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LENGTH CHANGE OF ELECTRON-IRRADIATED GERMANIUM*

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The purpose of this Letter is to report length contractions in n-type germanium due to electron bombardment at liquid-helium temperature and to propose the interpretation that these length contractions are produced by an electronic effect which dominates over the expansions caused by the atomic effect. In contrast to n type, the length changes of a p-type sample irradiated under the same conditions are smaller by more than an order of magnitude.

Simultaneous length and conductivity changes have been observed in degenerate n-type germanium single crystals during bombardment by 4.5-MeV electrons at liquid-helium temperature and during subsequent isochronal annealing. The irradiated portion of the sample measured 5 mm long, 4 mm wide, and 0.7 mm thick. The linear-accelerator electron beam passed through the sample in the [001] direction, and the length changes were measured in the perpendicular [110] direction. Changes in length of the sample produced changes in the spacing of a system of parallel plate capacitors, and these capacitors were compared with a standard capacitor by means of an ac ratio bridge. All capacitors were of the three-terminal type and the method of measurement was similar in principle to that used by White.[1] The sample and supporting framework for the capacitors was shaped from one large single crystal of germanium to minimize extraneous effects. The sensitivity and long-term stability of the system were such that changes in length on the order of 0.3 angstrom were detectable. Annealing was of the isochronal type and was accomplished by means of a heater and double exchange gas-vacuum system. The sample was held at each annealing temperature for 10 minutes before recooling to liquid-helium temperature. All measurements were made at liquid-helium temperature.

Degenerate n-type material was chosen for our initial experiments, rather than intrinsic material as used by other investigators, since the electrical measurements by Klontz and MacKay[2] and the stored-energy measurements by Singh and MacKay[3] have shown that irradiation effects in n-type material are more than 100 times greater than in p-type material.

Figure 1 shows the length change in a degenerate n-type sample as a function of the irradiation flux. From this plot $\Delta L/L = -6.2\times10^{-24}$ per incident electron/cm^2. Figure 2 shows the results for the same sample during a later run consisting of a relatively light bombardment followed by an isochronal anneal with points taken every 5 degrees. The general characteristics of the length and conductivity curves are quite similar. An annealing peak between 35 and 40°K is evident in both curves. A second sample of degenerate n-type material showed similar behavior.

Irradiation of a degenerate p-type sample at liquid-helium temperature resulted in a barely detectable contraction. The length-change effect is at least an order of magnitude smaller in p type than in n type. The fact that length

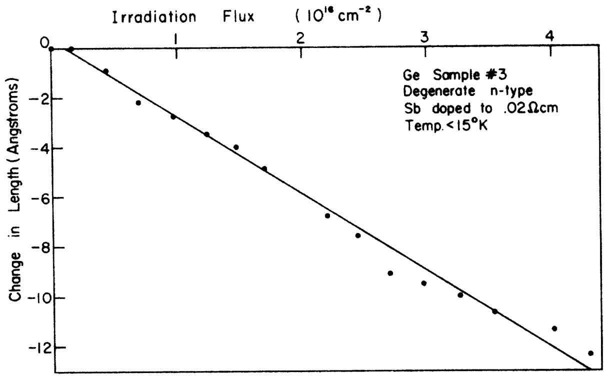

FIG. 1. Length change vs flux for degenerate n-type germanium. The irradiated portion of the sample is 5 mm long.

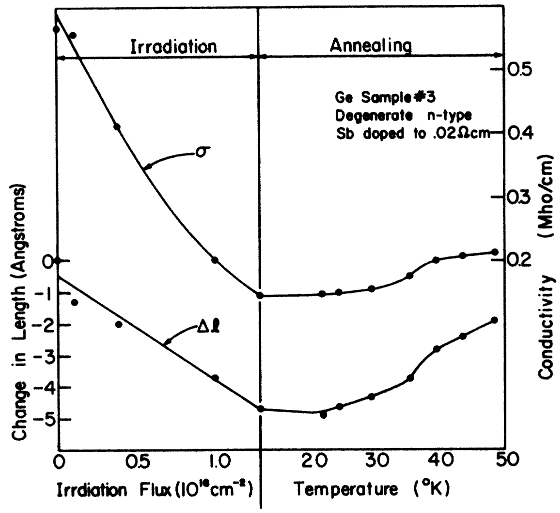

FIG. 2. Length change and conductivity of degenerate n-type germanium during relatively short bombardment and isochronal anneal. All measurements are taken at 4.2°K. The sample has a total irradiation history of 1.3×10^{17}/cm^2. A 75°K anneal was performed prior to this plot.

changes in p type are very small compared to changes in n type is consistent with the results of electrical measurements on irradiated germanium.

The observed contractions in length are in contrast to the expansions previously reported in radiation damage experiments. Vook and Balluffi[4] irradiated intrinsic germanium at 25°K and 85°K with 10.2-MeV deuterons and measured an expansion of $\Delta L/L = +1.5\times10^{-21}$ per incident deuteron/cm^2. Wittels[5] irradiated intrinsic germanium at 40°C with fast neutrons and measured an increase in lattice parameter of $\Delta C/C = +1.4\times10^{-24}$ per incident neutron/cm^2. Vook[6] irradiated intrinsic germanium at 86°K with 2-MeV electrons and reported a barely detectable value of $\Delta L/L = +(1.5\pm3.9)\times10^{-25}$ per incident electron/cm^2.

