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Lifetime of Electrons in p-Type Silicon

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The dependence of lifetime of electrons on temperature in p-type silicon can be explained on the basis of the Shockley-Read-Hall theory by assuming a level for the recombination centers at 0.2 ev from the valence band. The variation of lifetime with injected carrier density can also be explained by the same model.

1. INTRODUCTION

Measurements described in this paper of minority carrier lifetime in the vicinity of a silicon p-n junction show that lifetime is a function of both minority carrier density and temperature. These experiments provide an indication of the processes involved in the recombination of holes and electrons. The results are consistent with the Shockley-Read-Hall theory of recombination centers.[1,2]

2. THEORY

The Shockley-Read-Hall theory of electron-hole recombination in semiconductors explains why lifetimes observed in germanium and silicon are several orders of magnitude shorter than those predicted from direcs electron hole recombination. The model employed it shown in Fig. 1. It assumes that recombination takes place through the agency of imperfections of some sort in the crystal.

The recombination process can be characterized by the concentration of centers N_t, the energy level of centers E_t, the thermal densities of electrons and holes n_0 and p_0, and the capture constants for holes and electrons $C_p=1/\tau_{p0}$ and $C_n=1/\tau_{n0}$. τ_{p0} is the lifetime for holes injected into high-conductivity n-type specimen, τ_{n0} is similarly the lifetime of electrons in high-conductivity p-type specimen. C_n and C_p are assumed constant in the temperature range investigated.

For small values of injected carrier density δn the theory gives for the lifetime τ_0:

$$\tau_0=\frac{\dfrac{1}{C_p}(n_0+n_1)+\dfrac{1}{C_n}(p_0+p_1)}{n_0+p_0}, \tag{1}$$

where

$$n_1=N_c e^{(E_t-E_c)}/kT$$

and

$$p_1=N_v e^{(E_v-E_t)}/kT$$

represent the numbers of electrons and holes in the conduction and valence bands for the case in which Fermi level falls at E_t, and N_c and N_v are the effective densities of states in the conduction and valence bands, respectively. For large values of injected carrier densities δn Shockley and Read obtain:

$$\tau=\tau_0\frac{\left(1+\dfrac{\delta n(\tau_{p0}+\tau_{n0})}{\tau_{p0}(n_0+n_1)+\tau_{n0}(p_0+p_1)}\right)}{1+\dfrac{\delta n}{n_0+p_0}}. \tag{2}$$

Equations (1) and (2) provide means for determining the energy level of the recombination centers and the ratio of capture cross sections for electrons and holes assuming that all the centers lie at a single energy level within the energy gap.

3. EXPERIMENT

The junction recovery time[3] method of measuring lifetime was used in our experiments. This type of measurement yields results depending upon the carrier density within one diffusion length from the p-n junction. By using p-n grown junctions of large cross section one may observe lifetime very close to the body lifetime even in the presence of high surface recombination velocity. Each specimen used was cut from a p-n grown junction crystal and etched in CP-4 to a size of 0.100 in.×0.100 in.×0.500 in. The resistivity of the p side was 50 to 100 times higher than that of the n side. This disparity insured predominating injection of electrons from the low resistivity to the high-resistivity side. The electron lifetime was then measured on the high-resistivity side of the junction.

The effects of the space-charge region of the junction have been neglected in view of the large ratio of injected carrier density to the capacitance current density.[3] Some of the crystals were rejected when the oscilloscope trace indicated more than one time con-

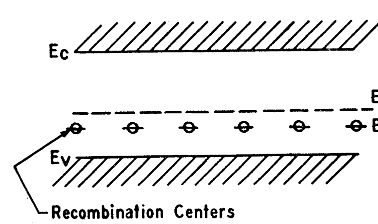

Fig. 1. Model for the recombination of electrons and holes.

[1] W. Shockley and W. T. Read, Phys. Rev. **87**, 835 (1952).
[2] R. N. Hall, Phys. Rev. **87**, 387 (1952).
[3] B. Lax and S. Neustadter, J. Appl. Phys. **25**, 1148 (1954).

