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Energy Levels in Neutron-Irradiated *n*-Type Silicon

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Pulsed-field effect experiments have been performed on neutron-irradiated *n*-type silicon samples with the aim of detecting deep-lying radiation-induced energy levels and estimating their electron capture cross sections. These experiments provide evidence in favor of two, deep-lying states in the upper part of the energy gap, at 0.15 ev and 0.37 ev below the conduction band edge. The electron capture cross sections associated with these two levels strongly suggest that both are acceptor-like.

WERTHEIM[1] has recently reported on an investigation of the energy level structure in neutron-irradiated silicon. Two ohm-cm phosphorus-doped *n*-type samples were exposed to integrated fission neutron fluxes of the order of 10^{14} or less per cm^2. From the behavior of the Hall coefficient as a function of temperature, it was deduced that neutron bombardment of silicon gives rise to a spectrum of energy levels running from 0.16 ev below the conduction band toward the middle of the gap. On the other hand, infrared absorption experiments performed by Fan and Ramdas[2] on various irradiated *n*-type specimens revealed the existence of three sharp bands only, at 1.8, 3.3, and 5.5 microns, of which at least two were also found after electron bombardment. Such a state of affairs was interpreted as suggesting that, insofar as the basic location of the energy levels is concerned, electron and neutron bombardment damage should be equivalent.[3] In the upper part of the energy gap of electron-irradiated silicon, two discrete deep-lying electron trapping levels have been detected: one at about 0.16 ev from the conduction band ($E_c-0.16$ ev) and another one at $E_c-0.36$ ev.[4] The purpose of this note is to present evidence that similar levels do also exist in neutron-irradiated silicon.[5]

Our samples were cut from a 15 ohm-cm phosphorus-doped crystal, packed in dry ice, and exposed for a few minutes in the Brookhaven National Laboratory graphite reactor using pneumatic tube facilities (*PN*). The specimen of Fig. 1 was in *PN*-4 for four minutes, with a resulting damaging dosage estimated at 2.5×10^{14} *n*/cm^2. On the basis of Hall coefficient measurements performed before and after irradiation, it can be seen that the carrier concentration as a function of temperature reflects the introduction of two electron-trapping centers.[6] By lowering the temperature from 400 to 250°K, about 7×10^{13} carriers per cm^3 are frozen out of the conduction band by a very deep trap which should be located between $E_c-0.4$ ev and $E_c-0.3$ ev, since the Fermi level was scanning this part of the forbidden band in the quoted temperature range. A similar phenomenon can be observed in the temperature range $200>T>100$°K, which points toward another discrete level somewhere between $E_c-0.2$ ev and $E_c-0.1$ ev. At still lower temperatures, the carrier concentration behaves similarly to that of a highly compensated specimen, though the faster rate of freezing out might be indicative of the shallow trap.

As evidence in favor of two deep-lying discrete energy levels in the upper part of the energy gap of neutron-

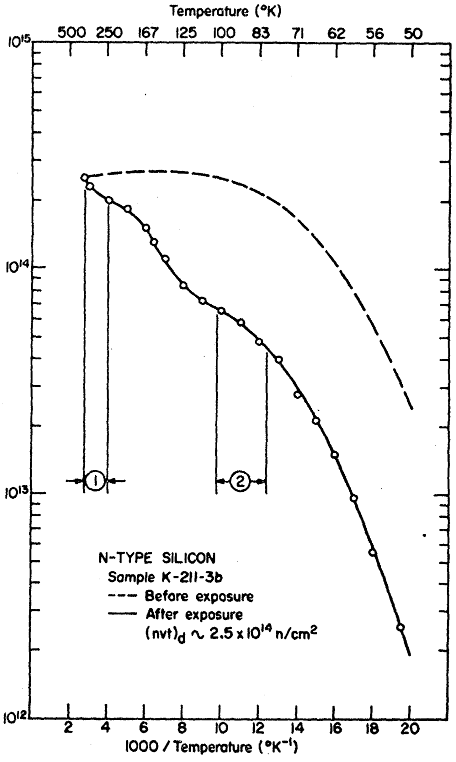

FIG. 1. Carrier concentration *versus* reciprocal temperature, before and after pile neutron irradiation, in a 15-ohm-cm *n*-type silicon specimen.

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[1] G. K. Wertheim, Phys. Rev. **111**, 1500 (1958).

[2] H. Y. Fan and A. K. Ramdas, J. Phys. Chem. Solids **8**, 272 (1959).

[3] C. A. Klein, Proceedings of the Gatlinburg Conference on Radiation Effects in Semiconductors [J. Appl. Phys. **30**, 1222 (1959)].

[4] D. E. Hill and K. Lark-Horovitz, Bull. Am. Phys. Soc. Ser. II, 3, 142 (1958).

[5] It is now well established that any type of irradiation produces predominantly shallow levels close to the band edges (see reference 3). They will not be considered here.

[6] Note that the Hall coefficient factor was uniformly taken as equal to one. Such an approximation appears acceptable in the light of Morin and Maita's mobility ratio determinations [F. J. Morin and J. P. Maita, Phys. Rev. **96**, 28 (1954)].

