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

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The mean energy ϵ_∞ for electron-hole pair generation in silicon by α particles has been measured at different temperatures. For a given temperature, this value has been obtained by extrapolating to infinite collecting electric field the actual data at various finite fields. The experimental values are reported as a function of the forbidden energy gap, and compared with a theoretical expression due to Shockley.

I. INTRODUCTION

THE mean energy for an electron-hole pair generation in germanium and silicon was first measured by use of the avalanche multiplication phenomenon.[1,2] Recently much more accurate measurements have been made possible by the development of the semiconductor radiation detector.[3–5] Halbert and Blankenship,[3] Koch *et al.*,[4] and Baldinger *et al.*,[5] using various ionizing particles (α,β,N^{14}), did not find significant differences in the value of the mean energy. Different values were observed only for particles producing high ionization density, such as fission fragments. We felt it worth while to repeat such measurements with the semiconductor detector technique for one type of particle (α), with view to establishing a possible dependence on temperature of the mean energy ϵ_∞ for electron-hole pair generation.

II. EXPERIMENTAL LAYOUT

The block scheme of the system is shown in Fig. 1. It consists mainly of a silicon detector placed in vacuum at controlled temperatures in the presence of an α source, a pulse-amplifying chain made up of a compensation charge preamplifier,[6] an amplifier with an *RC-RC* shaping network, and a multichannel pulse height analyzer; a calibrated generator of a voltage step injects through a 0.1-pF standard condenser (General Radio 1403-N) a known charge that allows the absolute calibration of the charge released by the semiconductor detector.

For the measurements, surface barrier semiconductor detectors were used because in the preparation of such a device there are no operations that can modify the bulk properties of the single crystal with which one starts; furthermore, in these semiconductor detectors, the dead layer does not exceed thicknesses equivalent to 40–50 μg/cm², corresponding to about 20 keV of energy lost by an α particle. The measurements were performed with semiconductor detectors prepared starting with *n*-type silicon of various resistivities and minority carrier lifetimes, and with commercial semiconductor detectors.

The amplifying chain includes a charge preamplifier and a spectrum expander[6]; the main amplifier has an *RC-RC* shaping network with the two time constants equal to 1 μsec. The pulses were analyzed with a conventional pulse height analyzer; the spectrum expander and the main amplifier were set to have an equivalent of 1.9 keV of the α-particle energy per channel.

The amplitude of the standard voltage step used in the charge generator was determined by the sum of the voltage of a Zener diode, fed at constant current, and the emitter-collector saturation voltage of a transistor with a constant base current; the two devices were held at constant temperature. The absolute value of the step amplitude was repeatedly measured by a potentiometric method and its reproducibility was ascertained within 0.5%.

The source of α particles was a thin layer of ThC and ThC′. The measurement of the output charge from the semiconductor detector due to the 8.780-MeV α particles of ThC′ was performed by comparison of the output pulses with the ones obtained upon injection of the standard charge on the detector at different temperatures and applied voltages.

III. DISCUSSION

The values of ϵ(eV/pair) vs $1/(V+V_0)^{1/2}$ for two detectors, where V is the applied voltage and V_0 the diffusion potential, are plotted in Fig. 2 for various values of detector temperature; $(V+V_0)^{1/2}$ is proportional, for abrupt junctions, to the electric field.

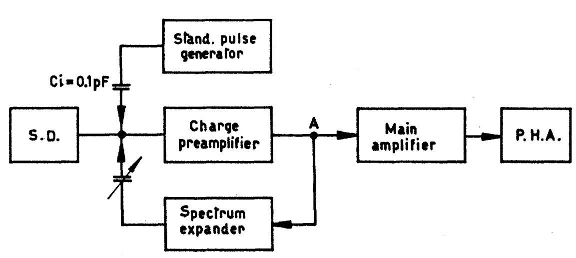

Fig. 1. Block scheme of experimental apparatus.

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[1] K. G. McKay and K. B. Mc Afee, Phys. Rev. **91**, 1079 (1953).
[2] V. M. Patskevich, V. S. Vavilov, and L. S. Smirnov, Zh. Eksperim. i Teor. Fiz. **33**, 804 (1957) [translation: Soviet Phys.—JETP **6**, 619 (1958)].
[3] M. L. Halbert and J. L. Blankenship, Nucl. Instr. Methods **8**, 106 (1960).
[4] L. Koch, J. Messier, and J. Valin, Nat. Acad. Sci.–Nat. Res. Council, Publ. **871**, 52 (1961).
[5] E. Baldinger, W. Czaja, and J. Gutmann, Helv. Phys. Acta **35**, 559 (1962).
[6] G. Fabri, E. Gatti, and V. Svelto, Nucl. Instr. Methods **15**, 237 (1962).

