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S. F. da Cunha and S. Almairac

CENTRO BRASILEIRO DE PESQUISAS FÍSICAS

Av. Wenceslau Braz,71 - Botafogo - ZC-82

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S. F. da Cunha

Centro Brasileiro de Pesquisas Físicas

and

S. Almairac

Centre d'Etudes d'Electronique des Solides - Montpellier - France

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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 $T^{-3/4}$

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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 conductions mechanisms in GaSb saturated by diffusion with Li at 723°K, which corresponds to the condition $[Li_{Ga}]^+ = [Li_{Ga}Li]^-$, 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°K.

In the range 6°K to 300°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^2. 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 nanovoltimeter. 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. $R_H = \frac{d}{B} \Delta R(cm^3/C)$ where $\underline{d}$ is the thickness of the samples and ΔR 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 donnor and one acceptor level, the variation in the concentration of free carriers $\underline{p}$ as a function of the concentration of impurities N_D and temperature is given by the classical formula:

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

where $\underline{p} >> (N_A - N_D)$; $\beta = 4$ is the spin degeneracy factor of the acceptor level, determined by Effer and Etter (4); $N_V = 1{,}813 \times 10^{15}\ T^{3/2}\ cm^{-3}$ 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 exaustion 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 familly 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 desapeare 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.

$$n_i \simeq N_A - N_D$$

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 ρ 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 ρ presents a change of

inclination. The extrapolation of log ρ at temperature T^* will allow us to determine the conductivity of the free carriers at this temperature. Since ρ_V^* is the doble of ρ* the mobility of the impurities μ_i can be estimated from

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

The values of μ_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:

$$\rho^{-1} = C_1 \exp - \frac{\varepsilon_1}{kT} + C_2 \exp - \frac{\varepsilon_2}{kT} + C_3 \exp - \frac{\varepsilon_3}{kT} \qquad (3)$$

$$\varepsilon_1 > \varepsilon_2 > \varepsilon_3$$

The first term represents the conductivity of the valence band, with activation energy ε_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 ε_3. ε_2 and ε_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, $\varepsilon_3 = 0$.

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 ro 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 $\varepsilon_3 = 0$. 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 $d_{th} \leq 3\, a_o$ where a_o is the effective Bohr radius. In GaSb this condition means that $d_{th} \leq 47{,}7$ A. 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 Å.

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

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

The values of μ_i for our samples are less than μ_L by an order of magnitude (Table 1).

A third test consist of examining the activation energy ε_3 of the resistivity. If we accept conduction by hopping the resistivity is given by

$$\rho = \rho_o \exp - \frac{\varepsilon_3}{kT} \qquad (5)$$

Miller and Abrahms (8) have proposed that for low concentration the influence of the compensation k is included in ε_3 and that ρ_o is independent of k. By this theory, ε_3 can be calculated, for $k > 0{,}03$, by

$$\varepsilon_3 = \frac{\delta\, e^2}{\varepsilon}\left(\frac{4\pi N_A}{3}\right)^{1/3} \qquad (6)$$

where δ depends on k. The values of ε_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 $\frac{\mu_L}{\mu_i} \simeq 10$ 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 ρ.

We observe that from 300°K, when the temperature decrease, μ_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, μ_H increases exponentially with temperature. Similar behavior was absorved 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 theorv (9,10). We may conclude that not only the conduction mechanism of diffusion by accustic phonous is to be considered but also the optic phonous.

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 μ_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

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Simple	3'	3	$1p_7$	B_s	4_p
N_A (cm^{-3})	$6,57x10^{16}$	$7,98x10^{16}$	$8,08x10^{16}$	$1,07x10^{17}$	$1,22x10^{17}$
$(N_A-N_D)(cm^{-3})$	$7x10^{14}$	$4,8\ x10^{15}$	$3,2\ x10^{15}$	$3,2\ x10^{16}$	$1,2\ x10^{16}$
K	0,98	0,93	0,95	0,7	0,9
ε_3 exp (meV)	0,6	0,49	0,6	0,35	0,38
ε_3 cal (meV)	0,35	0,34	0,34	0,3	0,39
d (A)	154,3	144,8	144,2	131,3	125,7
μ_i cm^2/V seg	43,8	22,03	14,36	55,8	62
μ_t cm^2/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.

