Radiation Defect Introduction Rates in *n*- and *p*-Type Silicon in the Vicinity of the Radiation Damage Threshold

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Radiation defect introduction rates have been studied in *n*- and *p*-type silicon by analyzing the effects of electron irradiation on diffused *n* on *p* base and *p* on *n* base silicon junctions. The electron energy was varied between 125 and 800 keV; this range included the silicon radiation damage threshold. Plots of the product of the probability of producing a defect and the minority capture cross sections of the defects in the two kinds of junctions exhibited similar dependence on electron energy. However, the magnitudes of these products differed by a factor of about 200 in the two structures, the *n* on *p* base junctions exhibiting the slower decay rate. It is shown that although the microscopic nature of the radiation defects may differ in *n*- and *p*-type silicon, the rate-determining process is the same in both kinds of material. This process must be the production of vacancy-interstitial pairs as a result of Coulomb scattering by the high-energy electrons. However, the shape of the curve relating the probability of defect introduction to electron energy does not agree with theoretical curves, this in spite of a large increase in reliability of data over previously reported experiments in silicon.

I. INTRODUCTION

RADIATION defects introduced into silicon as a result of irradiation by electrons with energies in excess of 100 keV have been subjected to a number of investigations.[1–4] One of these[1] was concerned with the way in which the defect introduction rate $\Delta(E_B)$ varied with electron energy E_B in the vicinity of the radiation damage threshold E_{B0}. In that study, $\Delta(E_B)$ and E_{B0} were measured by observing changes in a *p*-*n* junction parameter related to the minority carrier lifetime τ. It was shown that in silicon E_{B0} was equal to about 145 keV which was interpreted to mean that the minimum energy E_{L0} which a silicon atom must acquire before it can be expelled from its lattice site is 12.9 eV. In that paper it was also shown that the dependence of $\Delta(E_B)$ on E_B in germanium did not fit the theoretical curve obtained by treating the damage production process as though it involved Coulomb scattering of the electron by the nucleus and the existence of a single well-defined threshold value. However, the silicon data were not sufficiently reliable (for reasons given in that paper and summarized below) to construct the $\Delta(E_B)$ vs E_B curve for that material and to compare it with theory. There is a special reason why such a comparison with theory is more meaningful in silicon than in germanium. Natural germanium is composed of a number of isotopes with the appreciable abundances, namely, Ge^{70}(20.4%), Ge^{72}(27.4%), Ge^{73}(7.8%), Ge^{74}(36.6%), and Ge^{76} (7.8%). It has been pointed out[1] that such a 10% spread in atomic weights of abundant isotopes could lead to a smoothing out of the $\Delta(E_B)$ vs E_B curve which would be difficult to account for theoretically. By contrast with germanium, natural silicon is practically a single isotope since it is composed of 92.2% Si^{28}, 4.7% Si^{29}, and 3.1% Si^{30}. Thus, the complication which arises from this isotope effect should be less serious in silicon than in germanium.

In spite of these facts, no further study of the dependence of $\Delta(E_B)$ on E_B in silicon by any method has been reported in the literature. (By way of contrast, a thorough study of this functional relation has been made for germanium based on observation of radiation induced changes in conductivity σ.[5]) Furthermore, $\Delta(E_B)$ vs E_B curves have not been studies in both *n*- and *p*-type material for any semiconductor even though there is evidence that the microscopic composition of radiation defects can be quite different in the two conductivity types.[2] Such differences in defect composition could lead to differences in the shapes of $\Delta(E_B)$ vs E_B curves and perhaps to differences in the threshold energies for production of these various defects. There were therefore two reasons for undertaking work reported in this paper. The first was to determine the shape of the $\Delta(E_B)$ vs E_B curve for silicon with an accuracy sufficient to ascertain the true extent of divergence between theory and experiment and to warrant attempts to modify the theory to conform more closely to the experimental curves. The second goal was to compare $\Delta(E_B)$ vs E_B in both *n*- and *p*-type silicon in order to determine whether one could infer differences in the primary defect introduction processes from the shapes of the two curves.

As regards the first of these goals, silicon junction technology has advanced considerably in the years since the earlier experiments were performed. The alloy junctions used in that study were really equivalent to "thick" targets, i.e., the damage region did not extend throughout the active region of the *p*-*n* junction so that these data required corrections of dubious validity

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[1] J. J. Loferski and P. Rappaport, Phys. Rev. **111**, 432 (1958).

