane.

Detailed information about the principle of the ion drift process and its application to the production of *p-i-n* junctions are given in references 5 to 7. The electric characteristics of the *p-i-n* junctions under reverse bias are illustrated in figure 1. No space charge exists in the 1 mm wide intrinsic region. This region is very sensitive to radiation damage, because charged centers eventually produced by the radiation, alter the characteristics of the junction appreciably.

IRRADIATION

The *p-i-n* junctions were irradiated with the gamma-rays of a ^{60}Co source, which emits equal numbers of 1.17 and 1.33 MeV photons.

Irradiations are performed at room temperature, (7 ± 1) °C, during a 100 hour period, with the slice at a distance of 5 cm from an 8 Curie source; the dose was then 8.3×10^{14} ($\pm$ 10 %) photons. cm^{-2}. No reverse bias is applied across the junction during this period.

EXPERIMENTAL METHOD

The experimental approach to the determination of irradiation effects was made by capacity measurements. Figure 2 shows an illustrative set of measurements of the capacity of the junction versus the applied reverse bias. Some comment upon these results will be given now. The measurements labelled *a* belong to the original *p-n* junction, which exists after the lithium has been diffused into the slice, but before lithium ion drift has been carried out. Because the space charge in this narrow junction has constant gradient, the capacity is proportional to $V^{-1/3}$.

Capacity measurements on the *p-i-n* junction give the result *b*. Since the thickness of a wide *p-i-n* junction is only slightly dependent on the reverse bias, also the capacity is nearly constant. The drawn lines in *a* and *b* are calculated. Apart from quantities such as time and temperature for lithium diffusion and lithium ion drift, the calculations involve the area A of the junction. The value $A = 4.29$ cm^2, which was measured from the dimensions of the slice, proves to yield the proper results.

Immediately after the gamma irradiation a capacity-voltage characteristic like *c* is found. The increase of the capacity indicates that the junction width for a given value of bias has decreased, therefore that space charge is created.

Since the gamma-rays create uniform damage, a uniform space charge in the former *i*-region is expected. For the lower values of reverse bias, the relationship $C \propto V^{-1/2}$, valid for junctions with constant space charge, is indeed found. For the higher values of reverse bias, the junction is depleted to the width of the *p-i-n* junction before irradiation. The capacity curve *c* then coincides with curve *b*.

After the irradiation the junction behaves like a p^+-p-n^+, or p^+-n-n^+, junction. The sign of the space charge cannot be deduced from capacity measurements.

The same behaviour is shown by the curves *d*1, *d*2 and *d*3, which are measured in this sequence in a period of 3 weeks after the irradiation. During this period the junction was kept at room temperature, under a bias large enough to deplete the whole junction. The decrease of capacity as function of time, exhibited by the curves *d*, shows that the space charge in the junction decreases. During this recovery process the space charge remains uniformly distributed over the former *i*-region. From

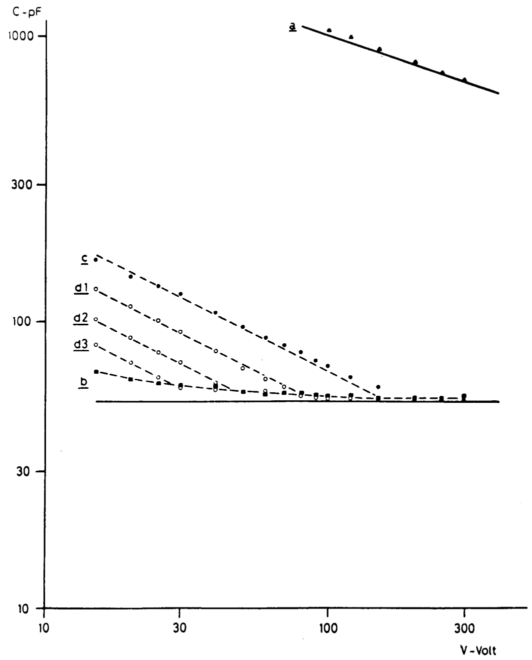

FIG. 2. — The capacity C as function of the reverse bias V for
a : p-n junction, before lithium ion drift (▲),
b : p-i-n junction, after lithium ion drift, before irradiation (■).
c : p^+-p-n^+ junction, immediately after the irradiation (●),
d : p^+-p-n^+ junction, successive times after the irradiation (○).

the capacity-voltage measurements, at the lower values of the reverse bias in the cases c and d, the space charge or ion density n may be calculated through the formula

$$n = \frac{2 \cdot C^2 \cdot V}{q \cdot \varepsilon \cdot A^2}$$

in which C = capacity, V = reverse voltage, q = electron charge, ε = dielectric constant of silicon ($\varepsilon_r = 11.8$) and A = area of the junction.

