Recombination of Electrons at Ionized Donors in Silicon at Low Temperatures*

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Recombination cross sections for electrons at ionized, group-V donors in silicon have been measured between 1.5 and 20 K. The results are in good agreement with the theoretically predicted temperature dependence above 4 K, although the magnitude of the experimental cross section is larger by more than 2 orders of magnitude.

In this Letter we report new measurements of the magnitude and temperature dependence of the recombination cross section for electrons at ionized donor impurity centers in silicon. Earlier experimental results of Levitt and Honig[1] reported recombination cross sections which varied as $T^{-0.5}$, in disagreement with theoretical predictions of a T^{-1} to $T^{-1.5}$ dependence for ionized impurity capture as calculated by Brown and Rodriguez.[2] Attempts to reconcile this disparity led to several proposed explanations. Experimental difficulties including a question of hot carriers due to photoexcitation[3] ($\lambda = 2$ μm)[3] or substantial Hall-factor corrections[4] have been suggested. Other attempts have sought the explanation in terms of complications from impurity hopping conduction[3] not accounted for by theory, or the proposal that neutral impurity capture, rather than ionized, was dominating the recombination process.[5] We have resolved this discrepancy by measurements on less-compensated samples over a wider range of temperatures. The theoretical and experimental temperature dependences are now in good agreement, indicating that the giant trap mechanism of ionized impurity recombination[6] is valid for n-type silicon, a point which has been in question for over ten years.

The experimentally determined cross section is defined as $\sigma = (\tau\langle v\rangle N^+)^{-1}$, where $\langle v\rangle$ is the thermal carrier velocity, τ is the carrier lifetime, and N^+ is the density of ionized donors. Cross sections were determined by measuring the carrier lifetime at about 10 and 20 K for five samples, having doping densities listed in Table I. The cross sections are shown in Fig. 1, along with the earlier experimental results of Levitt and Honig. Carrier lifetimes were measured from the signal decay of a photoconductive response produced by a pulsed CO_2 laser.[7] $N^+ = N_a + n$ was determined from analysis of Hall measurements and resistivity of the sample under experimental conditions. The carrier density was always small compared to the density of donors ionized by compensation. At the same time, however, sufficient background laser intensity was provided so that the sample resistivity did not exceed 1000 Ω cm. Thus, lifetimes

TABLE I. Summary of sample properties.

Sample	N_d (cm^{-3})	N_a (cm^{-3})
Si:Sb No. 1[a]	7.4×10^{15}	5.3×10^{12}
Si:P No. 1[a]	9.5×10^{15}	4.2×10^{12}
Si:P No. 5[b]	3.3×10^{14}	8.6×10^{12}
Si:P No. 6[a]	4.3×10^{13}	7.7×10^{12}
Si:As No. 1[a]	1.4×10^{16}	6.0×10^{12}
Si:As No. 3[c]	7.5×10^{16}	1.8×10^{13}

Sample obtained from [a]D. Thornton and A. Honig, [b]J. Stannard, [c]N. Sclar.

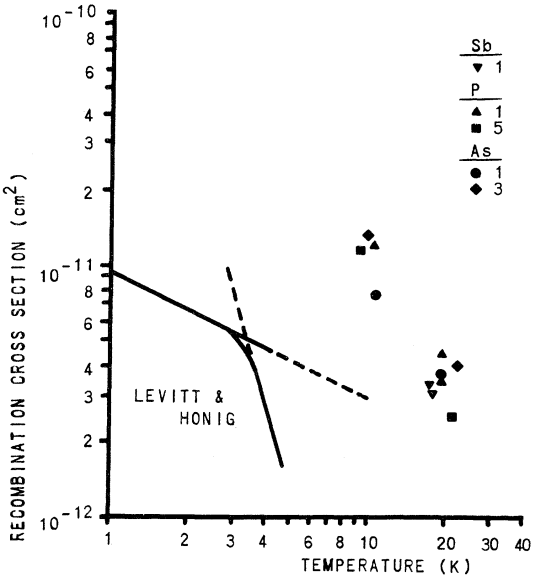

FIG. 1. Recombination cross section for five silicon samples, whose properties are listed in Table I. Also shown are cross-section results of Levitt and Honig (Ref. 1) between 1 and 4 K on more heavily compensated samples.

on the order of several nanoseconds could be measured without interference from dielectric relaxation effects. At 10 K, our measured lifetimes were between 1.2 and 6 nsec.