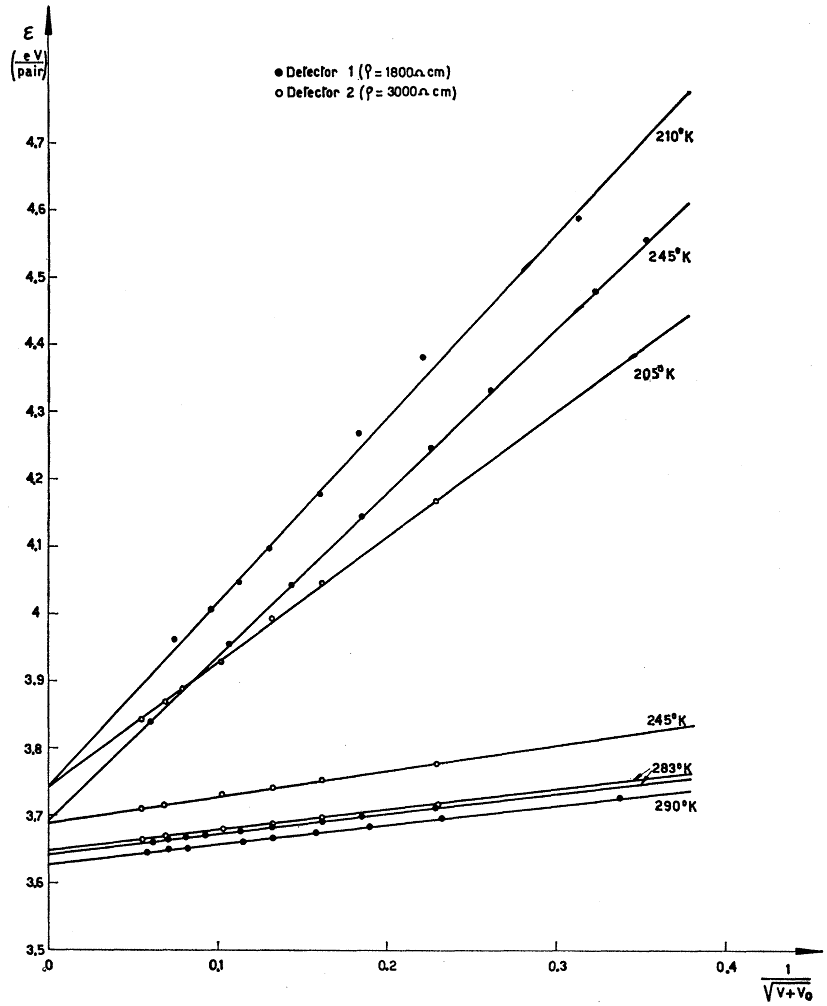

FIG. 2. ε (eV/pair) as a function of $1/(V+V_0)^{1/2}$ for different values of the semiconductor detector temperature.

It is to be noted that the slopes of the straight lines that interpolate the experimental points are, for equal temperatures, different for various detectors; the intercepts of these straight lines with the y axis, hence, the value of ϵ ($=\epsilon_\infty$ by extrapolation to an infinite field), turns out to be equal, within the errors, for all the detectors and is a function only of the temperature.

The slope of the straight lines in Fig. 2 can be explained by considering trapping phenomena. Actually, at low temperature, corresponding to the large slopes of the straight lines, it was possible to observe at the output of the preamplifier-charge compensator system (point A of Fig. 1) tails in the pulses, that can be explained by the release of trapped charge with a time constant of few μsec. The pulse tails decreased for increasing reverse voltage and were no longer observable at high values of bias. Since in our experiments, due to the short time constants of the main amplifier, the variable fraction of trapped charge does not contribute to the output pulse, we observe, as can be inferred from Fig. 2, a dependence of output-pulse amplitudes on the reverse voltage.

The curves of Fig. 2 show that the trapped charge decreases by increasing both temperature and reverse voltage. Roughly speaking, this can be explained by assuming that trapping is a decreasing function of the random speed of the carriers in the space charge region and by remarking that such a speed is a function both of the lattice temperature and of the electric field,[7] neglecting a possible direct dependence of the trapping cross section on electric field. Moreover, by extrapolating to infinite electric field, we get rid of direct recombination in the ionization column, because the time during which the column is held together by its own electric forces vanishes for infinite electric field.