EXPERIMENTAL RESULTS

The time dependence of the ion density in a reverse biased junction at room temperature (19 ± 1) °C, after gamma irradiation, is shown in figure 3.

When no reverse bias is applied to the junction, some increase of the junction capacity, instead of anneal, is observed.

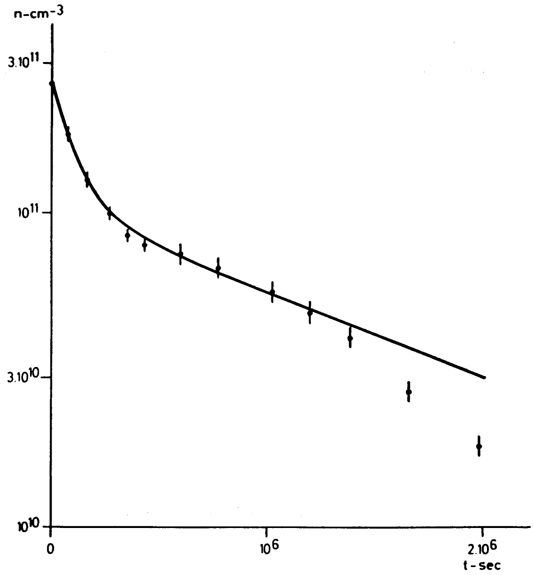

FIG. 3. — The time dependence of ion density n in a reverse biased junction at room temperature after irradiation.

MODEL

A good deal of the observed phenomena may be understood on the basis of the following tentative model :

1. Electrons, with energies up to about 1 MeV, are produced by the Compton process.

2. The electrons create vacancies and interstitial atoms in collision processes with silicon atoms.

3. Already at temperatures below room temperature the primary irradiation defects, have sufficient mobility to diffuse over large distances in the lattice [8]. A process known to occur with high probability is capture of a vacancy by dissolved oxygen, by which A-centers, stable at room temperature, are created. An A-center production rate of approximately 10^{-3} defects.cm^{-3}/photon.cm^{-2} is found in both quartz crucible grown and float zoned silicon [9]. The assumption that in our samples A-center production takes place to the same extent is supported by the fact that phosphorus, and other pentavalent impurities, are certainly only present in concentrations much smaller than 10^{14} atoms.cm^{-3}. This excludes a serious competition for vacancy capture by E-center formation. The amount of defects found in our work is, moreover, well consistent with the cross-sections reported in the literature.

The electron acceptor level at $E_c - 0.17$ eV, associated with the A-center, will be unoccupied, since in the near intrinsic material the Fermi level is below this value. The A-center therefore carries no charge.

4. In the experiments of Vavilov, Smirnova and Chapnin it was shown that lithium ions interact with the A-center [10] and other radiation produced defects [11]. The perturbation by the near positive lithium ion pushes the (E_c − 0.17 eV) acceptor level of the A-center downwards below the Fermi level. The complex center therefore captures an electron, becoming again a neutral defect. Because of the compensation of the positive lithium ions by the captured electrons, a negative space charge, due to excess boron ions, is set up.

Reiss, et al [12], derived a formula for the time constant associated with pairing reactions. They find

$$\tau_2 = \frac{1}{4 \, . \, \pi \, . \, n \, . \, R \, . \, D} \tag{1}$$

in which n and D are concentration and diffusion constant, resp., of the mobile species, R is an effective reaction radius and τ_2 the relaxation time. Since in the interaction of lithium ions and A-centers no long range forces are present, R must be of interatomic dimensions. The process gives rise to space charge generation, describable by the formula

$$\frac{d\rho}{dt} = G \, . \, \exp(-\, t/\tau_2)\,,$$

where G, the generation rate at $t = 0$, is time independent.

5. The adjustment of the electric field in the junction region to the space charge, gives rise to a space charge neutralization process.

