MEASUREMENT OF THE MEAN ENERGY REQUIRED TO CREATE AN ELECTRON-HOLE PAIR IN SILICON BETWEEN 6 AND 77°K

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(Received 4 August 1966)

Recent measurement by Emery and Rabson[1] of ϵ, the mean energy required to create an electron-hole pair with ^{207}Bi conversion electrons at 20°K in lithium-compensated silicon, resulted in a surprisingly high value of 5.22 ± 0.02 eV. Previous measurement of the relative pulse height of ^{207}Bi conversion electrons with the use of surface barrier detectors of 3000 and 6700 Ω-cm resistivity silicon by Dodge et al.[2,3] indicated that ϵ was very close to its room-temperature value of approximately 3.6 eV in the temperature interval 4.2-12°K. More recent measurements of ϵ at 4.2°K by Fabjan, Kenawy, and Rauch[4] are in good agreement with the measurements of Dodge et al.

The measurements of Emery and Rabson together with the measurements of Dodge et al. would imply that ϵ exhibits a sharp peak at a temperature between 12 and 20°K. The existence of such a peak would be embarrassing to the existing theory of ϵ.[5] The theory relates ϵ to the band-gap energy E_g, the ratio λ_i/λ_R of the mean free paths between ionizing and phonon collisions, and the phonon energy $\hbar\omega_R$ at the Raman frequency, by the following expression:

$$\epsilon = 2.2E_g + (\lambda_i/\lambda_R)\hbar\omega_R. \qquad (1)$$

None of these quantities is expected to exhibit rapid variation with temperature. Furthermore, although Dodge et al. observed attenuated pulse heights in both lithium-compensated and non-lithium-compensated silicon detectors in the temperature interval around 20°K, these attenuated pulse heights were not interpreted as due to first-order changes in ϵ. In the case of non-lithium-compensated silicon, the attenuated pulse heights were attributed by Dodge et al. to the long dielectric relaxation time of the undepleted silicon. This assumption successfully explained their extensive experimental data. The mechanism responsible for the attenuation of pulse heights from lithium-compensated silicon detectors was not experimentally explored in detail but was thought to be due to some less interesting process than a change in ϵ. The possibility of structure in ϵ as a function of temperature together with the implicit disagreement between the results of previous measurements provide justification for the remeasurement of ϵ reported here.

Measurement of ϵ as a function of temperature was carried out with the use of the cryostat shown in Fig. 1. A copper disk suspended from the top of the sample-space vacuum container by two thin-walled stainless-steel tubes served as a heat sink for the detector. Four carbon resistors were symmetrically embedded in the disk; two of the resistors were used as thermometers and two were used as heaters to elevate the temperature of the detector–heat-sink system above 4.2°K. The temperature of the copper heat sink was measured

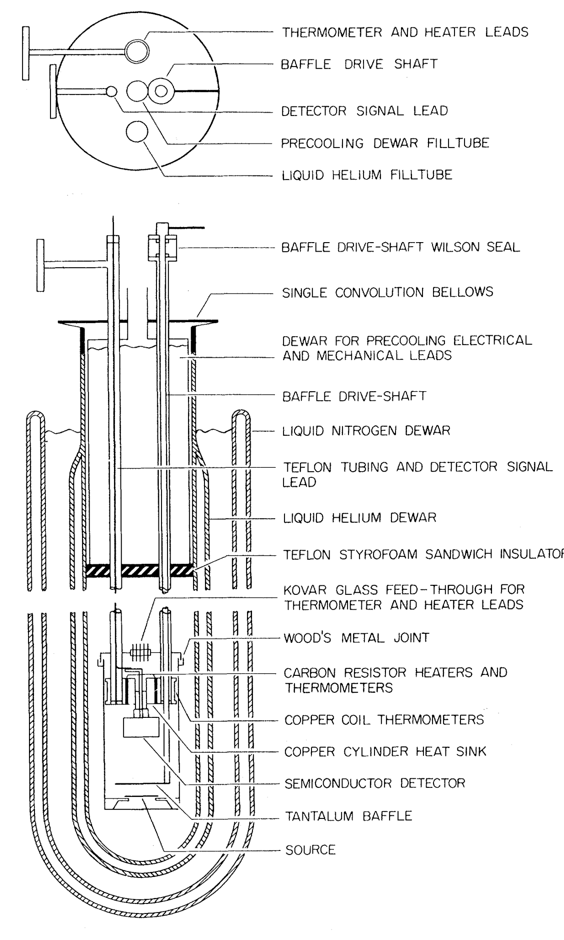

FIG. 1. The cryostat used for the measurement of ϵ.