From these remarks, it follows that the intercepts

[7] J. B. Gunn, in *Progress in Semiconductors,* edited by A. F. Gibson (Heywood and Company Ltd., London, 1957), Vol. 2, p. 211.

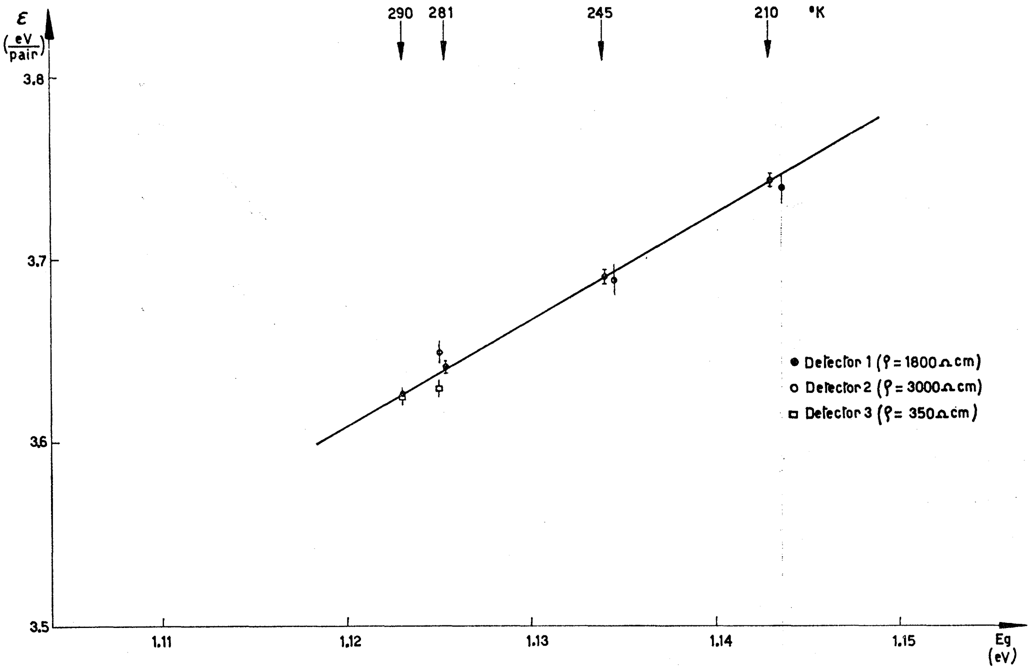

FIG. 3. Values of ϵ_∞ (ϵ for infinite electric field) as a function of forbidden gap E_g.

ϵ_∞ of the straight lines of Fig. 2 can be interpreted as the mean energy for an electron-hole pair generation in silicon, as was done by Baldinger *et al.*[5] The values of ϵ_∞ so obtained are shown in Fig. 3 as a function of the temperature and, hence, of the forbidden gap E_g, as deduced by Smith.[8]

The values so obtained can be compared with the phenomenological theory given by Shockley,[9] who calculated, for the energy of electron–hole pair generation, the expression

$$\epsilon_\infty = 2.2E_g + rE_R, \qquad (1)$$

where $r = L_i/L_R$ is the ratio of carrier mean free path between ionizations and mean free path between scattering by Raman modes, E_R being the energy of a phonon at the Raman frequency. By comparing the equation and our experimental data, we obtain the behavior of rE_R with respect to temperature (Fig. 4).

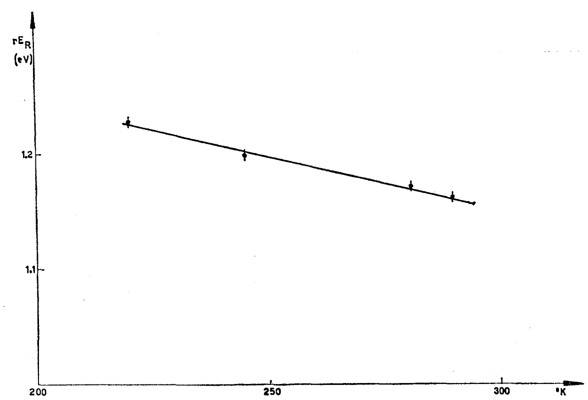

FIG. 4. rE_R of Shockley's expression (1) vs temperature.

ACKNOWLEDGMENTS

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[8] R. A. Smith, *Semiconductors* (Cambridge University Press, New York, 1959), p. 352.
[9] W. Shockley, Czech. J. Phys. **B11**, 81 (1961).