Letters to the Editor

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High Electric Field Effects in *n*-Indium Antimonide

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(Received April 4, 1958)

PULSED current-voltage measurements have been made on a single crystal of *n*-InSb at 77°K up to a current density of 10^4 amp/cm^2. In order to avoid heating, the data were taken with 1-μsec pulses at a repetition rate of 1 cps. Beyond about 2×10^3 amp/cm^2 the current increased rapidly for small further increases in voltage. The electric field at the threshold was about 200 volts/cm for no applied magnetic field. Hall effect measurements (also taken under pulsed electric fields) at 7000 oersteds showed that the initial carrier concentration of about 2×10^{14} cm^{-3} was increased by a factor of ten in going from the onset of the rapid current increase to the highest current attained.

Figure 1 shows the current-voltage characteristics and R_H, the Hall coefficient, at 77°K. R_H is plotted as a function of the voltage in the presence of the 7000-oersted field. From constant-current lines in Fig. 1 and the requirement of constant carrier concentration, the magnetoresistance ratio, $\Delta\rho/\rho_0$, can be calculated. These results are shown in Fig. 2. For currents higher than two amperes, R_H began to decrease rapidly, so that $\Delta\rho/\rho_0$ would no longer have the usual significance.

There are three mechanisms that might have explained these results. The first is the possibility of impact ionization of donors having an activation energy near the center of the forbidden energy gap. The second is minority-carrier injection at the contacts. The third is impact ionization across the forbidden gap with the resultant creation of electron-hole pairs. On the basis of similar measurements made at 232°K the first possibility was ruled out. The second one was abandoned because of the good shapes of the current and voltage pulses and the results in the presence of the magnetic field. Hence the third mechanism, that of electron-hole pair creation, remains to explain the data. To our knowledge this is the first detailed report[1] of such an effect in a bulk semiconducting crystal (i.e., no junctions).

The large decrease in $\Delta\rho/\rho_0$ shown in Fig. 2 (for constant electron density) is tentatively attributed to both the decrease of mobility of the hot electrons and the possible significant change in the distribution function of the electrons in the presence of strong electric and magnetic fields. A detailed experimental study of the effect over a wide range of magnetic fields might reveal detailed features of such changes in the distribution function.

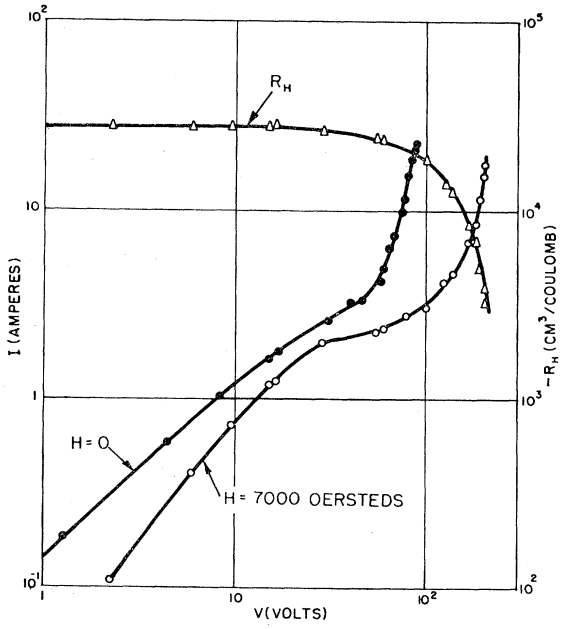

FIG. 1. Current-voltage characteristics and Hall coefficient at 77°K. The voltage was measured across a distance of 0.254 cm along the crystal. The cross sectional area was 2.34×10^{-3} cm^2.

From the data in Fig. 1 it is possible to compute v_d, the drift velocity of the electrons, in the presence of the 7000-oersted magnetic field. Such calculations show that v_d exhibits saturation at a value of about 2.4×10^7 cm/sec for electric fields greater than 150 volts/cm.

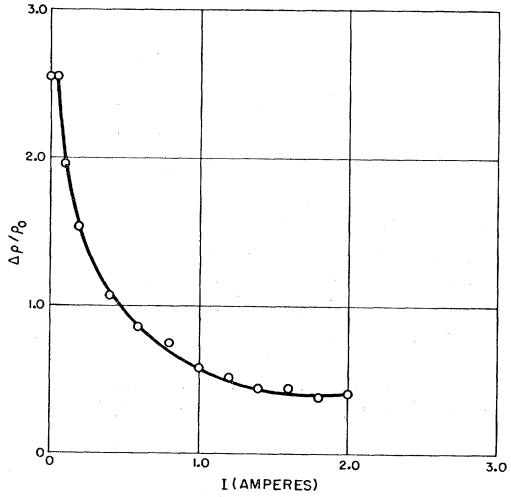

FIG. 2. Magnetoresistance ratio as a function of current at 77°K for $H=7000$ oersteds. The current was in the [110] direction while the transverse magnetic field was in the [001] direction.