[2] G. K. Wertheim, Phys. Rev. **110**, 1272 (1958).

[3] D. E. Hill, Phys. Rev. **114**, 1414 (1959).

[4] G. N. Galkin, N. S. Rytova, and V. S. Vavilov, Fiz. Tverd. Tela **2**, 2025 (1960).

[5] W. L. Brown and W. M. Augustyniak, J. Appl. Phys. **30**, 1300 (1959).

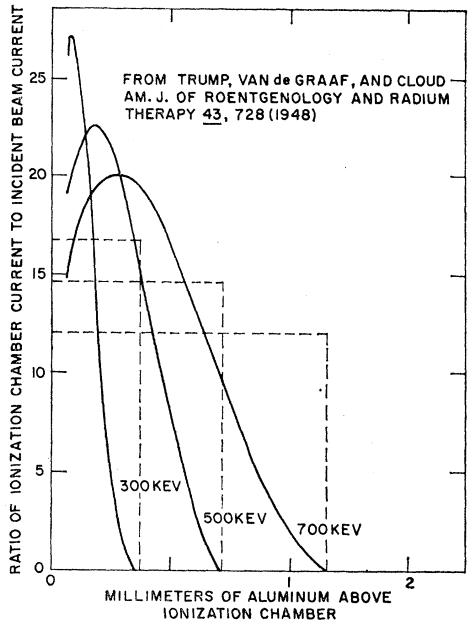

FIG. 1. Density of ionization as a function of penetration into aluminum.

before one could begin to compare them with theory. Furthermore, "an appreciable contact series resistance"[1] affected the interpretation of the silicon data. Both of these problems were eliminated in this study by the use of diffused junctions which have thinner active regions and no contact resistance problems. The accuracy of the data was further improved by devising a null detection circuit which made it possible to measure much smaller defect introduction rates than in the earlier experiments.

While these considerations justify a more thorough examination of the $\Delta(E_B)$ vs E_B curve in silicon of either conductivity type, a few words are needed to explain why this study was extended to include both n- and p-type material. Previous studies[2–4] had led to the conclusion that electrons with energies between 0.7 and 4.5 MeV introduce levels at 0.03, 0.17, and 0.4 eV below the conduction band energy E_c, and at 0.055 and 0.27 eV in excess of the valence band energy E_v. Only the deep-lying levels, i.e., those at $E_c-0.17$, $E_c-0.40$, and $E_v+0.27$ eV, are possible sites for minority carrier recombination, and it must be certain of these levels which caused the changes in τ used to measure E_{B0} and $\Delta(E_B)$ as a function of E_B. Two investigations have been concerned with the problem of determining the roles played by these three deep-lying levels in the recombination process. According to Wertheim's study, recombination of minority holes in n-type Si proceeds via the level at $E_v+0.27$ eV, whereas minority electrons in p-type Si recombine through the level at $E_c-0.17$ eV. Furthermore, Wertheim hypothesized that the damage site associated with the $E_v+0.27$-eV level contained two defects separated by 50 Å whereas the defect at $E_c-0.16$ eV consisted of close spaced defects of opposite charges. Subsequent work by Watkins and Corbett[6] has led to the conclusion that *a* level at $E_c-0.17$ eV consists of an oxygen atom in a lattice vacancy which is not in agreement with Wertheim's description of the damage site. To complicate matters further, Wertheim's interpretation of the recombination process in silicon has been challenged by Galkin *et al.*[4] who pointed out certain difficulties in Wertheim's treatment of his data and re-examined the problem both experimentally and theoretically. They concluded that hole recombination in *n-type* silicon occurs via the level at $E_c-0.16$ eV, which is in sharp disagreement with Wertheim's conclusion. In an even more recent publication, Malovetskaya *et al.*[7] have proposed, on rather weak evidence, that the defect responsible for the level at $E_v+0.27$ eV consists of an oxygen atom in association with an interstitial silicon atom produced during the irradiation. If such a complementarity exists between the lifetime controlling defects in n- and p-type silicon, then the shapes of the $\Delta(E_B)$ vs E_B curves in the two materials ought to be the same. If the microscopic makeup of the defects does not possess such complementarity, then the shape of the curves could be different and one might even expect to observe differences in E_{B0} values.

