TABLE I. Room temperature properties of various samples, and characterization of their spectra at liquid nitrogen temperature.

Sample No.	Type	ρ(ohm cm) 300°K	τ(μsec) 300°K	Im- purity[a]	Spectrum ($\sim$80°K)[b]
M103	p	30	200		normal (1)
P104	p	0.5	55		abnormal (2)
M104	n	15	400		normal (1)
PC201	n	7	39		abnormal (3b)
DP277	n	5	55		normal (1)
E-30	n	25	10	Au	normal (1)
DP177	n	2	7	Au	normal (1)
M95[c]	n	45	$\sim$3	Fe	abnormal (3b)
M108[c]	n	40	$\sim$3	Fe	abnormal (3a)
M56	n	30	$\sim$3	Fe	normal (1)
M105	n	35	$\sim$3	Fe	abnormal (3a)
P11	n	30	$\sim$3	Fe	abnormal (3a)

[a] Other than conventional donors or acceptors.
[b] The numbers in brackets refer to the figure which best represents the observed spectrum at liquid nitrogen temperatures.
[c] Breakdown diodes.

peak should increase faster than the background. Unfortunately, when one goes to very high signal levels appreciable distortion in the observed spectrum will result because of the saturation of the M/C ratio. It might then be impossible to observe the effects of trap saturation even if these existed. Over the range of injection curves where our data are meaningful, we have not seen the saturation effect. Increasing the ambient light level in an attempt to saturate the traps dc-wise, likewise produced no observable effect.

CONCLUSIONS

The spectrum of injected carriers in clean germanium is shown to be qualitatively identical with the spectrum of holes in p-type germanium in its wavelength and temperature dependence. In some germanium samples, anomalous spectra are observed at low temperature. These anomalies may be caused by the trapping of injected carriers.

ACKNOWLEDGMENT

Semiconducting Cadmium Telluride

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(Received August 17, 1954)

Both n-type and p-type conductivity can be obtained in cadmium telluride. The intrinsic band gap of cadmium telluride is 1.45 ev. Electron and hole mobilities are at least 30 cm²/volt sec. The activation energies of p-type impurities are much larger than those of n-type impurities in cadmium telluride, indicating an explanation for the failure to find p-type conductivity in cadmium sulfide or selenide.

INTRODUCTION

MEASUREMENTS on the conductivity of cadmium sulfide and cadmium selenide have indicated the presence of only n-type conductivity.[1] The purpose of this note is to report that both n-type and p-type conductivity can be obtained in cadmium telluride, the third member of this family.

EXPERIMENTAL

Crystals of CdTe were grown from a slow cooling of the reaction product of New Jersey Zinc "super-pure" Cd, American Smelting and Refining "high-purity" Te, and the proportion of impurity desired.[2] Both Cd and Te were further purified by the zone-melting process[3] before being used in this preparation. For test, crystals were shaped into approximately rectangular samples, the ends of which were plated with nickel and copper, and then leads were soldered to the plated portions.

RESULTS

Figure 1 gives the transmission data[4] from which a band gap of about 1.45 ev can be determined for CdTe. This gap should be compared with the gap of CdSe, 1.74 ev, and the gap of CdS, 2.42 ev.

It is found in general that n-type conductivity is obtained in CdTe if impurities are chosen from groups III or VII of the Periodic Table, and p-type conductivity is obtained for impurities from groups I or V. Typical point-contact rectification curves are given in Fig. 2 for n-type CdTe:Ga and p-type CdTe:Sb.

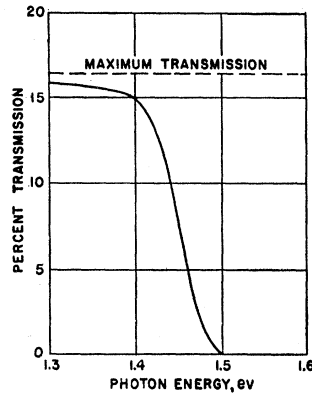Hall effect measurements give a value of 30 cm²/volt sec as a lower limit for the mobility in both n-type and

[1] R. W. Smith, RCA Rev. **12**, 350 (1951).
[2] Much of the growth and treatment of these crystals was carried out by E. Blanche Lawton.
[3] W. G. Pfann, J. Metals **194**, 747 (1952).
[4] Measurements by H. B. DeVore.

