Solid State Communications, Vol. 61, No. 12, pp. 803–805, 1987.
Printed in Great Britain.

0038–1098/87 $3.00 + .00
Pergamon Journals Ltd.

THE HALL COEFFICIENT FOR ELECTRONS IN A NEARLY FULL IMPURITY BAND

M. Benzaquen, D. Walsh and K. Mazuruk

McGill University, Physics Department, 3600 University Street, Montreal, PQ, H3A 2TB, Canada

(*Received 23 September* 1986 *by R. Barrie*)

At 3 K a change of sign of the Hall coefficient R_H of a 35% compensated *n*-InP crystal is observed where the variable-range hopping regime dominates the conductivity. This effect is not observed for a more compensated sample and is consistent with hopping conduction by holes in a nearly full band of localized donor impurity states.

ALTHOUGH THE MOTT LAW [1, 2] for variable-range hopping conduction is now established for crystalline semiconductors [3–7], and the effect of the Coulomb gap in the density of localized states has been theoretically shown to be weak or non-existent [8], there is a shortage of experimental information concerning the temperature dependence of the Hall coefficient R_H and the Hall mobility μ_H. This appears to be due to difficulties related to both the very high resistivities involved in hopping conduction and its extremely fast temperature dependence. Accurate measurements proved nevertheless to be possible on lightly doped compensated *n*-GaAs [9]. *n*-InP having similar characteristics, we extended the measurements of variable-range hopping conductivity to these crystals and now report on the hall coefficient data.

The samples are two *n*-InP epitactic layers grown on semi-insulating (1 0 0) InP by Metal-Organic Vapour Phase Epitaxy (MOVPE) and lightly doped with Si to reduce their resistivity. The measurements were performed under low field conditions such that the electrical properties of the samples were independent of the applied electric and magnetic fields. For best resolution, this required frequent adjustments of the constant current source as the temperature T of the sample and holder naturally recovered from its lowest value at a very slow rate. T was obtained with a precision Carbon-Glass sensor giving 0.01 K resolution in our range of interest. The samples were mounted in a standard bridge configuration. The error estimates are 20% for R_H and μ_H at the lowest temperatures.

Samples 1 and 2 follow the Mott law for variable-range hopping conduction below approximately 4.5 K, the corresponding parameters having already been reported [6]. Table 1 gives the acceptor concentration, N_A, and donor concentration, N_D, for both samples, along with the compensation ratio K. These values were calculated by using the model described by Rode [10] for the drift mobility in the form that does not account for non-parabolicity corrections, and further calculating

Table 1. N_D, N_A, compensations and excitation energies to the conduction band

Sample	N_D (cm^{-3})	N_A (cm^{-3})	K	E_c (meV)
1	2.1 10^{15}	1.2 10^{15}	0.57	5.76
2	1.0 10^{16}	3.5 10^{15}	0.35	3.50

the Hall factor to fit the experimental data in the 5–300 K range, keeping consistency with the variations of the Hall electronic concentration n_H vs T [11]. The average error of the fit for μ_H was less than 5%. For n_H, the fit was excellent at low and high T although the theoretical curve of n_H fell above the experimental points by 20% at intermediate T. Values of the degeneracy factor of the donor level larger than 1/2 improve the fit of n_H.

We note that sample 1 is about two times more compensated than sample 2, and that the doping levels of both samples fall below the ones corresponding to the Mott transition without being too far from it. This yields a reasonably low resistivity and a measurable Hall mobility. Above 10 K, for both samples, conductivity is controlled by electrons in the conduction band. However, extraction of the excitation energy from the temperature dependence of the conductivity is often unreliable due to the enormous change in the magnitude of the electron mobility as one goes from impurity band transport to conduction band transport (see Fig. 4). Consequently, the excitation energies to the conduction band, E_c, of Table 1 were extracted from the plot in Fig. 1 of ln[$|R_H|$] vs $1/T$ from 10 to 20 K, which shows an approximate constant slope, as expected, since both the Fermi level and the effective density of states are relatively constant over this temperature range. Between 4 and 10 K, in Fig. 2, R_H for sample 1 shows a behaviour characteristic of a two band conduction model for carriers of same sign [12], the carriers being electrons in this case. Below 5 K, the rapid variation in R_H is due to

