tinctive types, this classification apparently having little or no relation to the steady-state characteristics. Typical response curves are shown in Fig. 2. In each case the forward current between pulses was 40 milliamperes and the potential V was carried from a small positive value to -50 volts with a rise time of approximately 0.03 microsecond. Curve A represents a large class of varistors showing no appreciable effect of hole withdrawal. Curve B shows a small or moderate burst, having an exponential decay with a time constant of the order of 0.1 microsecond. In curve C, the reverse current first rises roughly in proportion to the voltage, then drops very abruptly and once more rises, after which

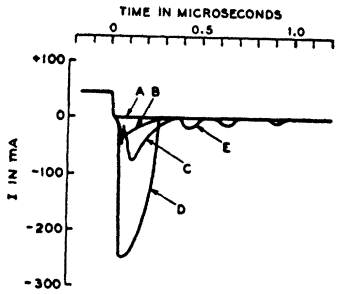

FIG. 2. Pulse study of germanium diodes.

the decay is approximately exponential. Curve D shows a curious case (not particularly rare, however) representing a momentary dissipation of over 10 watts. The decaying portion of the wave form is concave upward, reaching the zero line with a remarkably sharp discontinuity. This phenomenon may be explainable in terms of the Herring shock wave.[2] Some units represented by curve D also display "bubbles" of current (curve E). These bubbles are usually observed upon initial application of the test conditions, and commonly decrease in amplitude and vanish within five or ten seconds. The bubbles, or trains of them, recur with each applied pulse but may progress gradually toward the right or left on the time axis during their appearance.

The large bursts of power associated with these effects may be expected to change the characteristics of the units, and Mr. R. R. Blair has suggested that they may account for certain previously unexplained cases of damage to varistors in switching applications. Further studies using steep wave fronts backed by ample power appear likely to contribute to the basic understanding of semiconductors.

We wish to express our thanks to Mr. W. L. Shockley and other members of Bell Laboratories for helpful suggestions in connection with this work.

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The Elastic Constants of Germanium Single Crystals

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THE interest in the properties of germanium single crystals arising from their use as semiconductors and transistors has led us to make measurements of the elastic constants of two single crystals.

One crystal (sample A) was grown from the melt, and two orientations were determined approximately by x-rays. Longitudinal and shear wave measurements of velocities were made along the 100 and 110 directions by the process described in an earlier communication.[1] This process determines the velocity within about

TABLE I. Elastic properties of sample A.

Direction of propagation	Direction of particle motion	Type of mode	Equation for velocity	Measured velocity cm/sec. $\times 10^{-5}$	Elastic constants dynes/cm^2 $\times 10^{-11}$
110	110	long	$v=\left(\frac{c_{11}+c_{12}+2c_{44}}{2\rho}\right)^{\frac{1}{2}}$	5.39	15.5
110	$1\bar{1}0$	shear	$v=\left(\frac{c_{11}-c_{12}}{2\rho}\right)^{\frac{1}{2}}$	2.75	4.06
110	001	shear	$v=(c_{44}/\rho)^{\frac{1}{2}}$	3.54	6.70
100	100	long	$v=(c_{11}/\rho)^{\frac{1}{2}}$	4.92	12.95
100	010	shear	$v=(c_{44}/\rho)^{\frac{1}{2}}$	3.54	6.70

$\frac{1}{2}$ percent. The longitudinal and shear-wave velocities are shown by Table I. The elastic constants are calculated from the velocity measurements using a density of 5.35. From these measurements we obtain the elastic constants (in dynes/cm^2)

$$c_{11}=12.92\pm0.12\times10^{11},\quad c_{12}=4.79\pm0.12\times10^{11},$$
$$c_{44}=6.70\pm0.07\times10^{11}.$$

The other crystal (sample B) was obtained by an improved method for growing pure germanium crystals[2] and a more accurate method was devised for measuring velocities for small samples.[3] Hence it was thought worth while to re-measure the elastic constants. A carefully oriented 110 section was used and the measured velocities are shown in Table II. From these values the three elastic constants are found to be (in dynes/cm^2)

TABLE II. Elastic properties of sample B.