II. GENERAL DISCUSSION OF THE EXPERIMENT

In our experiments, changes in the p-n junction short-circuit current per unit area I_s associated with minority carriers injected into a body of the semiconductor as a result of the ionization caused by the defect-producing electrons were used to detect the radiation defects in a manner similar to that described in reference 1. It was shown there that the minority carrier lifetime τ was related to the radiation flux φ as follows:

$$\frac{1}{\tau(\varphi)}=\frac{1}{\tau(0)}+vf_B\Delta(E_B)\sigma_c\varphi, \tag{1}$$

where $\tau(\varphi)$ is the minority carrier lifetime after an exposure to a flux φ, $\tau(0)$ is the initial value of lifetime, v is the thermal velocity of the carriers, f_B is the occupancy factor for the bombardment induced recombination centers,[8] σ_c is the minority carrier capture cross section of the centers, and $\Delta(E_B)$ is the probability that an electron of energy E_B will produce a recombination center. This equation will remain applicable provided that (1) the injection level is small, and (2) the majority carrier concentration is large compared to the number of recombination centers introduced by the radiation so that the Fermi level does not change during the irradiation.

[6] G. D. Watkins and J. W. Corbett, Phys. Rev. **121**, 1001 (1961).
[7] V. M. Malovetskaya, G. N. Galkin, and V. S. Vavilov, Fiz. Tverd. Tela 4, 1372 (1962).
[8] W. Shockley and W. T. Read, Phys. Rev. **87**, 835 (1952); R. N. Hall, *ibid.* **87**, 835 (1952).

By means of a circuit described below, the actual parameter we monitored was the ratio (I_s/I_B) as a function of integrated flux; this ratio represents the current multiplication in the solid, i.e., the number of electron-hole pairs produced in the solid for each primary electron incident on the sample, so that by definition

$$I_s(\varphi)/I_B(\varphi)=m(\varphi), \quad (2)$$

where $m(\varphi)$ is the multiplication after exposure to a flux φ. If the diffusion length L in the semiconductor is much greater than the range of the electrons, every minority carrier produced by the primary beam is collected by the junction and the multiplication for this particular case (designated m_0) is given by

$$m_0=E_B/w_0, \quad (3)$$

where w_0 is the average energy expended in generating an electron-hole pair. For silicon, the measured value of w_0 is 3.6 eV/pair.[9]

If, on the other hand, the minority carrier diffusion length is small compared to the range of the electrons R, then

$$I_s=egL, \quad (4)$$

where e is the electronic charge and g is the generation rate per cc. Equation (4) is valid only if the generation can be considered uniform over a few diffusion lengths. This condition is roughly satisfied in the junctions used for the experiments described in this paper (L lies between 25 and 50 μ whereas R lies between 120 μ for 150-keV electrons and 600 μ for 500-keV electrons). Figure 1 shows the actual distribution of ionization with distance as given in the literature. If the experimental curve is approximated by the rectangle shown in the figure, then the assumed uniform generation rate becomes

$$g=(E_B/w_0R)(I_B/e). \quad (5)$$

As is evident from Fig. 1, the approximation is weakest for the low-energy electrons. If Eq. (5) is combined with the relation $L=(D\tau)^{1/2}$, where D is the minority carrier diffusion constant, then one can write

$$I_s=(E_B/w_0R)D^{1/2}I_B\tau^{1/2}. \quad (6)$$

Substitution of (6) into (1) and rearrangement of terms leads to

$$\frac{E_B^2I_B^2}{R^2}\left[\frac{1}{[I_s(\varphi)]^2}-\frac{1}{[I_s(0)]^2}\right]=\frac{w_0^2}{D}vf_B\sigma_c\Delta(E_B)\varphi, \quad (7)$$

where $I_s(0)$ and $I_s(\varphi)$ are the initial value of I_s and its value after the cell is exposed to a flux φ.

If we use the definition

$$w(\varphi)=E_BI_B(\varphi)/RI_s(\varphi)=E_B/Rm(\varphi), \quad (8)$$

where $w(\varphi)$ is the apparent energy expended per electron pair generated, then Eq. (7) becomes

$$[w(\varphi)]^2-[w(0)]^2\equiv\Delta w^2=(w_0^2/D)vf_B\sigma_c\Delta(E_B)\varphi. \quad (9)$$

In the computation of w, we assumed that $R\cong 412E_B^{(1.265-0.0954\ \ln E)}$ mg/cm² as given by Katz and Penfold.[10]

According to Eq. (9), plots of w^2 versus φ should be linear. The slope of the lines is given by

$$\frac{dw^2}{d\varphi}=\frac{w_0^2}{D}vf_B\sigma_c\Delta(E_B). \quad (10)$$

For identical cells exposed to electrons of various energies E_B, the slopes of these lines will be proportional to $\Delta(E_B)$.