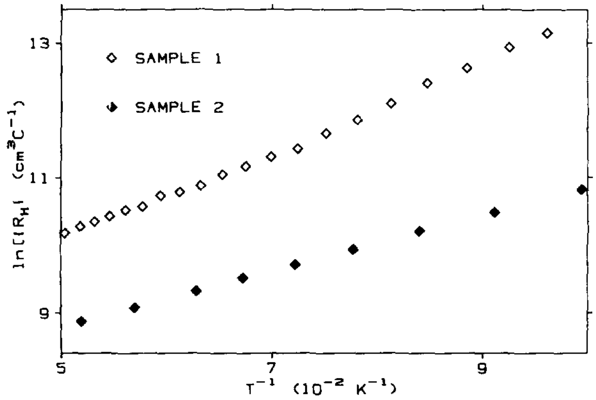

Fig. 1. ln$[R_H]$ vs $1/T$ between 10 and 20 K. The excitation energies to the conduction band quoted in Table 1 are extracted from the slopes.

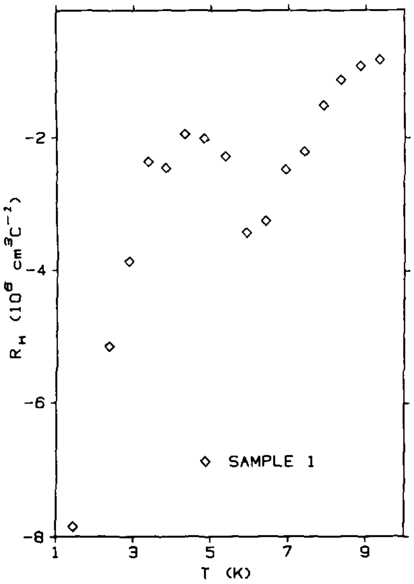

Fig. 2. R_H vs T between 1.4 and 10 K for sample 1. A two band behaviour is observed without change of sign.

the freeze-out of hopping electrons. R_H for sample 2 in Fig. 3 is interestingly different, displaying the normal negative sign for R_H at higher temperatures, when conduction electrons dominate the transport properties, but changes sign below 3 K where hopping conductivity dominates. This effect has also been observed in another purer InP sample, the data showing unfortunately excessive scatter. To our knowledge, this phenomenon has not been reported before, the relatively pure undoped crystals being heavily compensated and the lightly doped crystals too close or beyond the metal-insulator transition where the binding energy goes to zero. However, it is perfectly consistent with hopping conductivity in a nearly full impurity band where conduction is by holes. It also demonstrates that the donor impurity band is well separated from the conduction band. It is interesting to

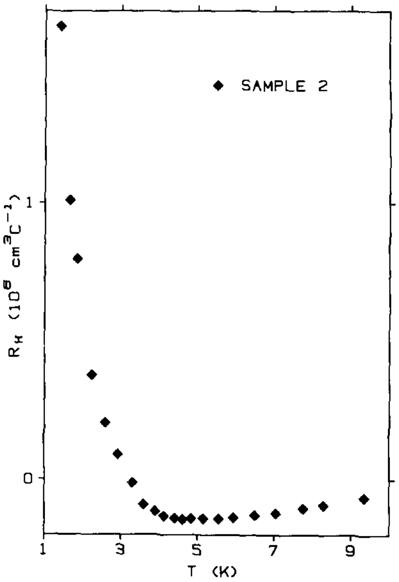

Fig. 3. R_H vs T between 1.4 and 10 K for sample 2. A change of sign is observed at approximately 3 K with a very fast increase at lower T.

note that the 3-site Hall model [13] for hopping conduction in non-crystalline solids, which says that the sign of R_H for holes is the same as the one for electrons, is not appropriate here. Figure 4 shows the low-T dependence of μ_H for both samples. Below 5 K sample 1 shows a linear dependence with T already observed in GaAs epilayers [9], while sample 2 shows a zero minimum in mobility at the change of sign of R_H, as expected.