Direction of propagation	Direction of particle motion	Type of wave	Equation for velocity	Measured velocity cm/sec. $\times 10^{-5}$	Elastic constants dynes/cm^2 $\times 10^{-11}$
110	110	long	$v=\left(\frac{c_{11}+c_{12}+2c_{44}}{2\rho}\right)^{\frac{1}{2}}$	5.410 ± 0.005	15.660 ± 0.03
110	$1\bar{1}0$	shear	$v=\left(\frac{c_{11}-c_{12}}{2\rho}\right)^{\frac{1}{2}}$	2.751 ± 0.002	4.049 ± 0.008
110	001	shear	$v=(c_{44}/\rho)^{\frac{1}{2}}$	3.547 ± 0.003	6.730 ± 0.01

$$c_{11}=(12.98\pm0.04)\times10^{11};\quad c_{12}=(4.88\pm0.04)\times10^{11};$$
$$c_{44}=(6.73\pm0.01)\times10^{11}.$$

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[2] This method is described by G. K. Teal and J. B. Little in a paper to be presented by title before the Oak Ridge meeting of the Physical Society (March, 1950).
[3] This method for measuring velocities by a phasing technique was described by H. J. McSkimin, J. Acous. Soc. Am. **22**, 86 (1950).

Energies of Some Gamma-Rays from ThC'', RaC, and Na^{24}

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February 23, 1950

PRECISE values for the energies of the gamma-rays of nominal values 2.62 Mev from ThC'', and 2.2 Mev and 2.4 Mev from RaC, have recently become desirable in order to evaluate more accurately the binding energy of the deuteron.[1,2] Several measurements of the energies of these gamma-rays have been made and the results are presented in Tables I, II, and Fig. 3. In addition some measurements of the energy of the Na^{24} gamma-ray of nominal value 2.76 Mev, performed for another purpose, are given in Table II as they may be of interest in future disintegration studies.

TABLE I. Measurement of the 2.615-Mev ThC″ gamma-ray, using composite thin sources, by comparison of the "X" line from ThC″ with the K internal conversion line from the 0.4112±0.0001-Mev transition following Au^{198} decay.

Trial	X-line momentum (gauss-cm)	Gamma-ray energy (Mev)	Weight
1	9992	2.616	1
2	9992	2.616	1
3	9986	2.614	1
4	9990	2.615	1
5	9982	2.613	2
6	9989	2.615	2
Weighted mean	9988±13	2.615±0.004	

Previous studies of these gamma-rays have resulted in energy values ranging from 2.613 to 2.620 Mev for the ThC″ gamma-ray,[3,4] and energy values of 2.198 and 2.200 Mev,[5,6] and of 2.432 and 2.420 Mev for the two RaC gamma-rays,[5,6] while the most recent spectrometric determination of the Na^{24} gamma-ray energy has yielded the value[7] 2.758 Mev.

The measurements reported here are based upon comparisons of the gamma-rays with either the 0.4112±0.0001-Mev transition following Au^{198} decay[8] or the 1.3316±0.0010-Mev gamma-ray[9] from Co^{60}, utilizing internal or external conversion. The ThC″ gamma-ray energy has been found in both ways, while all other determinations employ the externally converted radiations. An iron-free single lens beta-ray spectrometer of focal length 9 cm was used, adjusted for line widths at half-maximum intensity ranging, in the different trials, from 1.6 to 1.9 percent in momentum. The supply current to the magnet was kept constant to within one part in 10^4, and was measured to the same accuracy by potentiometric determination of the potential drop across a single manganin resistor.

