

NOTAS DE FÍSICA

VOLUME XXI

Nº 9

TRANSPORT PROPERTIES OF LI-COMPENSATED GALLIUM ANTIMONIDE

by

S. F. da Cunha and S. Almirac

CENTRO BRASILEIRO DE PESQUISAS FÍSICAS  
Av. Wenceslau Braz, 71 - Botafogo - ZC-82

RIO DE JANEIRO, BRASIL

1973

---

## TRANSPORT PROPERTIES OF LI-COMPENSATED GALLIUM ANTIMONIDE\* +

by

S. F. da Cunha

*Centro Brasileiro de Pesquisas Físicas*

and

S. Almairac

*Centre d'Etudes d'Electronique des Solides - Montpellier - France*(Received 21<sup>th</sup> November 1973)

## ABSTRACT

The Hall coefficient, resistivity and Hall mobility of lithium doped high compensated GaSb were measured down to 6°K. In the two ranges of temperature, below and above the maximum of  $R_H$ , the results are interpreted as due to free hole transport and hopping charge transfer between impurity centers, respectively. At high temperatures the mobility was found to vary as  $T^{-3/4}$ .

---

\* This work was supported in part by the Conselho Nacional de Pesquisas.

+ Submitted for publication to Physica Status Solidi.

## INTRODUCTION

It was suggested by Van Maaren (1) while studying the diffusion of Li in GaSb that at low temperature, the conduction occurs through the impurity bands. To our knowledge neither Van Maaren nor others have so far investigated the conduction modes of highly compensated lithium doped GaSb, at low temperatures.

In this paper we try to determine the number of carriers and conduction mechanisms in GaSb saturated by diffusion with Li at 723<sup>o</sup>K, which corresponds to the condition  $[\text{Li}_{\text{Ga}}]^+ = [\text{Li}_{\text{Ga}}\text{Li}]^-$ , i.e., maximum resistivity. The study of the Hall coefficient and electrical resistivity as a function of temperature allowed us to analyse the mobility curves in the temperature range in which the measurements were performed.

## EXPERIMENTAL

The homogeneity of the GaSb samples saturated with Li by diffusion (2) was controlled to within ten per cent by resistivity measurements using the four point probe method. After diffusion the samples were kept at 77<sup>o</sup>K.

In the range 6<sup>o</sup>K to 300<sup>o</sup>K the Hall effect and resistivity measurements were made by the method of Van der Pauw (3). The applied magnetic field used for all Hall effect measurements was 0,7 Wb/m<sup>2</sup>. At very low temperatures the residual voltage due to imperfect symmetry of the contacts, is larger than the Hall voltage. In order to compensate for this residual voltage it was necessary to use a Keithley nanovoltmeter. The signal was there amplified and recorded as derivative of both the Hall effect signal and the residual signal.

## EXPERIMENTAL RESULTS

The plot of the Hall coefficient as a function of  $1/T$  is shown in fig. 1.  $R_H = \frac{d}{B} \Delta R (\text{cm}^3/\text{C})$  where  $d$  is the thickness of the samples and  $\Delta R$  is the variation of resistance with and without the applied magnetic field  $B$ .

Two observations can be made: 1 - In none of the samples the Hall coefficient changes sign in the whole range of temperature investigated; 2 - At low temperatures the Hall coefficient attains its maximum value  $R_H^*$  at  $T^*$ , then decreases rapidly to a minimum and tends to stabilize to a value a bit above this minimum for very low temperatures.

The analysis of the curves has to be made in two ranges of temperature. In the first range, below  $R_H^*$  conduction is due to holes in the valence band. In the second range, above  $R_H^*$ , conduction is due to impurities.

a) RANGE OF TEMPERATURE BELOW  $R_H^*$  - If we consider one donor and one acceptor level, the variation in the concentration of free carriers  $p$  as a function of the concentration of impurities  $N_D$  and temperature is given by the classical formula:

$$\frac{p(p + N_D)\beta}{N_V(N_A - N_D - p)} = e^{-\frac{E_A}{kT}} \quad (1)$$

where  $p \gg (N_A - N_D)$ ;  $\beta = 4$  is the spin degeneracy factor of the acceptor level, determined by Effer and Etter (4);  $N_V = 1,813 \times 10^{15} T^{3/2} \text{ cm}^{-3}$  is the density of states in the valence band, using the two bands model in GaSb;  $E_A$  is the activation energy of the acceptor level of Li in GaSb;  $p$  is the number of carriers determined experimentally for all temperatures;  $(N_D - N_A)$  is obtained experimentally from the exhaustion range.