The theoretical model used by Brown and Rodriguez considers initial capture into excited, hydrogenic s states, followed by cascade phonon-assisted transitions to either the ground state or back to the conduction band. Their cross section is defined as

$$\sigma_r = \sum_{n=2}^{7} \sigma_c(n) P_n ,$$

where $\sigma_c(n)$ and P_n are the capture cross sections and sticking probabilities of the nth s state. They have computed values of σ_r between 2 and 10 K. From photo-Hall measurements[8] we have also determined the dependence of lifetime on temperature, down to about 1.5 K. Normalizing this relative measurement to the pulse-decay measurements at 10 and 20 K, we can compare the theoretical temperature dependence predicted by Brown and Rodriguez to our results below 10 K. This is done in Fig. 2, using the photo-Hall data from our two purest samples, Si:P Nos. 5 and 6. The theoretical curve has been shifted up by a factor of 125 for this comparison. Good agreement in temperature dependence is seen down to 4 K. Below this temperature the photoexcited carriers are unable to thermalize before they are captured and comparison cannot be made to the theory which assumes thermal carriers.[9] This same difficulty is more serious in the experiments of Levitt and Honig, since the compensation densities of their samples were larger (2×10^{13} to 2×10^{16} cm^{-3}) than those reported here, implying lifetimes much shorter than thermalization times.

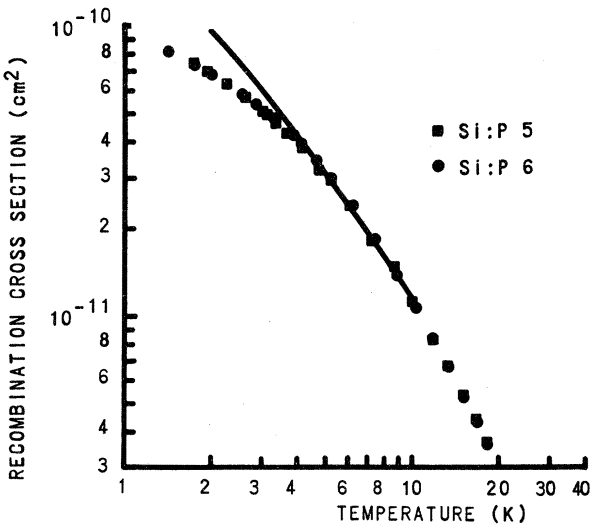

FIG. 2. Comparison of the theoretical temperature dependence of the cross section calculated by Brown and Rodriguez (Ref. 2), shown as a solid line, with the experimental temperature dependence obtained from photo-Hall measurements normalized to Fig. 1 at 20 K. Experimental points are for two samples, Si:P Nos. 5 and 6. The absolute magnitude of the theory lies a factor of 125 lower than shown.

Disagreement in magnitude between experiment and theory, although large, is not thought to be due to a basic conceptual error in the recombination model. The calculations of Brown and Rodriguez were made with parameters chosen deliberately to minimize the cross-section magnitude. According to Brown,[10] the dependence of the cross-section magnitude on very high powers of some parameters can explain the discrepancy in magnitude. Obviously, this contention should be tested with new calculations. No attempt has yet been made to include the effects of anisotropy, p states which are highly degenerate, or delayed reionization of trapped carriers. Excited states with principal quantum number higher than 7 may also be important, since the sticking probabilities are close to unity for n between 2 and 7 in silicon below 10 K. Overlap of highly excited states with neighboring capture centers should also be considered. New techniques, such as Monte Carlo simulation, can perhaps absorb the increased computational difficulty of these refinements in theory.

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[1]R. S. Levitt and A. Honig, J. Phys. Chem. Solids 22, 269 (1961).

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[3]R. A. Brown, Phys. Rev. 148, 974 (1966).

[4]J. R. Barker and C. J. Hearn, Phys. Lett. 26A, 148 (1968).

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[6]M. Lax, Phys. Rev. 119, 1502 (1960).

[7]P. Norton and H. Levinstein, Phys. Rev. B 6, 489 (1972). The experimental details and apparatus are descibed here, except that a much faster preamplifier has been obtained for this present work.

[8]We assume $n = G\tau$ and that G, the optical generation rate, is independent of temperature. 300-K radiation was used to excite the carriers.

[9]Thermalization in silicon, assuming energy loss via phonon emission, requires about 5×10^{-10} sec at 4 K, and 1×10^{-9} sec at 1 K. See P. Norton and H. Levinstein, Phys. Rev. B 6, 478 (1972).

[10]The temperature dependence will not change significantly with variations of these parameters, chiefly the velocity of sound and deformation potential; R. A. Brown, private communication.