All sources and radiators used were 4 mm in diameter. The measurement of the ThC″ gamma-ray energy, as illustrated in Fig. 1, was effected using a composite thin source prepared by irradiating a disk of gold leaf, 0.2 mg/cm² thick, in the Chalk River pile to an activity of 0.2 to 0.3 mc. After transfer to the end of an aluminum rod of the same diameter, which then formed the source holder, RdTh active deposit was collected on the active gold over a period of 2 to 3 days. At the time of use the ThB activity present amounted to about 30 μc. Care was taken to confine the deposit to the gold surface, and visual inspection of autoradiographs using inactive gold showed the deposit to be uniform.

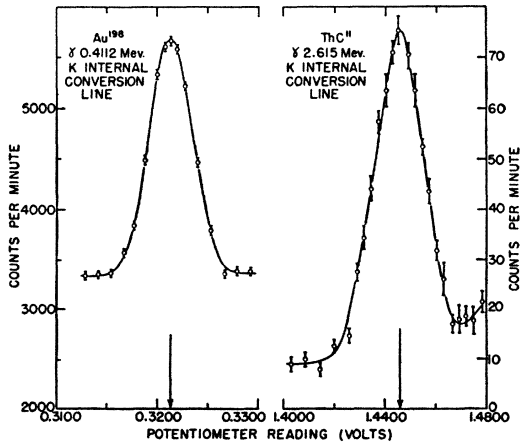

FIG. 1. (Left) K internal conversion line from the 0.4112±0.0001-Mev transition following Au^{198} decay. The continuum under the line includes 2040 counts per minute from the RdTh active deposit of the composite source. (Right) "X" line from ThC″. The rise at the high energy side is due to the neighboring L line. The vertical lines through the experimental points represent the standard deviations of the observed counting rates.

TABLE II. Gamma-ray measurements by comparison of external conversion K lines.

Gamma-ray nominal energy (Mev)	Comparison gamma-ray (Mev)	Trial	Weight	Radiator (mg/cm²)	Gamma-ray energy (Mev)	Weighted mean (Mev)
2.62 ThC″	1.3316 Co^{60}	1	1	25 U	2.615	
2.62 ThC″	1.3316 Co^{60}	2	1	25 U	2.617	2.616±0.006[a]
2.62 ThC″	1.3316 Co^{60}	1	1	8 Th	2.616	
2.62 ThC″	1.3316 Co^{60}	2	1	8 Th	2.614	2.615±0.005[a]
2.2 RaC	2.615 ThC″	1	2	43 U	2.208	
2.2 RaC	2.615 ThC″	2	2	25 U	2.209	
2.2 RaC	2.615 ThC″	3	1	25 U	2.205	2.208±0.006
2.76 Na^{24}	1.3316 Co^{60}	1	1	8 Th	2.756	
2.76 Na^{24}	1.3316 Co^{60}	2	2	8 Th	2.755	
2.76 Na^{24}	1.3316 Co^{60}	3	2	8 Th	2.755	2.755±0.005

[a] The value of 2.615 Mev as determined by the K line internal conversion comparisons of Table I is recommended over these results because of the superiority of the method with respect to thinness of source.

"Peak" measurements have been used in taking the ratio of momenta, the peak being taken as the axis of symmetry of the upper half of the line.

The series of external conversion measurements, one of which is plotted in Fig. 2, were made using U and Th radiators. The radiator, placed on the end of a brass or aluminum post, was left