In order to determine  $E_A$  and  $N_D$  the known values of  $(N_A - N_D)$  are fixed and several values of  $N_D$  are arbitrarily chosen; for each  $N_D$  we introduce  $p_i$ , corresponding to a experimental  $T_i$ , in the relation (1) and we obtain  $E_A(T)$ . This process is repeated for temperatures in the range of validity of the model and we can plot  $N_D$  in function of  $E_A$  for each value of  $T$ . A family of curves is obtained and the intersection point of these, uniquely determine the values of  $N_D$  and  $E_A$  that will satisfy equation (1). This determination was made by means of a Fortran program. With the value of  $N_D$  we can determine  $N_A$  and the compensation ratio  $K = \frac{N_D}{N_A}$  (Table 1). The values of  $E_A$  suggest that the residual level of GaSb disappears and give place to an acceptor level of 8 meV for all samples.

b) RANGE OF TEMPERATURE ABOVE  $R_H^*$  - According to the model proposed by Hung and Gliessman (5) two mechanisms of conduction are possible; by free carrier and by impurities. At very low temperatures it is the conduction by impurity that dominates and since the number of impurity centers is temperature independent one have.

$$n_i \approx N_A - N_D$$

and  $|R_H| = \frac{1}{n_i e}$ . Also in this model, for  $T^*$  the two mechanisms of conduction give rise to the same conductivity or

$$n_v e \mu_v = n_i e \mu_i$$

where  $v$  and  $i$  refers to free carriers and impurity respectively.

The variation of resistivity  $\rho$  with temperature was measured for the same interval of temperature that  $R_H$  and the results are shown in figure 2. At the temperature  $T^*$  where  $R_H$  is maximum,  $\log \rho$  presents a change of

inclination. The extrapolation of  $\log \rho$  at temperature  $T^*$  will allow us to determine the conductivity of the free carriers at this temperature. Since  $\rho_V^*$  is the double of  $\rho^*$  the mobility of the impurities  $\mu_i$  can be estimated from

$$\mu_i = \frac{\sigma_V}{n_i e} = \frac{1}{2\rho^* e(N_A - N_D)} \quad (2)$$

The values of  $\mu_i$  for some samples are listed in table 1.

It is suggested by Fritzseche (6) that the variation of resistivity with temperature can be represented by the following expression:

$$\rho^{-1} = C_1 \exp - \frac{\epsilon_1}{kT} + C_2 \exp - \frac{\epsilon_2}{kT} + C_3 \exp - \frac{\epsilon_3}{kT} \quad (3)$$

$$\epsilon_1 > \epsilon_2 > \epsilon_3$$

The first term represents the conductivity of the valence band, with activation energy  $\epsilon_1$  which intervene at high temperatures; The second term appears for intermediary dominium of concentration where there is formation of impurity band; The third term represents de conductivity by impurities (hopping) with activation energy  $\epsilon_3$ .  $\epsilon_2$  and  $\epsilon_3$  intervene at low temperature.  $C_1$  depend very little on temperature,  $C_2$  is independent of the impurity concentration and  $C_3$  decreases rapidly when the concentration of majorities carriers decreases. In the case of metallic conduction,  $\epsilon_3 = 0$ .

#### DISCUSSION OF THE CONDUCTION MECHANISM

We can see by what has been said so far that the mechanism of conduction at various temperatures depend on the concentration of majority

carriers and on the compensation. We must to analyse these results in order to classify the dominium of concentration corresponding to our samples. The metallic conductions do not intervene certainly for our samples by their own definitions and also because the curves of  $\log \rho = f(T^{-1})$  at very low temperatures do not indicate  $\epsilon_3 = 0$ . We only have now to discuss the other two types of conduction.