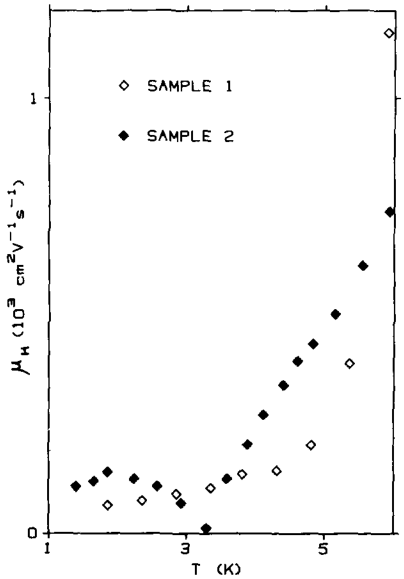

Fig. 4. Hall mobility vs T between 1.4 and 6 K. For sample 1 a linear behaviour is observed at the lowest temperatures. Sample 2 shows a zero minimum at the change of sign of R_H. At higher T, the usual $T^{3/2}$ behaviour is observed.

In conclusion, a change of sign in the T dependence of R_H for a n-InP crystal is observed for electrons in an almost full impurity band where the variable-range hopping conduction dominates. This effect, which is absent for a more compensated crystal, is attributed to hopping conduction by holes in a nearly full donor impurity band of localized states. Electrical transport measurements on low compensation III–V samples with relatively low resistitivity (close to the insulating side of the Mott transition to allow measurable mobilities) are highly desirable to confirm this preliminary results, but such samples are still difficult to produce, as a precise control of both the doping level and the compensation are needed.

Acknowledgements – We wish to thank Prof. N.F. Mott for valuable correspondence, and the Quebec Ministery of Education for financial assistance.

REFERENCES

1. N.F. Mott, *Philos. Mag.* **19**, 835 (1969).
2. N.F. Mott, *J. Non-Cryst. Solids* **1**, 1 (1968).
3. F.R. Allen & C.J. Adkins, *Philos. Mag.* **26**, 1027 (1972).
4. F.R. Allen, R.H. Wallis & C.J. Adkins, *Proc. of the 5th Int. Conf. on Amorphous Liquid Semiconductors*, (Edited by J. Stuke and W. Brening), Taylor and Francis, London, (1974).
5. M. Benzaquen & D. Walsh, *Phys. Rev.* **B30**, 7287 (1984).
6. M. Benzaquen, K. Mazuruk, D. Walsh & M.A. di Forte-Poisson, *J. Phys.* **C18**, L1007 (1985).
7. W.N. Shafarman & T.J. Castner, *Phys. Rev.* **B33**, 3570 (1986).
8. G. Vignale, Y. Shinozuka & W.Hanke, *Phys. Rev.* **B34**, 3003 (1986).
9. M. Benzaquen, K. Mazuruk & D. Walsh, *Can. J. Phys.* **63**, 732 (1985).
10. D.L. Rode, *Semiconductors and semimetals*, (Editred by R.K. Willardson and A.C. Beer), Academic Press, New York, (1975).
11. M. Benzaquen, K. Mazuruk, D. Walsh, C. Blaaw & N. Puetz, *J. Cryst. Growth* **77**, 430 (1986).
12. D. Walsh, A. Poirier, N. Chistoforou & J. Auclair, *J. Phys.* **C15**, 7043 (1982).
13. L. Friedman, *J. Non-Cryst. Solids* **6**, 329 (1971).