Irradiation by heavy particles is considered to produce clusters of defects or "thermal spikes." Only in the case of electron irradiation can one reasonably well expect to produce the fundamental isolated point defects which lead toward a more straightforward interpretation.

The customary interpretation of length-change experiments has been to attribute the length changes entirely to the vacancies and interstitials (or more complicated clusters) which are formed by the irradiation and recombine during the annealing. The application of this atomic interpretation to our results would lead to the conclusion that the fractional atomic volume change per vacancy-interstitial pair (f_v+f_i) is a negative quantity, whereas normally a vacancy-interstitial pair is believed to produce an expansion of the lattice.

However, we believe that an electronic effect exists which must be taken into consideration. Keyes[7] evaluated the effect of the electronic part of the strain energy on the elastic properties of germanium and found that the volume is dependent upon the carrier concentration. He concluded that both electrons and holes have the same effect of increasing the lattice parameter by the amount $\Delta C/C = +1.4\times10^{-24}n$, where n is the concentration of free electrons or free holes.

Figielski[8] calculated the expansion effect due to electron-hole pairs and computed $\Delta C/C = +3\times10^{-24}N$, where N is the concentration of electron-hole pairs, which is in agreement with the sum of the two effects as computed by Keyes. Figielski succeeded in measuring this effect in his photostriction experiment. The experimentally determined magnitude was a factor of two larger than his computed value.

In our experiment the electron bombardment of n-type germanium produces defects which act as double acceptors. This reduces the number of free electrons in the conduction band which should cause a sample contraction. Therefore, the measured length change can be expressed as the sum of two separate effects:

$$\Delta L/L = \text{atomic effect} + \text{electronic effect}. \quad (1)$$

The electron removal rate for 4.5-MeV electrons incident on nondegenerate n-type germanium at liquid-helium temperature has recently been measured[9] and found to be $dn/d\Phi = -13$. Assuming that this removal rate is also valid for degenerate n-type material and assuming Keyes' calculated value for the electronic effect, then the expected electronic effect is -18.2×10^{-24} per incident electron/cm^2. From this and our observed length change obtained from Fig. 1, which was $\Delta L/L = -6.2\times10^{-24}$ per incident electron/cm^2, Eq. (1) then yields an atomic effect of $\Delta L/L = +12.0\times10^{-24}$ per incident electron/cm^2. By using the electron removal rate $dn/d\Phi = -13$ and the fact that each vacancy-interstitial pair formed is a double acceptor, the change in length per vacancy-interstitial pair is calculated to be $\Delta L/L = +1.85\times10^{-24}$ per defect pair/cm^3. This implies a fractional atomic-volume change per vacancy-interstitial pair $(f_v + f_i) = +0.25$.

There are several factors which contribute to the uncertainty of the above calculations. Keyes' treatment compared the presence of electrons in the conduction band with their complete absence from the crystal, whereas in our case, electrons removed from the conduction band by the irradiation are trapped on tightly bound acceptor levels in the forbidden gap, which may quite plausibly not cause as large an effect. More work needs to be done concerning the dependence of the electronic effect upon the energy levels of the traps involved. Other factors are the rather large experimental uncertainties in the values of the deformation-potential constants needed in Keyes' calculation and the present uncertainty in the electron removal rate for degenerate material.

Even considering these uncertainties, it appears that the atomic effect is causing an expansion, but the magnitude of the contraction due to the electronic effect is larger, so that the observed contraction represents the difference between the two effects. It is hoped that our subsequent measurements will enable us to separate the two effects, and therefore allow us to determine both the electronic effect and the atomic effect experimentally.

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DOUBLE-QUANTUM PHOTOELECTRIC EMISSION FROM SODIUM METAL*

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Theoretical calculations for the two-photon surface photoelectric effect in a metal have been given by Smith[1] and others.[2-4] The theoretically predicted double-quantum photocurrent is proportional to the square of the incident radiation power and inversely proportional to the area irradiated.[1] Sonnenberg, Heffner, and Spicer[5] have recently reported on the two-quantum photoelectric effect from a semiconductor in which the volume photoelectric effect predominates, giving rise to relatively large currents. We would like to report the first observation of double-quantum surface photoelectric emission from a metal. Two-photon photoelectric current was obtained from a sodium surface of work function 1.95 eV when irradiated by photons of energy 1.48 eV from a GaAs laser.

The experimental apparatus is shown in the block diagram of Fig. 1. The radiation source was a pulsed GaAs semiconductor injection laser operated at 77°K and emitting a peak power of 400 mW at 8400 Å. A translation stage supporting a lens permitted the laser radiation to be focused onto a vapor-deposited sodium surface from which double-quantum photoemission was to be observed. This surface acted as a cathode for a specially constructed electron multiplier with a gain of 50 000. The amplified current was passed through a 1-MΩ load resistor followed by a low-noise preamplifier and a lock-in amplifier. Phase-sensi-