with the use of a copper-coil resistance thermometer[6] above 20°K and with the use of a carbon resistor thermometer below 20°K. The resistance of the thermometers was measured with a Mueller bridge. The thermometers were calibrated at the liquid nitrogen and helium boiling points, with an absolute accuracy ±0.5°K. The relative accuracy of the thermometers in their respective temperature ranges was estimated to be ±0.1°K. Measurements as a function of time at constant thermometer temperature were made to ensure that the detector and the thermometers were in temperature equilibrium. Typically, measurements at a given temperature were made over a two-hour period. The accuracy of the bias-voltage measurements was ±0.01%. Detector bias voltages at a given temperature were selected at random to minimize possible hysteresis effects.

The problems associated with long dielectric relaxation times of undepleted layers in silicon detectors in the temperature interval between ~12 and 30°K outlined above were eliminated by use of a detector (525 μ thick) which could be totally depleted at room temperature (and all lower temperatures) with a modest bias voltage (120 V). (The dielectric relaxation time of the undepleted layer of a high-resistivity detector typically approaches 1 μsec at 25-30°K and rapidly becomes larger than 1 msec as the temperature decreases. These long time constants produce attenuated output signals in amplifiers with finite bandwidths.)

Two basic mechanisms, trapping and recombination, are responsible for imperfect charge collection at finite charge-collecting field strengths. The ratio of the collected charge to the liberated charge, the charge-collection efficiency η, is given by $\eta=\eta_T+\eta_R$, where η_T takes into account charge loss by trapping and η_R charge loss by recombination. With the use of the relationship $\Delta q=e\Delta X/d$,[7] it can be shown that η_T is given to the first order in γ_e, γ_h by

$$\eta_T=\int_0^R N(y)\left[1+\gamma_{\rm h}\left\{\frac{(1+\alpha)}{2\alpha}\ln\frac{1+\alpha-2\alpha y/d}{1+\alpha}+\frac{y}{d}\right\}+\gamma_{\rm e}\left\{\frac{(1-\alpha)}{2\alpha}\ln\frac{1+\alpha-2\alpha y/d}{1-\alpha}-\left(1-\frac{y}{d}\right)\right\}\right]dy\bigg/\int_0^R N(y)dy \quad (2)$$

for a totally depleted surface barrier detector. In this formula $N(y)$ is the ionization density produced by the primary radiation, R is the range of the primary radiation, α is the ratio of the voltage V_d required to totally deplete the detector to the applied voltage V, and $\gamma=d/2\mu\tau V_d$, where d is the detector width and $\mu\tau$ is the mobility lifetime product. The subscripts e and h refer to electrons and holes, respectively. For $\alpha\ll1$,

$$\eta_T=1-\left[\gamma_{\rm h}\alpha\int_0^R N(y)\frac{y^2}{d^2}dy-\gamma_{\rm e}\alpha\int_0^R N(y)\left(1-\frac{y}{d}\right)^2dy\right]\bigg/\int_0^R N(y)dy \quad (3)$$

or $\eta_T=1-\text{constant}/V$.

It is much more difficult to estimate the dependence of η_R on bias voltage. In the absence of detailed knowledge of the dependence of η_R on bias voltage, we assume a dependence on V not stronger than that predicted by (2). This is expected to be a conservative estimate. The reciprocal of the pulse-height analyzer channel in which a conversion-electron peak occurred at a particular bias voltage, which provides a relative value of $\eta\epsilon$, is shown in Fig. 2 as a function of the reciprocal of the bias voltage for several temperatures. The straight lines represent a least-squares fit of the data to an expression of the form of (3).