FIG. 1. Percent transmission of a CdTe crystal as a function of the incident photon energy.

FIG. 2. Point-contact rectification curves for (1) n-type CdTe:Ga, and (2) p-type CdTe:Sb.

p-type CdTe. It is highly probable that the drift mobility for electrons is, at least, an order of magnitude larger.

The activation energy for n-type impurities is found to be much smaller than the activation energy for p-type impurities. Conductivity measurements to liquid helium temperature[5] give an activation energy of about 0.003 ev for iodine impurity in CdTe. Other n-type impurities have a comparably small activation energy.

The results of measurements of conductivity as a function of temperature for several p-type impurities are given in Table I. Only those crystals which showed ohmic current-voltage curves between applied voltages of 0.05 and 600 volts (for both polarities) were used for these experiments. All of the plots of log conductivity against $1/T$ obtained, consist of a single straight line between liquid nitrogen temperature and 100°C. The activation energies for these p-type impurities vary from about 0.3 to 0.5 ev.

The large activation energies for p-type impurities in CdTe make possible an explanation for the failure to detect any p-type CdS or CdSe; it is probable that the activation energies of p-type impurities are even larger in CdS or CdSe, for which the band gap is larger than in CdTe. (This is true of n-type impurities, e.g., the activation energy of iodine in CdS is found to be about 0.02 ev.)

TABLE I. Activation energies for p-type impurities in CdTe.

Impurity	Percent added[a]	Conductivity, 25°C, mho/cm	Activation energy, ev
Li	0.1	3×10^{-3}	0.27
Sb	0.01	3×10^{-5}	0.36
P	0.01	4×10^{-6}	0.38
Ag	0.1	5×10^{-7}	0.49
Pb	0.01	8×10^{-8}	0.51

[a] Weight percent added in the preparation; the proportion of impurity in the final crystals is not known.
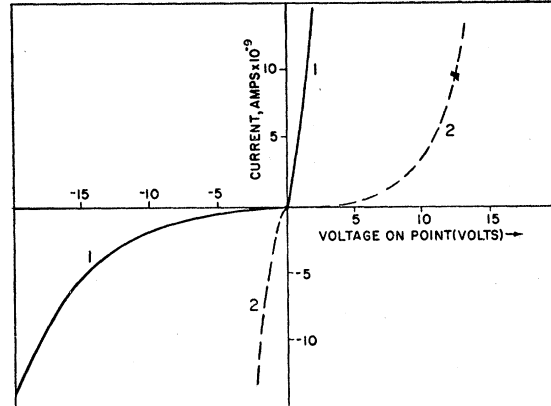
[5] Measurements by M. L. Schultz.

A possible explanation of the large difference in activation energy between n-type and p-type impurities in these materials may be made along the following lines. An n-type impurity in CdTe consists of an ion which has its full share of valence electrons, but which has an additional electron bound about it in order to maintain charge neutrality of the crystal as a whole. Since the electronic requirements of the ion itself are satisfied, the binding energy for the additional electron is not very large. A p-type impurity in CdTe consists of an ion which needs an extra electron to complete its own electronic requirements, but it must acquire this electron from a neighboring host-crystal ion which also needs this electron for its electronic requirements. The energy required to remove an electron from a Te ion and give it to a p-type impurity would probably be considerably larger than the energy to remove an excess electron from an n-type impurity.

When the conductivity vs temperature curves of the p-type impurities of Table I are subjected to Fermi-level analysis,[6] it is found that the calculated Fermi-level is independent of temperature and equal to the measured slope. This result means on the basis of the usual simple model,[7] that either (1) the concentration of acceptor centers in each of these samples is approximately equal to the concentration of levels in the uppermost kT-wide part of the valence band (assuming no donor centers present); or (2) the concentration of acceptor centers in each of these samples is approximately equal to twice the concentration of unintentionally present donor centers. The latter more likely possibility is very similar to the apparent "balance of impurities" reported by Debye and Conwell[8] for a series of germanium samples with arsenic impurity.

[6] See, for example, A. Rose, RCA Rev. 12, 362 (1951).
[7] R. H. Bube, J. Chem. Phys. (to be published).
[8] P. P. Debye and E. M. Conwell, Phys. Rev. 93, 693 (1954).