The experiments described in reference 1 were based on this idea; they involved a measurement of I_s as a function of flux in junctions made by alloying an n-type region into a p-type base. However, the surface onto which the electrons were directed was 0.020 cm from the junction so that instead of measuring the probability of defect production by electrons of energy E_B, those experiments yielded a kind of integrated probability for defect production since the passage of electrons through the thick region into which defects were being injected changed the energy of the incident electrons.[11] It was therefore difficult to compare such curves with theoretical curves for the probability of defect production as a function of energy which are most reliably calculated for a "thin" target.[12] In the experiments described in this paper, diffused p-n junctions were deliberately chosen because it was known that the active region of the junctions (i.e., the sum of diffusion lengths on both sides of the junction) extends only to a depth of 25 to 50 μ below the surface. The junction itself was located between 1.0 and 10 μ from the surface so that such structures provided considerably thinner probes for radiation defects than did the previously utilized alloy junctions. Such thin probes would make possible more meaningful comparisons to the rate of defect production predicted by atomic collision theory.[12]

III. EXPERIMENTAL PROCEDURE

A. Description of the Cells

The p-n cells were either commercially available cells[13] or else cells made in the laboratory by diffusion of boron into As-doped n-type wafers of 1 to 3 Ω cm initial resistivity. The n-p cells were made by diffusing phosphorus, antimony or arsenic into boron-doped

[9] K. G. McKay, Phys. Rev. **84**, 829 (1951).

[10] L. Katz and A. S. Penfold, Revs. Modern Phys. **24**, 28 (1952).

[11] J. J. Loferski and P. Rappaport, J. Appl. Phys. **30**, 1296 (1952).

[12] W. A. McKinley, Jr., and H. Feshbach, Phys. Rev. **74**, 1759 (1948).

[13] Purchased from Hoffman Semiconductors. Base resistivity ~1 Ω cm.

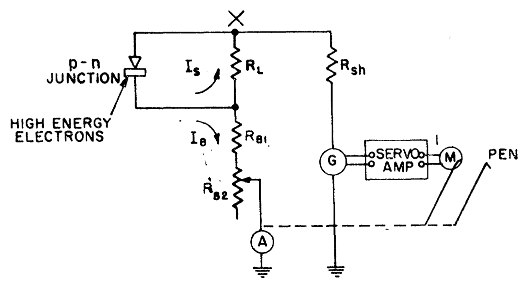

FIG. 2. Schematic diagram of circuit for recording I_s/I_B.

p-type wafers[14] of 1 to 3 Ω cm initial resistivity. Some of the p-type wafers were cut from floating zone crystals (1–3 Ω cm resistivity) whose O_2 content was lower than that of pulled crystals by a factor of about 10^2. Suitable Ohmic contacts were affixed to both sides of the junctions. The resulting structures had measured solar energy conversion efficiencies of about 10%. When they were irradiated by 125-keV electrons, the measured value of the product $Rw(0)$ lay between 4 and 5 eV/pair for both varieties of cells used in this study. In general, $Rw(0)$ values were lower in n-p cells than in p-n cells. The observed values of $Rw(0)$ indicate that $\tau(0)$ was about the same for both varieties of cells. The cells whose dimensions were about 0.6×0.6×0.050 cm were mounted in the vacuum system of a Van de Graaff machine on a water-cooled copper block and were irradiated by electrons in about 10-keV steps starting from 125 keV.