A first test consist in examining the average distances between the majority impurities. According to Mott (7) in order to have formation of an impurity band it is necessary that  $d_{th} \leq 3 a_0$  where  $a_0$  is the effective Bohr radius. In GaSb this condition means that  $d_{th} \leq 47,7 \text{ \AA}$ . The results of calculation of  $\underline{d}$  by the formula  $d_{exp} = \left( \frac{3}{4\pi N_A} \right)^{1/3}$  are indicated in table 1, and are all superior to  $47,7 \text{ \AA}$ .

A second test consists in examining the mobility. Mott (7) showed that there exist a mobility limit  $\mu_L$  below which the conduction by impurity band cannot be produced. This limit is given by

$$\mu_L = \frac{e}{6h} \left( \frac{3}{4\pi N_A} \right)^{2/3} \quad (4)$$

The values of  $\mu_i$  for our samples are less than  $\mu_L$  by an order of magnitude (Table 1).

A third test consist of examining the activation energy  $\epsilon_3$  of the resistivity. If we accept conduction by hopping the resistivity is given by

$$\rho = \rho_0 \exp - \frac{\epsilon_3}{kT} \quad (5)$$

Miller and Abrahms (8) have proposed that for low concentration the influence of the compensation  $k$  is included in  $\epsilon_3$  and that  $\rho_0$  is independent of  $k$ . By Miller's theory,  $\epsilon_3$  can be calculated, for  $k > 0,03$ , by

$$\epsilon_3 = \frac{\delta e^2}{\epsilon} \left( \frac{4\pi N_A}{3} \right)^{1/3} \quad (6)$$

where  $\delta$  depends on  $k$ . The values of  $\epsilon_3$  such calculated (Table 1) are in reasonable agreement with our experimental results.

We conclude from these tests in GaSb strongly compensated with Li, that the conduction at very low temperatures is done by hopping. The ratio  $\frac{\mu_L}{\mu_H} \approx 10$  however, is relatively small for to make a definite statement.

#### HALL MOBILITY INTERPRETATION

Figure 3 shows the variation of Hall mobility as a function of the temperature calculated from the experimental results of  $R_H$  and  $\rho$ .

We observe that from 300°K, when the temperature decrease,  $\mu_H$  increases as  $T^{-3/4}$  to a maximum value attained at a temperature superior to that at which the conduction by impurity intervenes. It quickly decreases and to very low temperatures, where the conduction by impurity dominates,  $\mu_H$  increases exponentially with temperature. Similar behavior was observed by Van Maaren in GaSb and, in general, in the III-V compounds having the same gamma of concentration.

Analysis of the variation of  $\mu = f(T^n)$  for our samples indicate that at high temperatures the values of  $n$  are one half of that suggested by the theory (9,10). We may conclude that not only the conduction mechanism of diffusion by acoustic phonons is to be considered but also the optic phonons.

For temperatures between 10°K and 60°K the two mechanisms of



transport by free carriers and by impurity are competitive and the decreasing of  $\mu_i$  indicates a transition from a process of strong mobility (free carriers) to a process a weak mobility (impurity). The lower temperatures the more conduction by hopping is dominant.

The mobility of impurity was also calculated by a graphical method, figure 4, extrapolating from very low temperatures to  $T^*$ . These results are in agreement with those obtained from equation (2) which substantiates the accuracy of the values of  $(N_A - N_D)$  given by  $1/eR_H$ .

#### ACKNOWLEDGEMENTS

*The authors wish to thank J. Bougnot and L. Gousskov for helpful discussions.*

Simple	3'	3	1p <sub>7</sub>	B <sub>s</sub>	4 <sub>p</sub>
$N_A$ (cm <sup>-3</sup> )	6,57x10 <sup>16</sup>	7,98x10 <sup>16</sup>	8,08x10 <sup>16</sup>	1,07x10 <sup>17</sup>	1,22x10 <sup>17</sup>
$(N_A - N_D)$ (cm <sup>-3</sup> )	7x10 <sup>14</sup>	4,8 x10 <sup>15</sup>	3,2 x10 <sup>15</sup>	3,2 x10 <sup>16</sup>	1,2 x10 <sup>16</sup>
K	0,98	0,93	0,95	0,7	0,9
$\epsilon_3$ exp (meV)	0,6	0,49	0,6	0,35	0,38
$\epsilon_3$ cal (meV)	0,35	0,34	0,34	0,3	0,39
d (Å)	154,3	144,8	144,2	131,3	125,7
$\mu_j$ cm <sup>2</sup> /V seg	43,8	22,03	14,36	55,8	62
$\mu_L$ cm <sup>2</sup> /V seg	602	762	726	436	360

TABLE 1

**FIGURE CAPTIONS**

Fig. 1 - Hall constant  $R_H$  as function of temperature.

