Energy for Electron-Hole Pair Generation in Silicon by Electrons and α Particles*

C. BUSSOLATI AND A. FIORENTINI
Istituto di Fisica del Politecnico, Milano, Italy

AND

G. FABRI
Laboratori CISE, Milano, Italy

(Received 27 July 1964)

The difference of response of Si semiconductor detectors to α particles and electrons has been tested. The mean energy required for electron-hole pair generation by electrons has been found to be different from that for α particles. These values are, respectively, $\epsilon_\infty=3.79\pm0.01$ and $\epsilon_\infty=3.61\pm0.01$ at a temperature of 300°K for electrons (365 KeV) and α's (5.477 MeV).

I. INTRODUCTION

RECENTLY, with the development of solid-state nuclear particle detectors, several measurements of the mean energy required to generate electron-hole pairs in Si by ionizing radiations have been performed. Experiments with different types of ionizing particles have not been able to show significant differences from one particle to another, so that, within experimental error, the mean energy for electron-hole pair appears to be the same.[1–5]

Shockley[6,7] has calculated this mean energy as

$$\epsilon_\infty=2.2E_g+(L_i/L_R)E_R, \qquad (1)$$

in which E_g is the energy gap between valence and conduction band, L_i and L_R the mean free path, respectively, for ionization and scattering with optical phonons, and E_R the energy of a phonon at the Raman frequency. This expression is deduced under the assumption that the ionization is essentially produced by a shower of secondary electrons due to the incident particle. As a consequence the mean energy should be, in a first approximation, the same for different particles.

Nevertheless, in connection also with previous work of our group,[4] we have repeated the measurements with a more sensitive setup to observe small differences between electrons and α particles and the temperature dependence of ϵ_∞.

II. EXPERIMENTAL SETUP

In order to get depletion layers thick enough to stop electrons having an energy of a few hundred keV we used Si surface-barrier detectors prepared with n-type Si of 21 000 $\Omega\times$cm resistivity. The source of electrons (internal conversion electrons of Sn^{113}) was prepared by depositing some drops of tin chloride in HCl solution on a Mylar foil 1.4 mg/cm^2 thick. As a source of α particles we used Am^{241} (ORTEC Am-1U). In order to prevent any energy loss, both the detectors and the sources were operated in high vacuum ($\sim10^{-5}$ mm Hg). The vacuum system, including a rotary and an oil diffusion pump, was equipped with a liquid-nitrogen trap. The vacuum chamber, in the part where the detector is placed, had copper walls, the other walls being stainless steel, to favor cooling. Cooling was obtained by putting part of the vacuum chamber in freezing mixtures (ice, ice+$CaCl_2$, solid CO_2+alcohol). The different temperatures were measured with a thermocouple. Since the sensitive part of the thermocouple could be placed in contact with the silicon slice, but only in proximity with it, the temperature in our measurements was known with low accuracy. In Fig. 3 the accuracy is shown only for the experimental points taken at low temperatures where it is worst.

Figure 1 shows the block diagram of the electronic chain used in our measurements. We have to point out that, while in measurements on α particles we used a spectrum expander,[8] we did not do so for measurements on electrons, in view of the fact that these have lower energy.

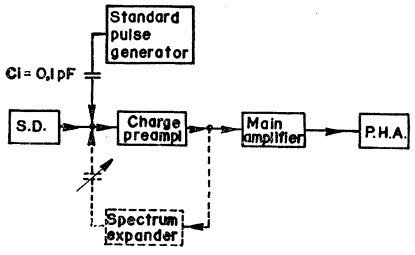

FIG. 1. Block scheme of experimental apparatus.

* Work supported by Consiglio Nazionale delle Ricerche.

[1] M. L. Halbert and J. L. Blankeship, Nucl. Instr. Methods 8, 106 (1960).
[2] L. Koch, J. Messier, and J. Valin, Natl. Acad. Sci.—Natl. Res. Council, Publ. 871, 52 (1961).
[3] E. Baldinger, W. Czaja, and J. Gutmann, Helv. Phys. Acta 35, 599 (1962).
[4] G. Fabri, E. Gatti, and V. Svelto, Phys. Rev. 131, 134 (1963).
[5] L. Koch and J. Messier, Compt. Rend. 252, 74 (1961).
[6] W. Shockley, Czech. J. Phys. B11, 81 (1961).
[7] A. G. Chynoweth, Natl. Acad. Sci.—Natl. Res. Council Publ. 871, 95 (1961).
[8] M. Bertolaccini, C. Bussolati, and S. Cova, Nucl. Instr. Methods (to be published).