B. Ratio Recording Circuit

Figure 2 shows how the cell was connected into a circuit designed to detect very small changes in the I_s/I_B ratio. In this figure, the irradiated junction has a load resistance R_L whose value is chosen to be low enough so that the current flowing through it will in fact be very nearly equal to the short circuit current I_s. The junction was so connected into the circuit that I_s and the beam current I_B were directed as shown by the arrows in the figure. The beam current I_B passed to ground through the fixed resistor R_{B1}, the variable resistor R_{B2} and ammeter A. The ammeter permitted a direct measurement of I_B and an integration of the total charge passing through the cell. If the resistances are so chosen that

$$I_s/I_B=(R_{B1}+R_{B2}+R_A)/R_L, \tag{11}$$

where R_A is the ammeter resistance, the point X will be at ground potential. The rest of the circuit is designed to change R_{B2} in such a way that the null condition Eq. (11) is satisfied at all times. The combination of the large shunt resistance R_{sh}, where $R_{sh} \gg (R_{B2}+R_{B2}+R_A)$, and dc amplifier, G, serves as a null detector. The output of the amplifier was fed into the servo amplifier of a Brown Electronik Recorder whose potentiometer had been disabled. A single turn slide wire potentiometer which constituted R_{B2} was driven by the amplifier motor M. The motor was also coupled to the pen of the recorder. The position of the pen on the strip chart could be simply related to the value of R_{B2} needed to preserve a null. The circuit can be made extremely sensitive to the I_s/I_B ratio. For example, if R_{B2} is chosen to be say 1% of $(R_{B1}+R_A)$, a 1% change in I_s/I_B will cause the pen to move from one end of the strip chart to the other. Besides this sensitivity the fact that the circuit records the ratio I_s/I_B instead of I_s alone means that the difficulties associated with drift in I_B from the Van de Graaff are eliminated. Because of this, it was possible to maintain E_B constant within ±1% (by means of a servo circuit associated with the generating voltmeter of the Van de Graaff) without having to compensate for I_B changes.

IV. LOCATION OF THE DAMAGED REGION BY ANALYZING SPECTRAL RESPONSE CURVES

A number of recent publications[15] describe how one can determine the values of diffusion length L on both sides of p-n junctions by analyzing photovoltaic spectral response curves. It has also been pointed out that changes in L can be followed very easily in this way. The

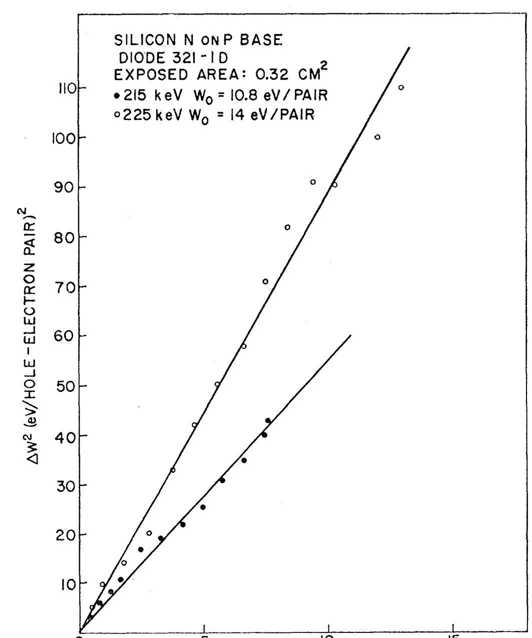

FIG. 3. Plot of $[w(\phi)]^2-[w(0)]^2$ vs electron flux for a silicon n-p cell at 215 and 225 keV.

[14] Most of the phosphorus-doped n-p cells were made at U. S. Army Signal Research and Development Laboratory, Ft. Monmouth, New Jersey, by Joseph Mandelkorn. Details of their fabrication have been described in a separate publication [J. Mandelkorn, C. McAfee, J. Kesperis, L. Schwartz, and W. Pharo, J. Electrochem. Soc. **109**, 313 (1962)].

[15] J. J. Wysocki and J. J. Loferski, RCA Rev. **22**, 38 (1961); V. K. Subashev, Soviet Phys.—Solid State **1**, 1344 (1960); B. Dale and F. P. Smith, J. Appl. Phys. **32**, 1377 (1961).

