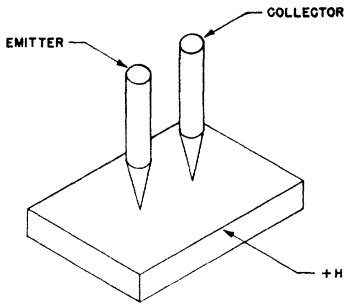

FIG. 1. Arrangement of electrodes.

high frequencies appears to be transmit time in the flow of holes from the emitter to collector. Bardeen has calculated the transit time to be $T=(2\pi s^3)/(3U_h\rho I_c)$. For typical operating conditions those that travel along the surface have a transit time of about 1.3×10^{-8} sec. For the longer important paths T may equal 2.6 to 3.9×10^{-8} sec. It is apparent that at high frequencies the effect of differences in transit angle will be an increased phase shift as well as a reduction of α since the hole current arriving at the collector will be dispersed in phase. Application of a transverse magnetic field as shown in Fig. 1 tends to compress the hole current toward the surface reducing the average path length resulting in less phase dispersion. Figure 2 shows the effect on α at frequencies from 100 kc to 10 Mc of a transverse magnetic field. This data was taken on a Bell Laboratories type "A" transistor. As can be seen most of the high frequency gain is recovered on the application of a + magnetic field bias. Negative magnetic field is substantially reduced by forcing the hole current to travel over widely varying

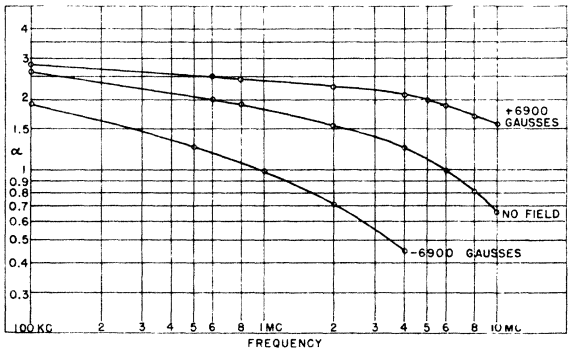

FIG. 2. Effect of frequency on the value of α.

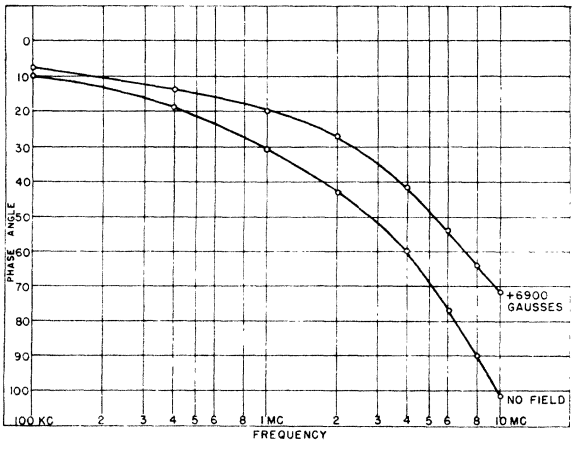

FIG. 3. Effect of frequency on the phase angle.

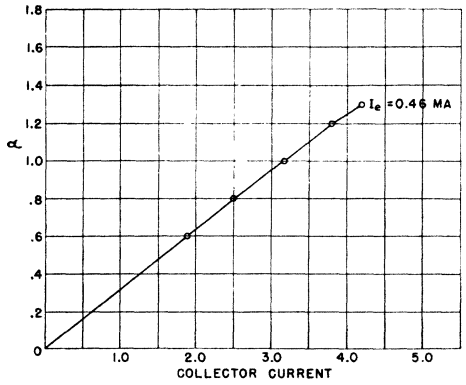

FIG. 4. Variation of α with collector current.

paths. Figure 3 shows the accompanying change in phase angle $\phi(I_{\text{collector}}/I_{\text{emitter}})$ with magnetic bias. The value of magnetic field strength was found not to be critical. In the particular unit shown here the increase in α was found to approach a saturation value at about 7000 gausses. In other units somewhat less field produced like results.

When the emitter current is small compared to the collector current the electric field strength accelerating holes from emitter to collector must be proportional to the collector current. If α is reduced by phase dispersion at high frequencies it would be expected that reducing the average transit time should increase α. Figure 4 shows the relationship between α and collector current at 10 Mc for an emitter current at 0.46 ma. As can be seen α is proportional to collector current. These results appear to be entirely consistent with the work of Shockley and Suhl.[2]

[1] J. Bardeen and W. H. Brattain, Phys. Rev. **75**, 1208 (1949).
[2] H. Suhl and W. Shockley, Phys. Rev. **75**, 1617 (1949).

Properties of Single Crystal Selenium Prepared from a Melt

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TO data studies of the electrical conductivity of selenium have been confined to microcrystalline hexagonal selenium crystallized from the amorphous phase and polycrystalline selenium deposited in the form of hollow needles from the vapor phase. In our laboratory single crystals have been grown from a melt.