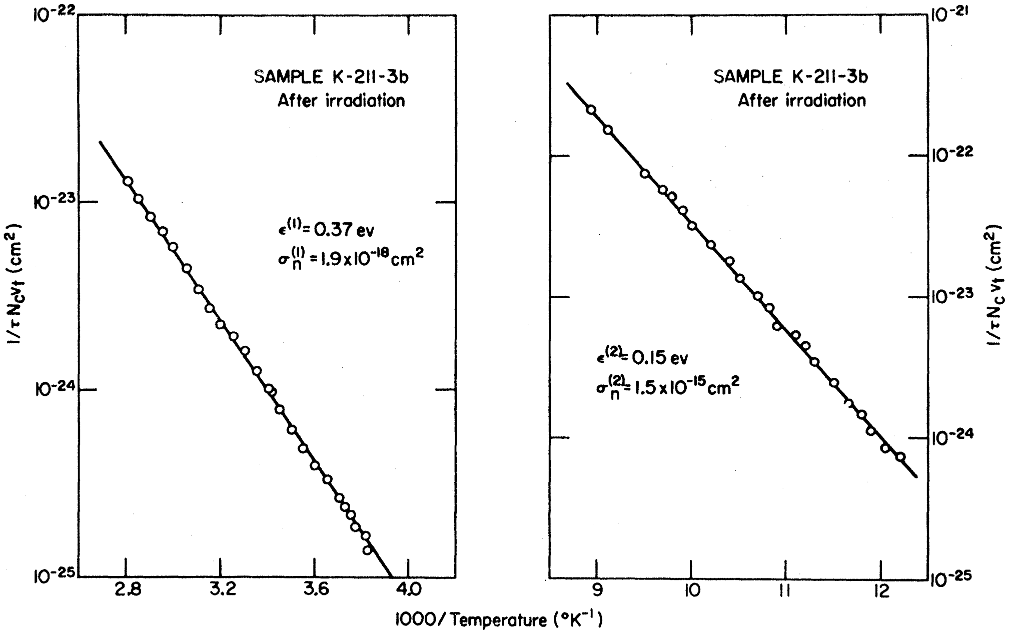

FIG. 2. Pulsed-field effect results for a 15-ohm-cm *n*-type silicon specimen, after pile neutron irradiation.

irradiated silicon became apparent, it was attempted to locate and describe these two levels with the help of the newly developed pulsed-field effect technique.[7] In such an experiment, the Fermi level in a region close to the space charge layer at the surface is "pulsed" toward the middle of the gap, and any state with an appropriate energy level will empty itself through thermal excitation. The free-carrier generation rate is then measured, and the kinetics of the process is related via detailed balance considerations to the majority carrier capture cross section associated with the responsible state. Investigations on gold-doped germanium have shown that, under proper conditions, a discrimination between bulk and surface states can be achieved. For *n*-type material, it was found that the quantity $1/\tau N_c v_t$, where τ is the relaxation time, N_c the density of states in the conduction band, and v_t the thermal velocity, obeys the equation

$$\frac{1}{\tau N_c v_t}=\sigma_n \exp\left[-\left(\frac{E_c-\epsilon}{kT}\right)\right], \tag{1}$$

if the generation process is controlled by centers with an energy level at $E_c-\epsilon$ and an electron capture cross section σ_n. The results of experiments performed along these lines on neutron-irradiated *n*-type silicon samples are illustrated in Fig. 2, which presents data obtained with the specimen of Fig. 1. At high temperatures (range 1 in Fig. 1), or more precisely with a Fermi level between $E_c-0.35$ ev and $E_c-0.25$ ev before applying the pulse, the quantity $1/\tau N_c v_t$ was found as shown in the left-hand side of Fig. 2, indicating that the deep trap is located at $E_c-0.37$ ev and characterized by an electron capture cross section of about 2×10^{-18} cm^2. In the temperature range 2, where the static Fermi level was found to be at about $E_c-0.10$ ev, the experiment did yield the straight line on the right-hand side of Fig. 2, which corresponds to a discrete energy level at $E_c-0.15$ ev with an electron capture cross section of 1.5×10^{-15} cm^2.[8] These experiments did not provide evidence in favor of other deep-lying levels in the upper half of the gap.

The implications of such results will be discussed in a forthcoming paper. Two main conclusions emerge. (1) Pile irradiation of pulled high-resistivity silicon gives rise to a set of discrete states, two of which exhibit energy levels in the upper part of the gap at similar locations as in electron-bombarded specimens. (2) The electron capture cross sections associated with these two states strongly suggest that both are acceptor-like, the level at $E_c-0.15$ ev belonging to a neutral center (if empty), the level at $E_c-0.37$ ev belonging to another neutral or rather slightly repulsive defect center.

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[7] G. Rupprecht, Bull. Am. Phys. Soc. **3**, 377 (1958).

[8] In electron-irradiated material, and on the basis of minority-carrier lifetime experiments, Wertheim obtained a capture cross section of 1.9×10^{-15} cm^2 for this level [G. K. Wertheim, Phys. Rev. **110**, 1272 (1958)].