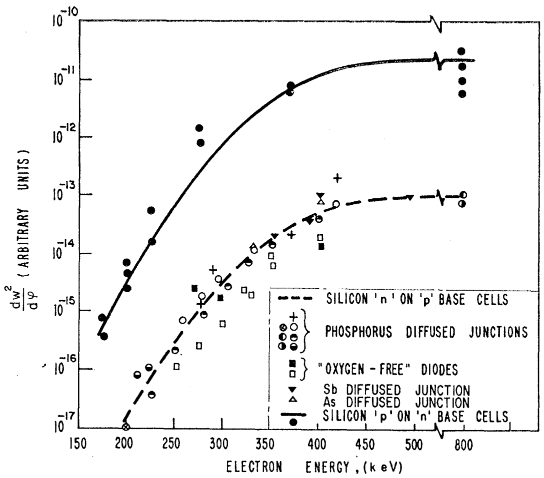

FIG. 4. Relative damage rates of silicon p-n and n-p cells as a function of electron energy.

spectral response of the p-n and n-p cells before and after irradiation by 250-, 300-, and 800-keV electrons was measured by Wysocki and Faughnan of these laboratories, who found that the principal change occurred in the long-wavelength response, i.e., the response to penetrating radiation. One is therefore led to conclude that the defects which are producing the observed decay in τ are not those injected into the diffused skin, but rather those generated in the base wafer which contributes the large portion of the long-wavelength response. This assertion is further supported by the fact that the thin ($<1\ \mu$ thick) diffused skin contains a very high initial concentration of recombination centers [low $\tau(0)$] so that very large additional concentrations would be needed before any change would be detected in the response to highly absorbed radiation.

V. EXPERIMENTAL RESULTS

When $[w(\varphi)]^2$ was plotted vs φ, as shown in Fig. 3, it was found that the linear relation predicted by Eq. (9) was in fact satisfied. The slopes of these lines, determined by a least-squares fit with the help of a computer, are shown in Fig. 4 for p-n and n-p cells. The dashed line in Fig. 4 was drawn through the n-p points considered most reliable. This curve was multiplied by a constant to give the best fit to the p-n points, and the result is shown as a solid line, which was extrapolated to lower energy. The separation of the two curves correspond to a factor of 220 in the value of $dw^2/d\varphi$ at a given energy.

First of all, note that there is considerable scatter within data for each kind of cell. Even after allowance for this scatter, it is clear that the slopes of the lines are higher for p-n than for n-p cells. This rather considerable difference in damage rates increased the difficulty of detecting damage below 225 keV in the n-p cells. For example, in order to determine the value of the slope at 200 keV a cell was irradiated for 26.1 h at a current of 2.5 μA which was the maximum current which could be tolerated without causing a temperature rise in the cell. The total flux was therefore 3.8×10^{18} electrons per cm^2. Even after this long irradiation the existence of damage was not confirmed with absolute certainty.

Figure 4 also shows decay rates for cells made by diffusing Sb and As into boron-doped p-type wafers of 1 to 3 Ω cm resistivity. The initial values of w in these cells indicated that $\tau(0)$ was very low, i.e., there was a large concentration of recombination centers in the active region of the cells at the outset. Because of the low values of $\Delta(E_B)$ in the vicinity of E_{B0}, it was not possible to introduce enough recombination centers into the active region of the cells for any reasonable combination of irradiation time and flux to produce a detectable change in $w(0)$ at energies below 300 keV. For energies in excess of 300 keV where damage was discernible, the measured values of $dw^2/d\varphi$ turned out to be as shown in the figure, i.e., very nearly the same as the values of this parameter in the "standard" phosphorus-doped cells. Thus, the method of n-p junction fabrication did not affect either the shape of the $\Delta(E_B)$ vs E_B curve nor the absolute value of the $dw^2/d\varphi$.

A few n-p cells were made by diffusing phosphorus into boron-doped p-type wafers which were characterized by oxygen concentrations of about 10^{13} to 10^{15} per cc as compared to 10^{17} per cc in the "standard" wafers used in cell fabrication. The resistivity of these wafers lay between 1 and 3 Ω cm. As is evident from the figure, the values of $dw^2/d\varphi$ for these cells were not significantly different from the values for the "standard" cells.

VI. DISCUSSION OF RESULTS

According to Eq. (7), the slopes of the Δw^2 vs φ lines are given by $(w_0^2/D)\sigma_c\Delta(E_B)vf_B$. As we have already pointed out, if the observations are confined to cells of a given resistivity type and resistivity value and if the Fermi level does not change during the irradiation, the shape of the curves should trace out $\Delta(E_B)$ vs E_B. Suppose that the radiation defect production process involves nothing more than the displacement of atoms from lattice sites as a result of Coulomb scattering by electrons. Assume further that there is a sharp threshold energy E_{B0} for this displacement process. Then the probability of displacing an atom as a function of electron energy can be computed by using the McKinley-Feshbach[12] analysis of this scattering problem, as has been done in references 1 and 5. Their treatment applies to an infinitely thin target, i.e., a target so thin that the energy of the electrons does not change appreciably during passage through it. The active region of the diffused cells which is between 25 and 50 μ thick is a reasonable approximation to this condition, at least for energies somewhat above E_{B0}; it is certainly a better approximation to a thin target than the alloy junctions used in the experiments described in reference