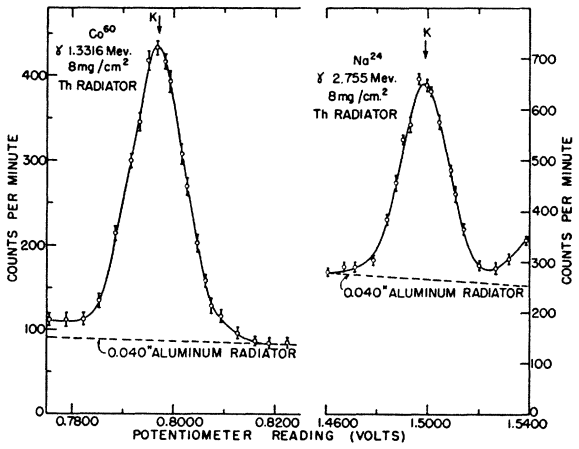

FIG. 2. (Left) K line from external conversion of the 1.3316±0.0010-Mev Co^{60} gamma-ray. The rise at the low energy side of the line is due to the L and M lines of the 1.172-Mev gamma-ray. (Right) K line from external conversion of the 2.755-Mev Na^{24} gamma-ray. The rise at the high energy side of the line is due to the neighboring L line.

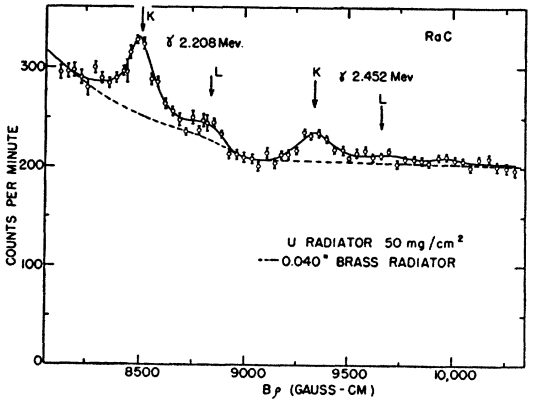

FIG. 3. Secondary electron spectrum of RaC above 2 Mev. The slight rise in the Compton distribution under the L line (2.208-Mev gamma-ray) is due to photoelectrons ejected from the thick brass radiator.

undisturbed during a trial. The post had been previously drilled out from the rear to within 0.040 in. of the radiator, and the sources were placed in position, alternately, from outside the vacuum chamber. Source strengths used were 3 mc RdTh, 7 mc Co^{60}, 5 to 10 mc Na^{24}, and 5 mc Ra. Peak determinations again were employed in taking the momentum ratios.

The secondary electron spectrum of RaC from 2.1 to 2.7 Mev is shown in Fig. 3. The second gamma-ray has an energy of 2.452 $\pm$0.012 Mev, and an intensity 35 to 40 percent of that of the 2.208-Mev gamma-ray. There is also some slight but inconclusive evidence of a weak gamma-ray of energy about 2.6 Mev.

Errors assigned include estimates of uncertainty in current measurement, relative peak shift, stray field correction, and location of the line peaks. The statistical accuracy and number of the experimental points form the basis for the weights assigned in column 4 of the Tables I and II.

It is a pleasure to acknowledge the aid and advice of Dr. L. G. Elliott, and the assistance rendered by Mr. D. W. Smellie.

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Infra-Red Absorption of Silicon*

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In a previous communication[1] the measurements on infra-red transmission through bulk silicon were reported. It was pointed out that for frequencies lower than that required for excitations across the forbidden energy gap the magnitude of absorption does not agree with the classical Drude theory for free charge carriers.

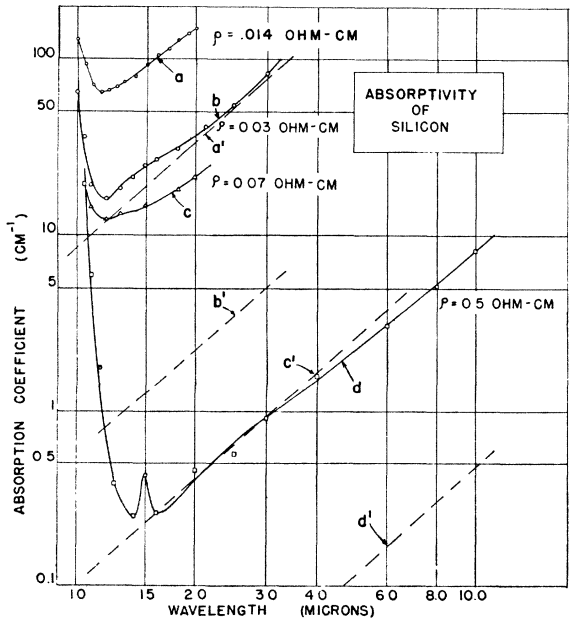

FIG. 1. Absorption coefficient as function of wave-length. The solid curves a, b, c, and d are determined experimentally. The corresponding dashed curves a', b', c', and d', are calculated from Eq. (2).