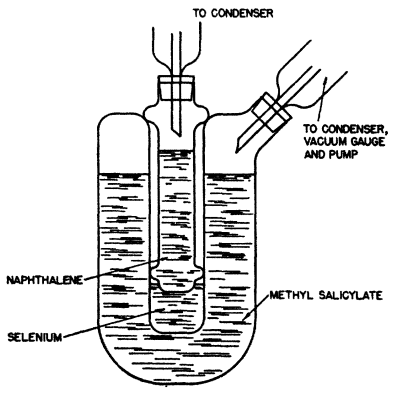

FIG. 1. Crystallization apparatus.

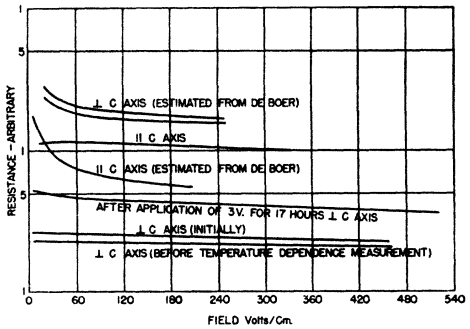

FIG. 2. Voltage dependence of resistance of selenium crystals.

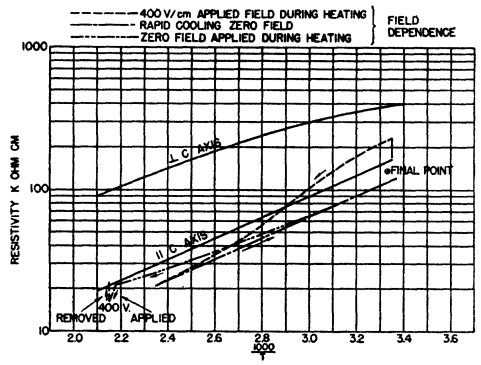

FIG. 3. Temperature dependence of resistivity of single-crystal selenium with and without high field. All measurements made at low field.

The arrangement in Fig. 1 was used. The outer container was filled with methyl salicylate boiling at atmospheric pressure at 223°C, the inner, with napthalene boiling at 218°C. Pure selenium was placed in the inner container and the entire system heated. After a length of time solid crystals of roughly cubical shape were removed from the matrix of coarse grained selenium. These were found to be hexagonal single crystals.

Electrostatic probe measurements of resistivity in vacuum were conducted. In polycrystalline material there exists the possibility that transitionary resistances at grain boundaries contribute largely to the resistance. In previous work on needle shaped crystals there has also existed the possibility of contributions of ordinary rectifier contact resistance at the ends of the crystal. The latter effect has been avoided by the method of testing. That grain boundary resistances are absent has been shown by the voltage independence of resistance. Previously tested polycrystal have shown a strong voltage dependence of resistance (especially near zero field). Figure 2 gives the data on the single crystals grown from a melt.

The resistivity of the crystals measured has been found to depend on the period of application of the field. This effect has also been observed as a function of temperature. Evidently the acceptors have a considerable mobility. The complete explanation of this effect and of the small deviations from Ohm's law at high fields will be the subject of further investigation.

The temperature dependence of resistivity is shown in Fig. 3. It is observed that the values of resistivity are about 1.6×10^5 ohm cm parallel to the c axis and, 4×10^5 ohm cm perpendicular to the c axis at room temperature. In the explanation of the observed h.f. resistivity of about 3×10^2 ohm cm for all polycrystalline samples (regardless of the d.c. resistivity which may vary from about 5×10^2 ohm cm to 10^6 ohm cm) and the correlation of that value with the resistivity of single crystals prepared from the vapor phase (10^5 ohm cm) it was postulated by Dr. Gudden that there existed a difference in the number of lattice defects in crystals from a melt and from a vapor. In a vapor the atoms of selenium are present as dimers and hexamers while in the melt and in amorphous selenium the atoms exist in long chains. On crystallization to the hexagonal lattice it was supposed that many defects would arise in the transition from the amorphous phase with a consequent increase in the number of acceptor levels and therefore in the conductivity. That this is not the case has been shown by the measurements on crystals prepared from a melt.

The activation energy of the single crystals can be calculated as about 0.25 ev parallel to the c axis and 0.24 ev perpendicular to the c axis. There appears a bend in the resistivity curve perpendicular to the c axis. Data on microcrystalline selenium shows that activation energies vary over a wide range depending on the quenching and crystallization temperatures, the impurity content (in an irregular manner) and the type of impurity, with the temperatures having the predominant effects. It has been reported from Dr. Gudden's laboratory that the activation energies decrease at higher frequencies and approach a value 0.01 ev. With new data on microcrystalline selenium and that in Fig. 3 it has been necessary to assume the presence of blocking layers at grain boundaries together with crystallite surface layers of abnormally high conductivity. The observed radical decrease of activation energy at high frequencies (to values much lower than those of single crystals) is easily understood in terms of this new model.