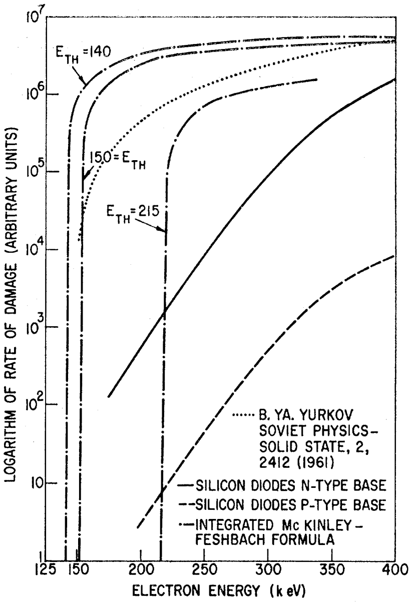

FIG. 5. Comparison of the energy dependence of theoretical and experimental rates of damage.

1. Figure 5 includes McKinley-Feshbach curves for the defect-production cross section as a function of E_B computed for three different threshold values in silicon, viz., 140, 150, and 225 keV. (The experiments do not yield absolute values of the cross section so that the ordinate of the experimental curves was chosen arbitrarily although the relative locations of the two experimental curves conform to the data.) It is obvious that the experimental curves do not have the same shape as do the theoretical ones. Now Yurkov[16] has calculated the total number of defects which can be produced by electrons in a target thick enough to stop them as a function of E_B. He also assumed a single discrete value of E_{B0} (150 keV). His calculation can be looked upon as a limit on the amount by which target thickness can modify the McKinley-Feshbach curve. His results are also included in Fig. 5, where it can be seen that the sharp knee of the McKinley-Feshbach curve has been softened considerably as a result of target thickness. However, our experimental curves rise even more gradually than do the Yurkov curves. It would therefore appear that the basic assumption of a sharp threshold and the consequent generation of vacancies which underlie the theoretical calculations do not provide an adequate description of the defect production process in silicon. Possible causes of this lack of agreement between theory and experiment were discussed in references 1 and 5 and their effects should be considered briefly. The isotope effect would not be as significant in silicon as in germanium because the spread of atomic weights for the principal isotopes in silicon is not very large. Target thickness could still be affecting the curve shape, but the fact that the experimental curve lies outside the range defined by calculations for thin and thick target implies that the observed discrepancy between the theoretical and experimental curve shapes cannot be explained in this way. Dependence of threshold on the initial direction of motion of the struck atom and a possible contribution from temperature broadening are two remaining mechanisms which might possibly account for the experimental curve shape. A better theory for orientation effects in silicon is needed before it will become profitable to modify theoretical curves to secure a better fit with experiment.

As for the role played by impurities in the defect production process, the fact that *n-p* cells with low and high oxygen concentrations exhibited similar $\Delta(E_B)$ vs E_B curves can be interpreted to mean that the concentration of this impurity which is known to affect the introduction rate of a particular kind of defect (the *A* center)[6] does not change the introduction rate in *p*-type silicon. (According to Wertheim, the *A* center controls τ in *p*-type material.) We are therefore tempted to conclude that whatever the structure of the defect on an atomic plane, the rate determining process (which as we shall show is essentially the same in *n*- and *p*-type silicon) is probably the scattering of an electron by a nucleus where the nucleus receives sufficient kinetic energy to leave its lattice site thus forming a vacancy. If this be the case, then we remain unable to explain why the experimental $\Delta(E_B)$ vs E_B curve obtained during this investigation does not conform more closely to theory. Such a disagreement between theory and experiment had previously been reported in germanium[1,5] so that these semiconductors exhibit similar behavior in this respect.