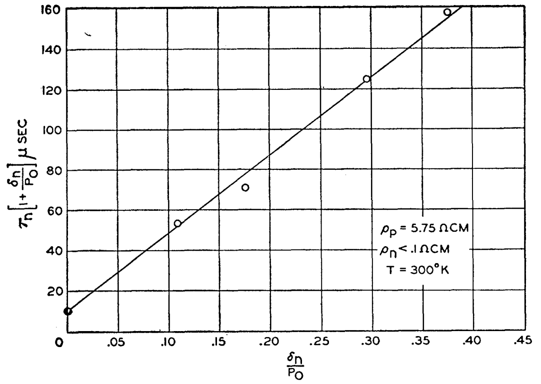

FIG. 2. Lifetime in p-type silicon *vs* injected electron density.

stant. This could have been due to defective junctions or to high trap densities near the junctions.[4] There was no indication of traps in the specimens retained for our experiment; the lifetimes were not sensitive to dc light and were found to decrease with the cross sections of the samples according to theory.[5]

4. RESULTS

Typical measurements of lifetime as a function of injected carrier density are shown in Fig. 2. Similar results have been obtained on samples from different crystals with resistivities of the p sides varying between 1 and 15 ohm-cm. The data are plotted as $\tau_n(1+\delta_n/p_0)$ *vs* $\delta n/p_0$ to facilitate comparison with theory (next section). The points have been taken at a temperature of 300°K. Figure 3 shows the points obtained in measuring lifetime *vs* inverse absolute temperature.

5. DISCUSSION

To interpret the data of Fig. 2 one can use a simplified form of Eq. (2). In view of the result described farther on and indicating that the recombination centers are located in the lower half of the energy gap, we assume that p_1 is larger than n_0 and n_1; τ is then given by:

$$\tau_n = \frac{\tau_0\left(1+\dfrac{\delta n(\tau_{p0}+\tau_{n0})}{\tau_{n0}(p_0+p_1)}\right)}{1+\dfrac{\delta n}{p_0}} = \frac{\tau_0(1+a\delta n)}{1+\dfrac{\delta n}{p_0}}.$$

A plot of $\tau_n[1+(\delta n/p_0)]$ *vs* $\delta n/p_0$ gives a straight line with a positive slope if $a>1/p_0$. Figure 2 confirms this relation, the value of "a" being about 10^{-14} cm^{-3} while $1/p_0=4.10^{-16}$ cm^{-3}. It is impossible to obtain the cross section for electron capture from this expression as neither τ_{n0} nor τ_{p0} is known. It can be estimated, however, that the ratio $\tau_{p0}/\tau_{n0}=C_n/C_p$ is considerably larger than unity. This would indicate that the cross section of the empty traps for an electron capture is higher than that of occupied traps for capture of a hole. It is interesting to note that Burton[6] has found, in the case of copper and nickel recombination centers in germanium, a result opposite to ours.

The experimental points in Fig. 3 can be fitted by an empirical expression of the form:

$$\tau_0=\tau_{n0}+Ce^{-(E_t/kT)}.$$

If the recombination centers lie in upper half of the gap, Eq. (1) would give

$$\tau_0=\tau_{n0}+\tau_{p0}(n_1/p_0),$$

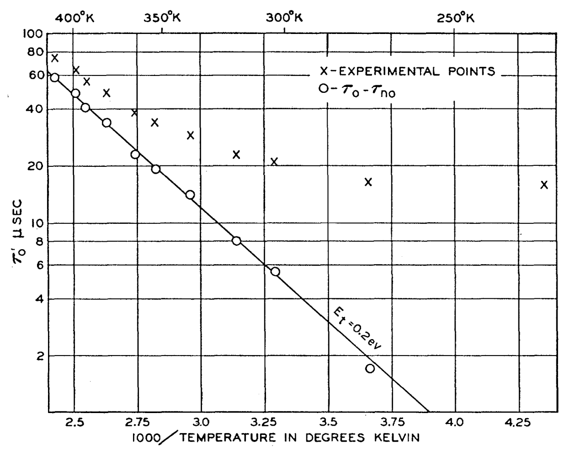

FIG. 3. Lifetime in 20Ω-cm p-type silicon *vs* $1000/T$. The slope of $\tau_0-\tau_{n0}$ gives the level of recombination centers within the energy gap.

and since $\tau_{p0}\gg\tau_{n0}$ and $n_1\geq p_0$,

$$\tau_0\approx\tau_{p0}(n_1/p_0).$$

For centers in lower half of the gap ($p_1\gg n_1$),

$$\tau_0=\tau_{n0}[1+(p_1/p_0)]=\tau_{n0}+Ce(E_v-E_t)/kT,$$

in agreement with the experimental data. Taking $\tau_{n0}=15$ μsec and plotting $\log(\tau_0-\tau_{n0})$ *vs* $T/1000$ gives a straight line. The slope corresponds to $E_t=0.2$ ev.

ACKNOWLEDGMENTS

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[5] W. Shockley, *Electrons and Holes in Semiconductors* (D. Van Nostrand Company, Inc., New York, 1950).
[6] Burton, Hall, Morin, and Severiens, J. Phys. Chem. **57**, 853 (1953).