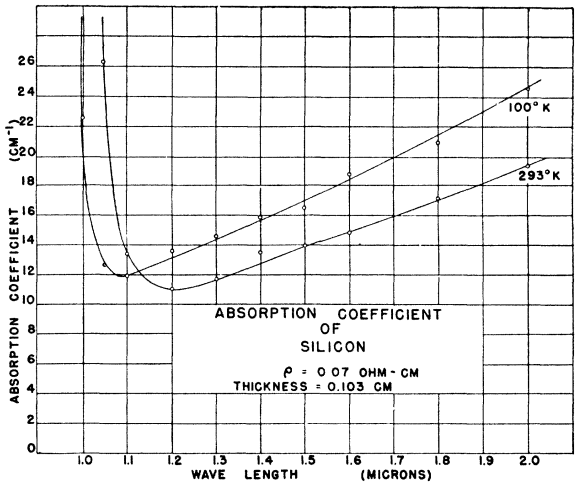

FIG. 2. Typical temperature dependence of absorption coefficient for samples with sloping Hall curves in the impurity range.

Results of further measurements on bulk samples of different resistivities are shown in Fig. 1. The dotted lines are calculated according to the Drude theory

$$\sigma = nk\nu = (e^2/2\pi m)[n_c\gamma/(\nu^2+\gamma^2)]. \quad (1)$$

In our measurements $\nu \gg \gamma$. In terms of the d.c. conductivity σ_0 and Hall constant R we have

$$\sigma = (e^2/4\pi^2m^2)(3\pi/8R^2\sigma_0\nu^2). \quad (2)$$

The absorption coefficient is

$$\mu = 4\pi k/\lambda = 4\pi\sigma/nc. \quad (3)$$

The calculated values are seen to be too low in all cases. As pointed out previously, the discrepancy is even larger for germanium. Quantum mechanically the absorption due to free carriers can be regarded as a broadening of the zero-frequency absorption line due to the scattering of electrons by the lattice. Such treatment gives an expression[2] idential to (1). However, for $\nu \gg \gamma$ the absorption should be regarded more appropriately as a two-stage process, the absorption of a photon leading to an intermediate state which goes over to a final state by interaction with the lattice.[3] In this case γ' determining the absorption will not be the same γ for d.c. conduction. This could be the reason for the discrepancy.

For a given frequency, μ of the different samples plotted against $n_c\gamma$ cannot be fitted well by a straight line. The plot of μ *versus* n_c seems to give a better fit to a straight line. Measurements on more samples of different varieties are being made to obtain a more reliable conclusion. If μ is really proportional to n_c, a possible explanation is an overlapping of energy bands. Mullaney[4] has shown that silicon has two bands of zero width at the top of the group of filled bands below the conduction band. Absorptions producing transitions of holes at the top to the interior of the filled bands should therefore extent to very low frequencies. Such absorption without the aid of lattice interaction will be just proportional to the number of holes. Measurements on an N-type sample showed that the absorption is comparable with that expected of P-type samples of the same n_c. Although Mullaney's treatment does not give narrow bands at the bottom of the conduction bands the treatment is admittedly unsatisfactory for those bands.

Measurements at low temperatures revealed absorptions due to the ionization of the impurity centers. Figure 2 shows a typical case where the absorption at 100°K is *higher* than at room temperature. The impurity activation energy is 0.058 ev and the impurity concentration N is 1.1×10^{18} as calculated from the Hall