Let us now direct our attention to the difference in damage rates exhibited by the two experimental curves for *n-p* and *p-n* cells. On the basis of the spectral response data cited above, it must be assumed that most of the damage with which we are concerned is occurring in the base material, i.e., in the *n*-type material of the *p-n* cells and in *p*-type materials of the *n-p* cells. With this in mind, consider the parameters which contribute to the measured value of the slope. Since w_0 is a basic parameter, it is the same for both resistivity types. Furthermore, the value of f_B does not change during irradiation because the Fermi level does not shift. If we use the Einstein relation to compute the minority carrier diffusion constants D_n and D_p from the mobility values in 1 Ω cm material, we obtain the ratio $D_n/D_p \cong 1.6$ where D_p is the diffusion constant of holes in *n*-type material, and D_n of electrons in *p*-type material. We can derive the ratio of the mean thermal velocities of carriers from elementary kinetic theory and the effective masses as $v_n/v_p \cong (m_p/m_n)^{1/2} \cong 1.4$. From these considerations, one is led to conclude that when one compares the damage rates of the two kinds of cells, one is in fact comparing the ratio of the values of

[16] B. Ya. Yurkov, Soviet Phys.—Solid State 2, 2412 (1961).

$\sigma_c\Delta(E_B)v/D$ for the two. Let $r(E_B)$ be defined as the ratio of the experimentally measured decay rates as follows:

$$r(E_B)=\frac{[\sigma_c\Delta(E_B)]_n v_p}{D_p}\frac{D_n}{[\sigma_c\Delta(E_B)]_p v_n}, \qquad (12)$$

where the subscripts n and p outside the brackets refer to the p-n and n-p cells, respectively. If we substitute the known value of $D_p v_p/D_p v_n \cong 1.6/1.4 \cong 1.1$, we can define $r'(E_B)$ thus:

$$r'(E_B)=r(E_B)/1.1=[\sigma_c\Delta(E_B)]_n/[\sigma_c\Delta(E_B)]_p. \qquad (13)$$

From the experimental curves in Fig. 4, $r'(E_B)$ has a value of about 200. The problem reduces to the following: How much of this ratio can be ascribed to a difference of σ_c values and how much to a difference in $\Delta(E_B)$ values?

According to Wertheim,[2] who studied damage introduction rates in n- and p-type silicon for $E_B=700$ keV, the value of σ_c was 8.0×10^{-13} cm^2 for holes in n-type silicon and 2×10^{-15} cm^2 for electrons in p-type material. Thus his data would lead one to expect a ratio of 400 in σ_c values in the two resistivity types at 700 keV. The data presented here indicate that the ratio of damage rates is of this same order of magnitude, so that this difference in damage rates for the two kinds of silicon can perhaps be contributed wholly to a difference in σ_c values.[17] If this is so, then $\Delta(E_B)$ has the same magnitude in both n- and p-type silicon, i.e., the process of defect introduction is virtually the same in the two conductivity types. This would support the proposal of Malovetskaya *et al.*[7] that the interstitial silicon atom plays the same role in p-type silicon as that attributed to the vacancy in n-type material.

In order to eliminate completely the possibility that E_{B0} differs in n- and p-type silicon, our data on n-p cells should be extended to lower energies. It is difficult, however, to maintain constant irradiation conditions for periods of the order of 50 to 100 h. During such long irradiations, the surface of the samples becomes covered by a bombardment-induced deposit which could cause a difference in surface properties resulting in an apparent change in I_s.

At this point, an observation on the general problem of threshold determinations in semiconductors is appropriate. In the case of the n-p cells, it was very difficult to observe any damage caused by electrons of E_B less than 200 keV. Changes were detectable only for exceedingly large integrated fluxes and even after such fluxes, the possibility of different radiation damage thresholds in n- and p-type silicon has not been completely eliminated. If the only cells at our disposal had been n-p cells, we would have been inclined to conclude that E_{B0} was about 200 keV. In a study of damage thresholds based on measurements of changes in conductivity, Novak[18] has also observed large differences in damage introduction rates for n- and p-type silicon, which could also be interpreted as differences in E_{B0}. All previous measurements of E_{B0} in semiconductors have been made on one resistivity type or one kind of p-n junction. The observations reported in this paper and the experiments of Novak suggest that it is prudent to measure E_{B0} in both resistivity types since substantial differences in damage rates and of the apparent values of E_{B0} may exist.

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[17] Note that Galkin *et al.* (reference 4) compute a considerably different value for σ_c in n-type material but since they do not give a value for p-type material, it is not possible to use their results to explain our data.

[18] R. L. Novak (to be published).