Fig. 2 - Resistivity as function of temperature.

Fig. 3 - Hall mobility as function of temperature.

Fig. 4 - Graphical determination of impurity mobility.

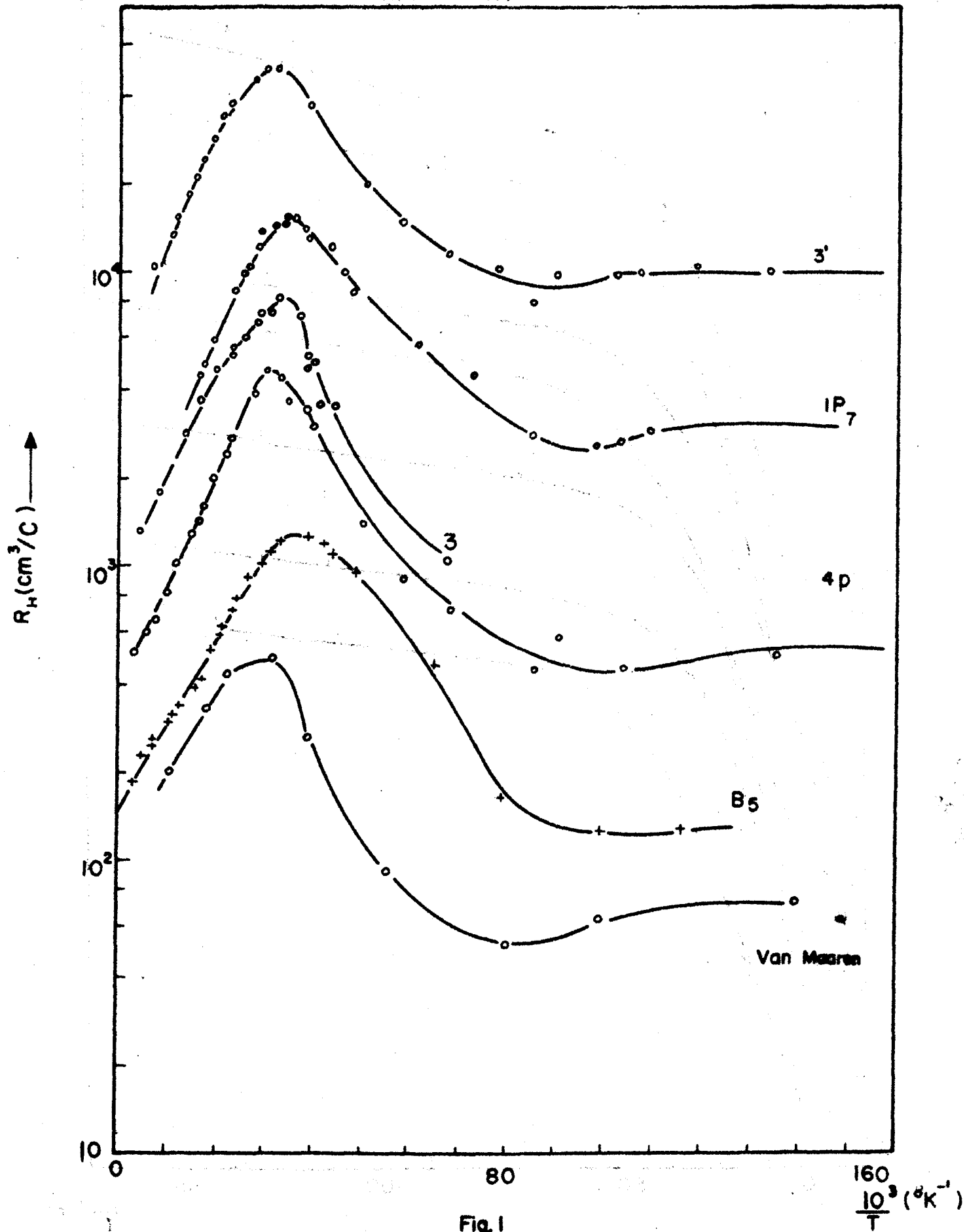