A general, quantitative treatment of this process is given as follows. The electric field $\boldsymbol{E}$, caused by a space charge ρ, is related to the latter by the Maxwell equation

$$\operatorname{div} \boldsymbol{E} = \rho/\varepsilon \, .$$

The electric field gives rise to a flow of lithium ions, which transports an electric current $\boldsymbol{J}$, given by

$$\boldsymbol{J} = q \, . \, n_{\mathrm{Li}} \, . \, \mu_{\mathrm{Li}} \, . \, \boldsymbol{E}\,,$$

when n_{Li} is the concentration of the lithium ions and μ_{Li} their drift mobility in silicon. The variation of space charge, caused by the transport of charge $\boldsymbol{J}$, is governed by the continuity equation

$$\frac{d\rho}{dt} + \operatorname{div} \boldsymbol{J} = 0\,.$$

Elimination of $\boldsymbol{E}$ and $\boldsymbol{J}$ from the above relations yields the expression

$$\frac{d\rho}{dt} = -\,\frac{n_{\mathrm{Li}} \, . \, q \, . \, \mu_{\mathrm{Li}} \, . \, \rho}{\varepsilon}\,.$$

This equation has the solution

$$\rho(t) = \rho(0) \, . \, \exp(-\, t/\tau_1)\,,$$

with

$$\tau_1 = \frac{\varepsilon}{n_{\mathrm{Li}} \cdot q \cdot \mu_{\mathrm{Li}}},$$

when the quantity n_{Li} does not change appreciably during the space charge neutralization process.

The ionic relaxation time τ_1 is the exact analogue of the dielectric relaxation time, governing electronic transients in dielectrics. Elimination of the lithium mobility by use of the Einstein relation gives

$$\tau_1 = \frac{\varepsilon \cdot k \cdot T}{n_{\mathrm{Li}} \cdot q^2 \cdot D_{\mathrm{Li}}} \qquad (2)$$

identical with the relaxation time in ion pairing processes [12].

DISCUSSION

In the model, sketched in the previous paragraph, the steps 4 and 5 are associated with the motion of lithium ions. These steps therefore may give rise to property changes in easily observable times at room temperature, while processes 1 to 3 are almost instantaneous. The space charge generating step 4 is always acting; on the other hand space charge recovery only occurs when reverse bias is applied. The model is in agreement therefore with the experimental facts, that,

1. long relaxation times are only observed, when lithium is introduced into the samples [10,11],
2. in the present experiment space charge increases when no bias is applied.

During the irradiation no bias is applied and space charge is built up by the processes 1 to 4. When after the irradiation the junction is reverse biased, process 5 comes into action, and the space charge decreases. After some time a space charge level is reached where space charge generation and anneal equilibrate. The time dependence of the space charge level is then governed by the longer relaxation time τ_2 associated with process 5.

The space charge variation is governed by the equation

$$\frac{d\rho}{dt} = G \cdot \exp(-\, t/\tau_2) - \frac{\rho}{\tau_1},$$

where the first term on the right represents the generation process 4 and the second term the recovery process 5.

Solution of this equation is the function

$$\rho(t) = \rho(0) \cdot \{\, \alpha \cdot \exp(-\, t/\tau_1) + (1 - \alpha) \cdot \exp(-\, t/\tau_2) \,\},$$

which was applied to fit the experimental data. The drawn line in figure 3 represents this curve for parameter values $\tau_1 = 30$ hours and $\tau_2 = 450$ hours. The experimental result $\tau_1 = 30$ hours compares well with the theoretical value from (2), as can be seen taking D_{Li} (19 °C) = 1.25×10^{-14} cm^2 . sec^{-1} from Pell's [13] data and $n_{Li} = 1.25 \times 10^{14}$ cm^{-3}.

For the relaxation time associated with process 4 was found experimentally $\tau_2 = 450$ hours. Theory provides relation (1)

$$\tau_2 = \frac{1}{4 \,.\, \pi \,.\, n_{Li} \,.\, R \,.\, D_{Li}}\,.$$

Substituting the same values for n_{Li} and D_{Li} as above, the capture radius for the interaction between a lithium ion and an A-center proves to be $R = 3.1$ Å which is certainly of correct order of magnitude.

ACKNOWLEDGMENTS

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DISCUSSION

Question n° 1 (P. H. Fang).

In the evaluation of the drift effect, does one have to take the two following factors into account ?

(1) The majority carrier distribution, especially near the boundaries of *p-i* and *i-n*.

(2) The differences of the position of conduction bands from the Fermi level in the three regions, *p*, *i*, *n*.

Answer :

The interpretation of the capacity-voltage characteristics is based on the Schottky model. The total reverse bias is the sum of the built-in diffusion potential and the externally applied bias.

Comment (W. L. BROWN) :

Coleman at Bell Laboratories has also much measurements on γ radiation of lithium drift detectors, though not with the same purpose. He finds that the net space charge added by radiation is negative, as by addition of acceptors.

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