Electrical Properties of Gold-Germanium Alloys*

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(Received July 14, 1953)

RECENT studies[1-3] have shown that zinc, and copper, as well as the third and fifth column elements, can act as activator elements in germanium. The present note deals with gold, which is shown to be an acceptor capable of taking up electrons at two distinct energy levels. The first acceptor level is 0.15 ev above the filled band, the second (trapping) level is 0.20 ev below the conduction band.

Gold-germanium alloys have been made using cp gold wire (exact purity unknown), gold wire (99.96 percent), and gold ingot[4] (purity checked in the G. E. Research Laboratory and found to be 99.99 percent or better). Consistent results were obtained using these materials.

Gold was added during growth of the single crystals in proportions ranging from 0.01 to 0.1 percent. *N*-type crystals showed an increase in resistivity at the point of addition; *p*-type crystals showed a decrease. The segregation coefficient (ratio of gold in the solid to that in the liquid) was found to be about 1.5×10^{-5}, assuming that each gold atom furnished two acceptor states. The solubility of gold appears to be about 10^{15} atoms/cm³.

Figure 1 shows Hall effect data, which also give the density of carriers, for samples cut from a gold-doped germanium ingot. Temperatures of measurement ranged from 77°K to 400°K. The

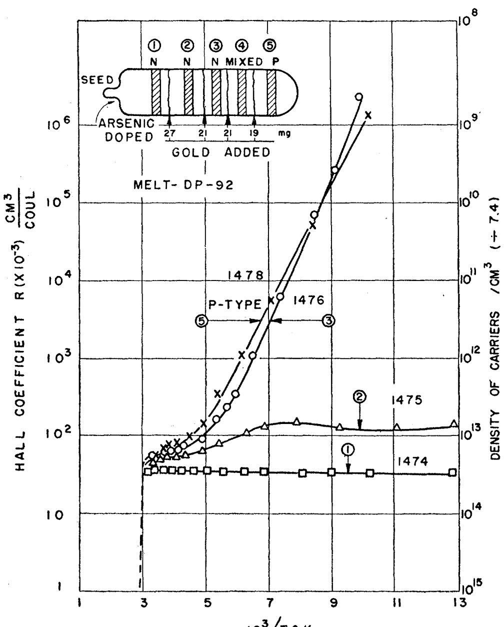

FIG. 1. Hall coefficient *vs* $1/T$°K for a series of germanium samples cut from wafers containing progressively increasing amounts of gold. The crystal was originally *n*-type before gold was added. Each successive wafer is more *p*-type as the result of the addition of gold, as well as the normal segregation process. The scale at the right represents (1/7.4) times the actual density of carriers.

steep slope is in contrast to the behavior of the usual impurities (including zinc and copper), for which the Hall curve is practically constant in this temperature range. The slopes indicated an ionization energy of ~0.20 ev for the *n*-type samples, ~0.15 ev for the *p*-type sample.

The observed results may be accounted for in terms of the scheme of Fig. 2. Acceptor levels at 0.20 ev below the conduction band and 0.15 ev above the filled band are indicated. The observed

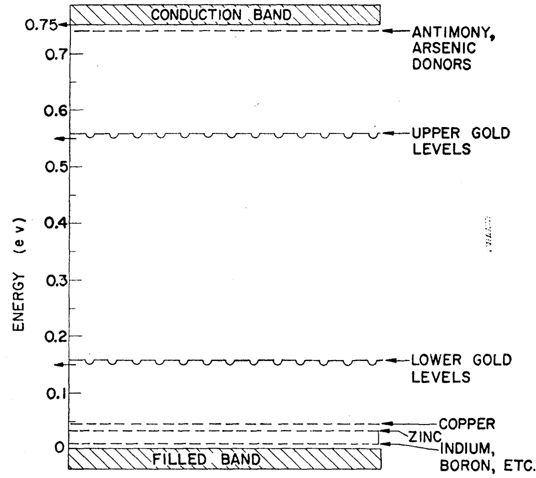

FIG. 2. Impurity level spectrum of germanium, based upon published work to date. Indicated are the acceptor levels of gold, as well as those of zinc and copper and the third column elements. The donor levels are those characteristic of the fifth column elements. The upper gold level is seen in conduction processes mainly as an electron trap, whereas the lower gold levels act both as electron traps and high-ionization energy acceptors.

properties are then determined by the degree to which these levels are filled by electrons from donor impurities. If no such impurities are present, the crystal is *p*-type.

These experiments also showed that the number of upper gold levels was equal to the number of lower gold levels, to within experimental error (±25 percent). This might be accounted for if each gold atom accepts one, then a second electron, to become Au^- and Au^{--}.

Several interesting properties have been discovered in gold-doped germanium at 77°K: (a) a slow-decay component has been found in the photoconductivity following illumination in the infrared; (b) current-pulsing, in some samples, leads to immediate loss of conductivity, followed by its slow reappearance; (c) new photoconductivity bands in the infrared, apparently associated with the levels discussed here, have been found by R. Newman. The phenomena, which will be discussed in detail in later reports, appear to be related to disturbance of the equilibrium between the various traps and the conduction bands.

By proper compensation of impurities, resistivities at 77°K as high as 5×10^7 ohm cm have been obtained. This is an aid in the doing of experiments in which the relatively high conductivity of germanium has been a hindrance.

The high ionization energy of gold in germanium also leads to simplification of the problem of studying germanium in the impurity ionization range, since many of these experiments can now be done in the range 77°K to room temperature.

* Some of these results were presented at the 1953 Durham meeting, American Physical Society [Phys. Rev. **90**, 208 (1953)].

1 W. C. Dunlap, Jr., Phys. Rev. **85**, 945 (1952).
2 C. S. Fuller and J. D. Struthers, Phys. Rev. **87**, 526 (1952).
3 F. J. Morin and J. P. Maita, Phys. Rev. **90**, 337 (1953).
4 I wish to thank M. D. Fiske for a supply of this gold.

Scintillation Response of Organic Phosphors

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(Received March 23, 1953; revised manuscript received July 14, 1953)

THE scintillation efficiencies and decay times of organic phosphors depend upon the nature and energy of the absorbed particles. From the available experimental data concerning these quantities we may infer the nature of the quenching processes which occur for ionizing particles and calculate the scintillation response of these phosphors.