Fig. 1

2-576

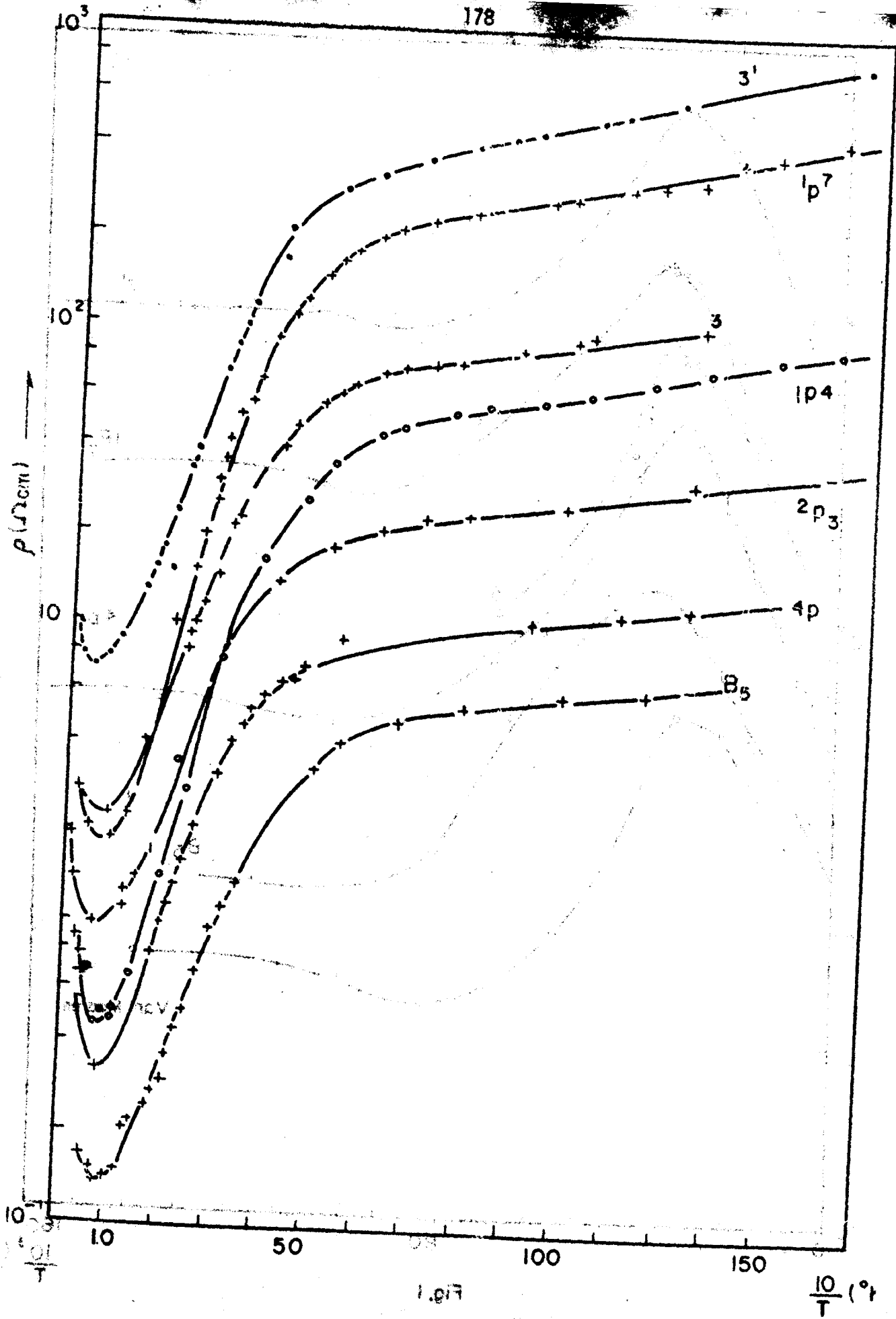
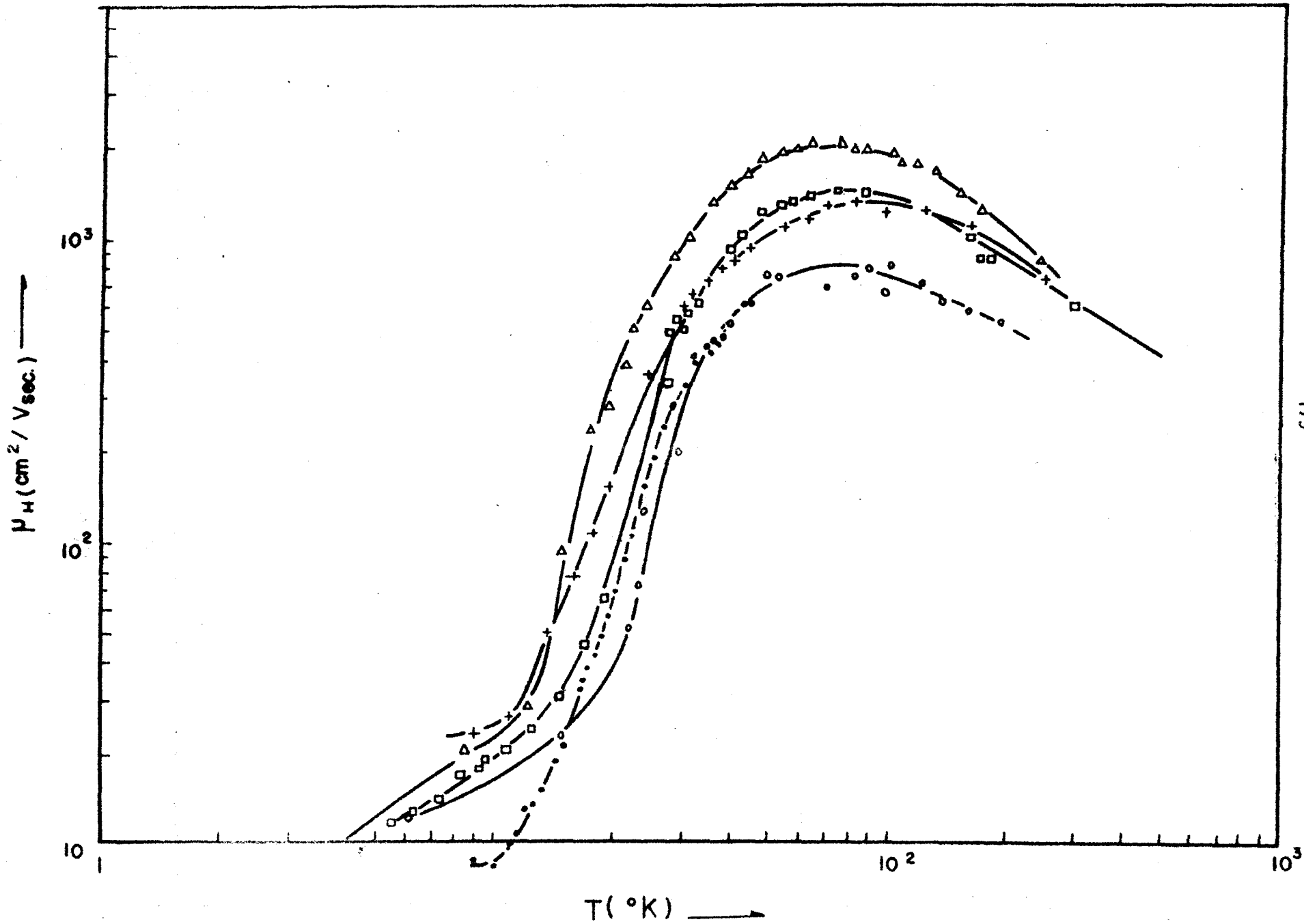