Spectra from a 30-μCi ^{207}Bi source were obtained with the use of standard electronic components (amplifier 10-to-90% rise time of 1.5 μsec, fall time of 4 μsec). The positions (pulse-height analyzer channel number) of the four most prominent conversion-electron lines were divided by the position of a simultaneously recorded pulser peak to correct for amplifier gain excursions (the maximum gain excursion during the 106-h run was 1.8%). The data from each of the conversion electron lines for which $\alpha\lesssim1$ were fitted to an expression of the form of (3) with a least-squares fit. The least-squares fits were used to determine the peak position extrapolated to infinite bias voltage. The peak position extrapolated to infinite bias voltage provided a relative value of ϵ. These four relative values for ϵ were then suitably normalized and combined. The value of ϵ normalized to the average value in the 6-77°K interval is shown in Fig. 3. The normalized values of Fig. 3 can be multiplied by the absolute value of ϵ

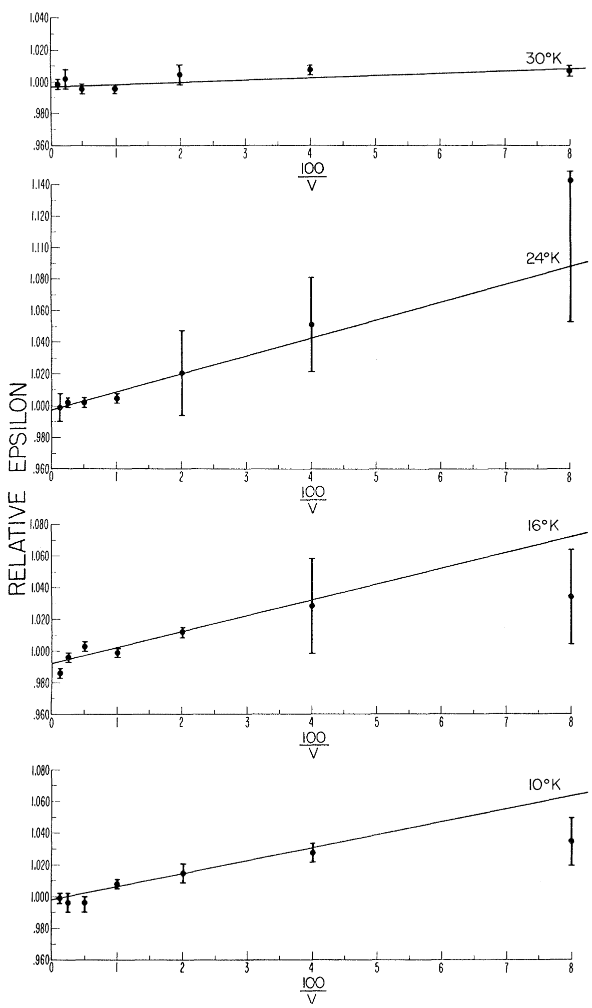

FIG. 2. Relative values of the product ηe, where η is the charge collection efficiency, for 480-keV ^{207}Bi conversion electrons as a function of the reciprocal of the bias voltage.

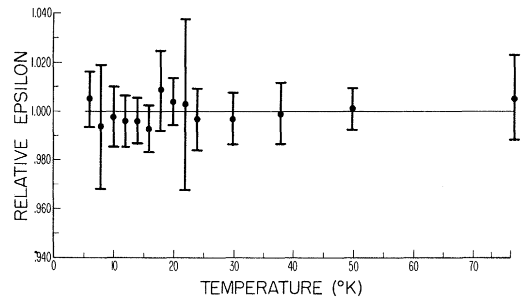

FIG. 3. The mean energy required to create an electron-hole pair normalized to the average value in the temperature interval 6-77°K.

(3.72 ± 0.11 eV/electron-hole pair at 77°K) given by Fabjan, Kenawy, and Rauch to obtain values of ϵ between 6 and 77°K.

Our data show that ϵ does not exhibit any pronounced maxima in the region around 20°K. The slight slope in the data shown in Fig. 3 can be explained by the Shockley theory by assuming that the only temperature-dependent quantity in (1) is the band-gap energy. This assumption leads to the prediction that ϵ should decrease by ~0.02% as the temperature decreases from 77 to 6°K. The experimental value is 0.001 ± 0.02%.

The authors wish to acknowledge many enlightening discussions with Dr. J. A. Coleman and Dr. N. Winogradoff on recombination processes in semiconductor devices.

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