All the qualitative features exhibited in Figs. 1 and 2 have been reproduced in another sample of the same crystal. Experiments in progress are designed to detect the band-gap recombination radiation which should be present once the threshold is passed.*

[1] In pulsed electric field measurements on *n*-germanium, J. B. Gunn [J. Electronics **2**, 87 (1956)] has reported a sudden increase in current at 6.3×10^4 v/cm, which he believed due to ionization of electron-hole pairs. The possibility that this effect was due to injection of minority carriers is not eliminated by his observations.

* *Note added in proof.*—After this Letter was written, we learned that A. C. Prior [J. Electronics and Control **4**, 165 (1958)] has reported current-voltage characteristics in InAs at room temperature similar to those reported here.

Correlations Suggesting the *d*-Shell Configuration and a Magnetic Exchange Mechanism in Iron Group Metals

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(Received March 28, 1958)

THE results of a recent neutron diffraction study of the antiferromagnetic properties of iron group trifluorides,[1] when correlated with those of other antiferromagnetic systems having rhombohedral or hexagonal symmetry, suggest that the alignment of the spins along the *c* axis of the crystal is a unique property of the *d*-shell configuration. For cobalt in such antiferromagnetic systems this spin orientation appears to be a unique property of the Co^{3+} ion. By association one is led to the conclusion that the ions in hexagonal cobalt metal exist with the usual *d*-shell configuration of Co^{3+} as the ground state. With this suggestion, it was thought profitable to pursue the consequences of assuming that in the other iron group metals the same situation obtains. The *d*-shell configurations of the trivalent ions are shown in Table I. In view of the success of the orbital approach[2] to magnetic exchange in the perovskite[3] and trifluoride type compounds, the scheme of occupation shown in this table suggests some interesting ideas, which will be discussed below.

It appears now that the orbital properties deduced from crystal field theory[4] are well suited for correlating these indirect magnetic exchange phenomena. On this basis the *d* levels of an ion in octahedral surroundings are split into a lower triplet t_{2g} and an upper doublet e_g; the t_{2g} orbitals are of the type d_{xy}, d_{yz}, and d_{xz} which point along the face diagonals of a cube, and the e_g orbitals are of the type d_{z^2} and $d_{x^2-y^2}$ which, taken together, form a nearly symmetrical octahedral orbital system pointing along the cube edges. In the case of a compound of the perovskite type, the e_g orbitals overlap the oxygen ions which lie near the midpoints of the cube edges and constitute the intermediary in the indirect magnetic exchange. Now when one uses the spatial properties of these orbitals and their respective electron occupations as shown for the trivalent ions in Table I and correspondingly for other ionic states, all the magnetic structure data in the perovskites and trifluorides can be accounted for on the basis of three types of exchange situations. These situations are governed by what appears to be the general principle that whenever an electron of an anion *p* orbital is excited into an overlapping orbital of a neighboring magnetic cation, the *p* electron enters (a) with its spin parallel to that of the magnetic ion when its overlapping orbital is empty and (b) with its spin antiparallel if its overlapping orbital is half filled.

TABLE I. Trivalent ion *d*-shell configurations.

Cr^{3+}	Mn^{3+}	Fe^{3+}	Co^{3+}	Ni^{3+}
↑↑↑00	↑↑↑↑0	↑↑↑↑↑	↓↑↑↑↑↑	↓↑↓↑↑↑↑

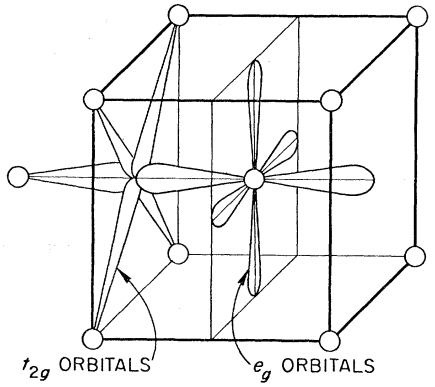

FIG. 1. Partial schematic representation of orbital arrangement in a body-centered cubic structure.

It is interesting now to investigate the possibilities of the orbital approach to the magnetic properties of the transition metals. This approach leads to some very striking results, which depend on (a) accepting the *d*-shell ground-state configurations in the metals as that appropriate to the 3+ ion, for which the evidence is that presented above, and (b) assuming a crystal field splitting of the *d* shell similar to, but presumably smaller than, that observed for crystalline compounds.

With these assumptions one can account for the common magnetic properties of the 3*d* metals. The two most striking cases of bcc. iron and bcc. chromium will be treated here. Figure 1 shows part of the t_{2g} orbitals of the metal ions on one face of a cube, and it shows the octahedral e_g orbitals of a body-centered ion. There are three such cube faces associated with each metal ion, which is assumed to be 3+. There are thus left over as "itinerant" electrons just three electrons per ion. Let us place one of these electrons at each orbital meeting point. If this electron makes alternate exchanges between the six orbitals at the meeting point, we will have the following situation for iron for which all orbitals (Fe^{3+}) are half filled. On the assumption that an electron which is promoted into an excited