Fig 2



T (°K) →

Fig. 3

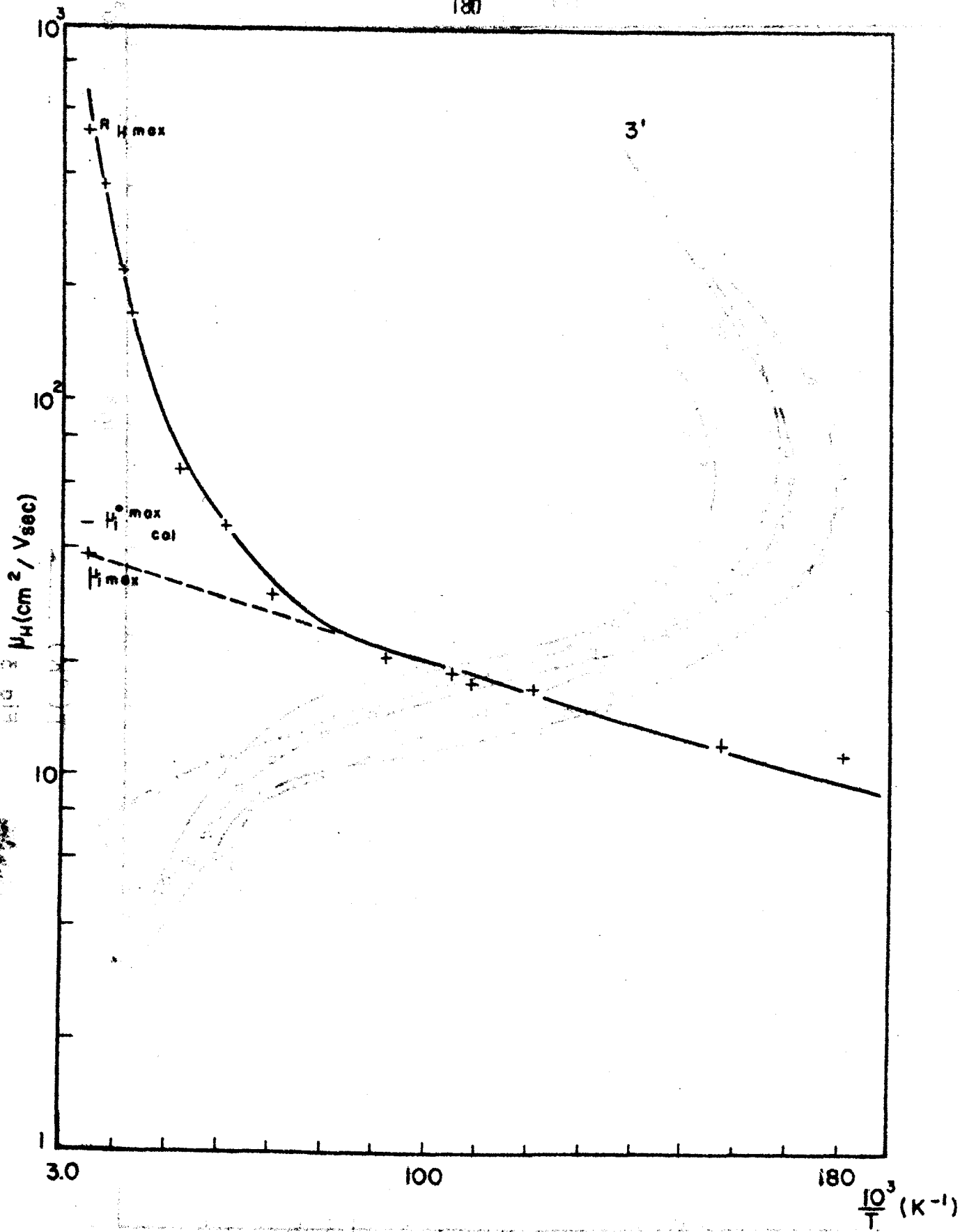


Fig 4

$j_H(\text{cm}^2/\text{Vsec})$

## REFERENCES

1. Van Maaren, Thesis 1965, ed. "Bronder-Offset" Rotterdam.
2. S. F. da Cunha, Thesis 1972, Montpellier, France.
3. Van der Pauw, Philips Res. Rep. 13, 1, 9 (1958).
4. Effer and Etter, J. Phys. Chem. Sol. 25, 451 (1964).
5. Hung G. S. and J. Gliessman, Phys. Rev. 79, 726 (1950).
6. H. Fritzche, K. Lark-Harovetz, Phys. Rev. 113, 999 (1959).
7. N. Mott and W. D. Twose, Advances in Phys. 10, 107 (1961).
8. Miller and Abrahams, Phys. Rev. 120, n<sup>o</sup> 3, 745 (1960).
9. F. J. Blatt, Sol. St. Phys. 4, 388 (1950).
10. H. Ehrenreich, J. Phys. Chem. Sol. 8, 130 (1959).