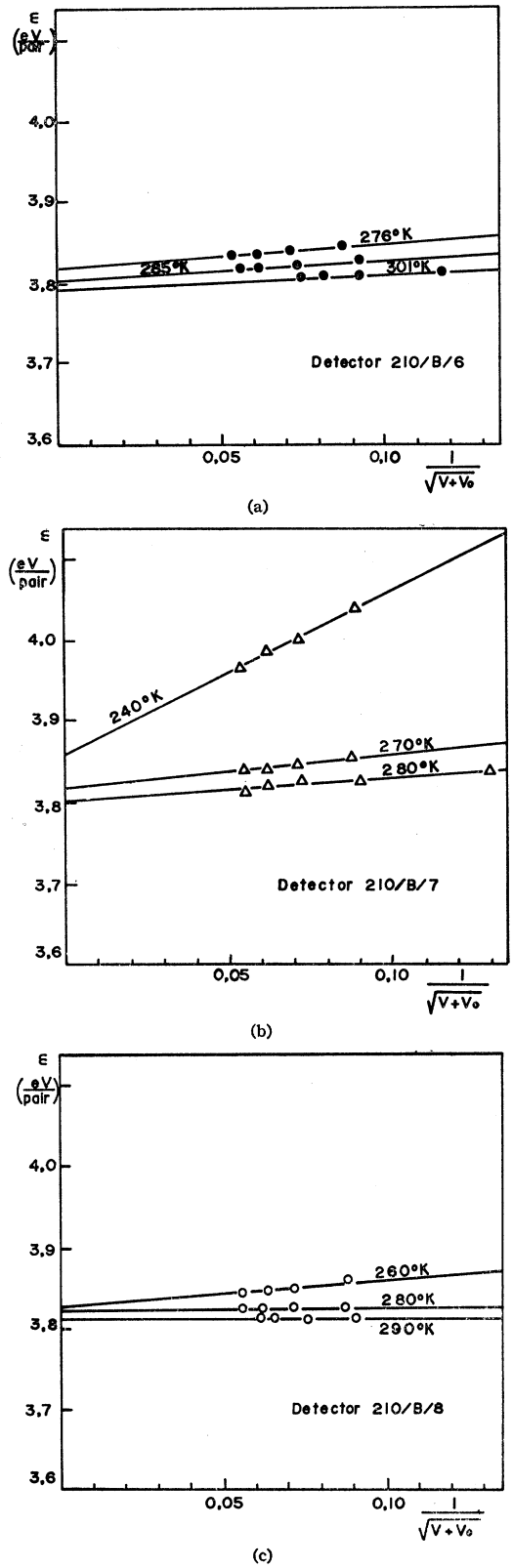

FIG. 2. ϵ (eV/pair) as a function of $1/(V+V_0)^{1/2}$ for different values of the semiconductor detector temperature.

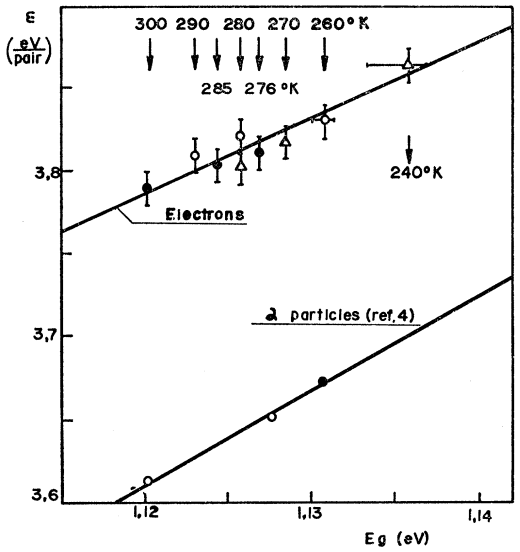

FIG. 3. Values of ϵ_∞ (ϵ for infinite electric field) as a function of forbidden gap E_g.

The equivalent energy per channel was about 1.4 keV in both cases. The standard pulse generator is essentially the same one described in Ref. 4. The amplitude of the voltage pulses, measured with a potentiometric method, proved to be reproducible through repeated measurements within 0.5%, its thermal stability being better than 1/5000.

III. MEASUREMENTS

For the determination of the mean energy per pair, we used two calibrated pulses and two internal conversion (or α) lines. The α lines corresponded to 5.477 and 5.435 MeV α particles and the conversion electrons to 365 and 389 keV (K and $L+M$ lines). Both for electrons and α's, two calibrated pulses of different amplitudes were chosen so as to give artificial lines very close to the particles spectra. Of course one of the four lines used in each measurement was redundant and served only for checking purposes. The values of the mean energy at a given temperature were obtained by extrapolating to infinite electric field[3,9] the values relative to different polarizations of the detector.

The measurements reported in Fig. 3 for α particles were done only as a check of the technique and proved to agree with the results given in Ref. 4.

The values of ϵ (eV/pair) versus $1/(V+V_0)^{1/2}$, where V is the applied voltage and V_0 the diffusion potential, for electrons are plotted in Figs. 2(a), 2(b), and 2(c) for three detectors at various values of temperature; $(V+V_0)^{1/2}$ is proportional, for abrupt junctions, to the electric field.

[9] E. Baldinger, J. Gutmann, and G. Matile, Z. Angew. Math. Phys. 1, 90 (1964).

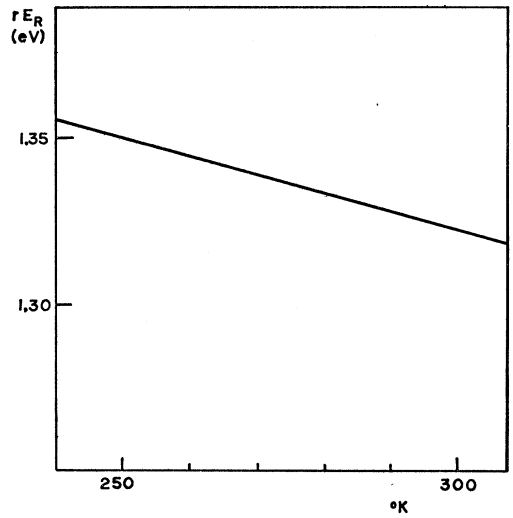

FIG. 4. L_i/L_RE_R of Shockley's expression (1) versus temperature.

Our results are shown in Fig. 3 and one can see that not only do they disagree with those for α particles, but the disagreement is so large that it cannot be easily explained. The parameter L_i/L_RE_R of Shockley's expression is reported in Fig. 4.

According to the assumption that all the charge is generated by a shower following the primary electrons ejected by the incident particle, one cannot expect to find relevant differences from one particle to another, at least in a first approximation. Nevertheless, our results could be explained on the basis of some second-order effect related either to a slight dependence of ϵ_∞ upon the energy of the primary particle (though up to now, there is no evidence for it), or to the fact that different particles have both different spectra of primary electrons and can also lose energy in different ways.

ACKNOWLEDGMENTS

We wish to thank Professor A. Bisi and Professor E. Gatti, who helped us by many suggestions and frequent discussions.

PHYSICAL REVIEW VOLUME 136, NUMBER 6A 14 DECEMBER 1964

Correlation Factors for Impurity Diffusion. bcc, Diamond, and fcc Structures

JOHN R. MANNING
Metallurgy Division, National Bureau of Standards, Washington, D. C.
(Received 17 July 1964)

A general equation for the impurity correlation factor is derived in terms of effective escape frequencies. This equation applies even when the vacancy-jump frequency for association of a vacancy-impurity complex differs from the frequency far from an impurity. Parameters in this equation are calculated for body-centered cubic, diamond, and face-centered cubic structures. In these calculations, it is assumed that vacancy jumps which do not involve a nearest neighbor of the impurity are unaffected by the impurity but that association and dissociation jumps, which do involve nearest neighbors of the impurity, are affected. Analytical expressions for the correlation factor in terms of vacancy-jump-frequency ratios are obtained. In the bcc and fcc structures, results are given for two cases: (A) where all dissociative jumps are equally likely, and (B) where a vacancy which makes a dissociative jump to a second-nearest-neighbor site is still partially bound to the impurity, but vacancies which make dissociative jumps to other sites are not. In the diamond structure, case A cannot be distinguished from case B. Results for the diamond structure and for case A in the fcc structure differ only slightly from previous more approximate results. A comparison is made between the present random-walk method of calculating correlation factors and the pair-association method.

I. INTRODUCTION

WHEN diffusion occurs by a vacancy mechanism, the atoms do not pursue a random walk. Instead, an atom, after exchanging with a vacancy, has a greater-than-random probability of making a reverse jump by re-exchanging with the same vacancy. This causes the atom to pursue a correlated walk and introduces a correlation factor f into the diffusion equations.[1–3]

The correlation factor for impurity diffusion depends on the vacancy-jump frequencies near the impurity.[2,3] Simple expressions for the impurity-correlation factor in terms of vacancy-jump frequencies have been calculated previously for a number of cubic structures.[4] These expressions apply when every vacancy jump from

[1] J. Bardeen and C. Herring, *Atom Movements* (American Society for Metals, Cleveland, 1951), p. 87; also *Imperfections in Nearly Perfect Crystals*, edited by W. Shockley (John Wiley & Sons, Inc., New York, 1952), p. 261.
[2] A. D. LeClaire and A. B. Lidiard, Phil. Mag. 1, 518 (1956).
[3] K. Compaan and Y. Haven, Trans. Faraday Soc. 52, 786 (1956).
[4] J. R. Manning, Phys. Rev. 116, 819 (1959).