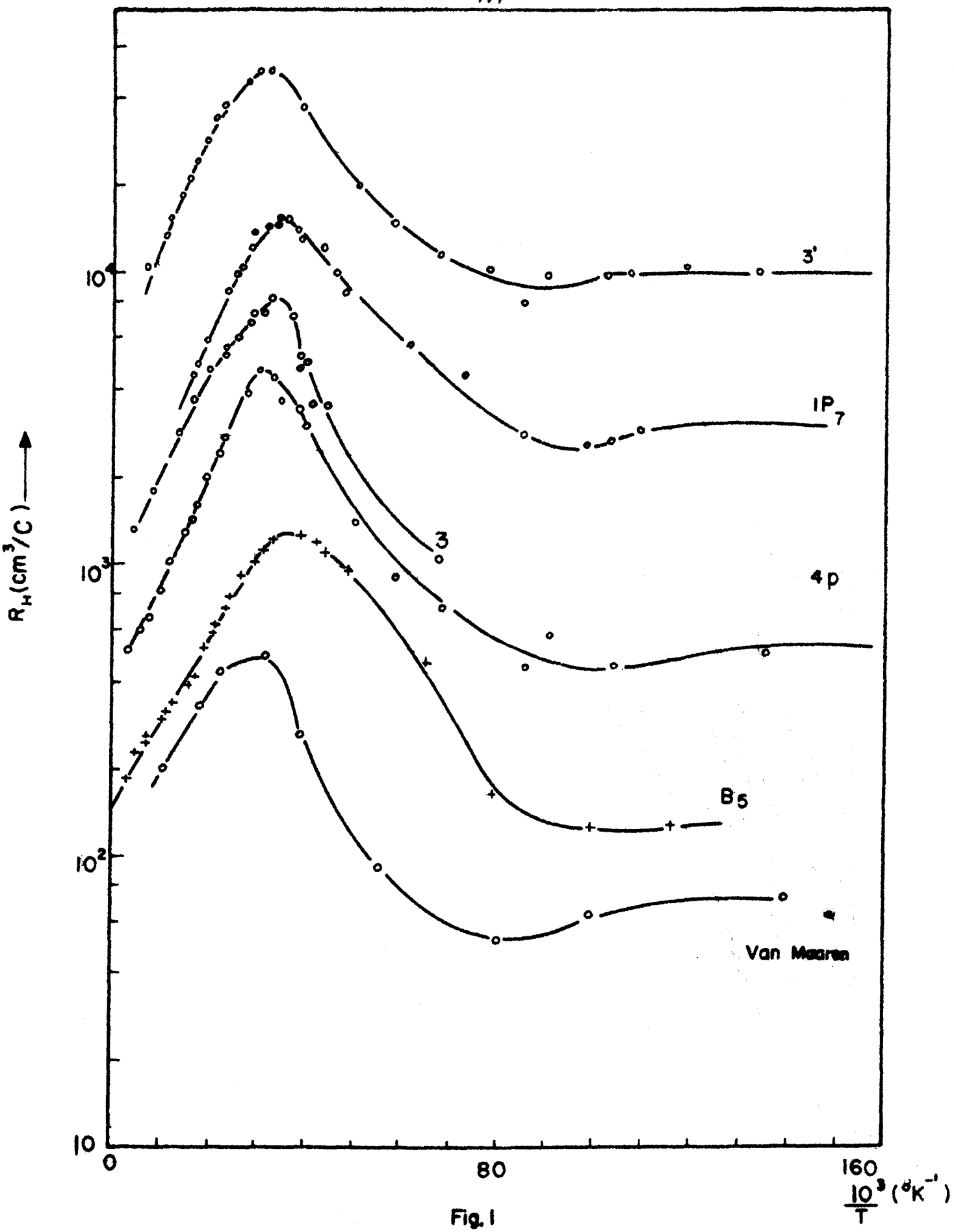
$R_H(cm^3/C)$
10^4
10^3
10^2
10
0
80
160
$\frac{10^3}{T}(^oK^{-1})$
3'
1P7
3
4p
B5
Van Maaren

Fig. 1

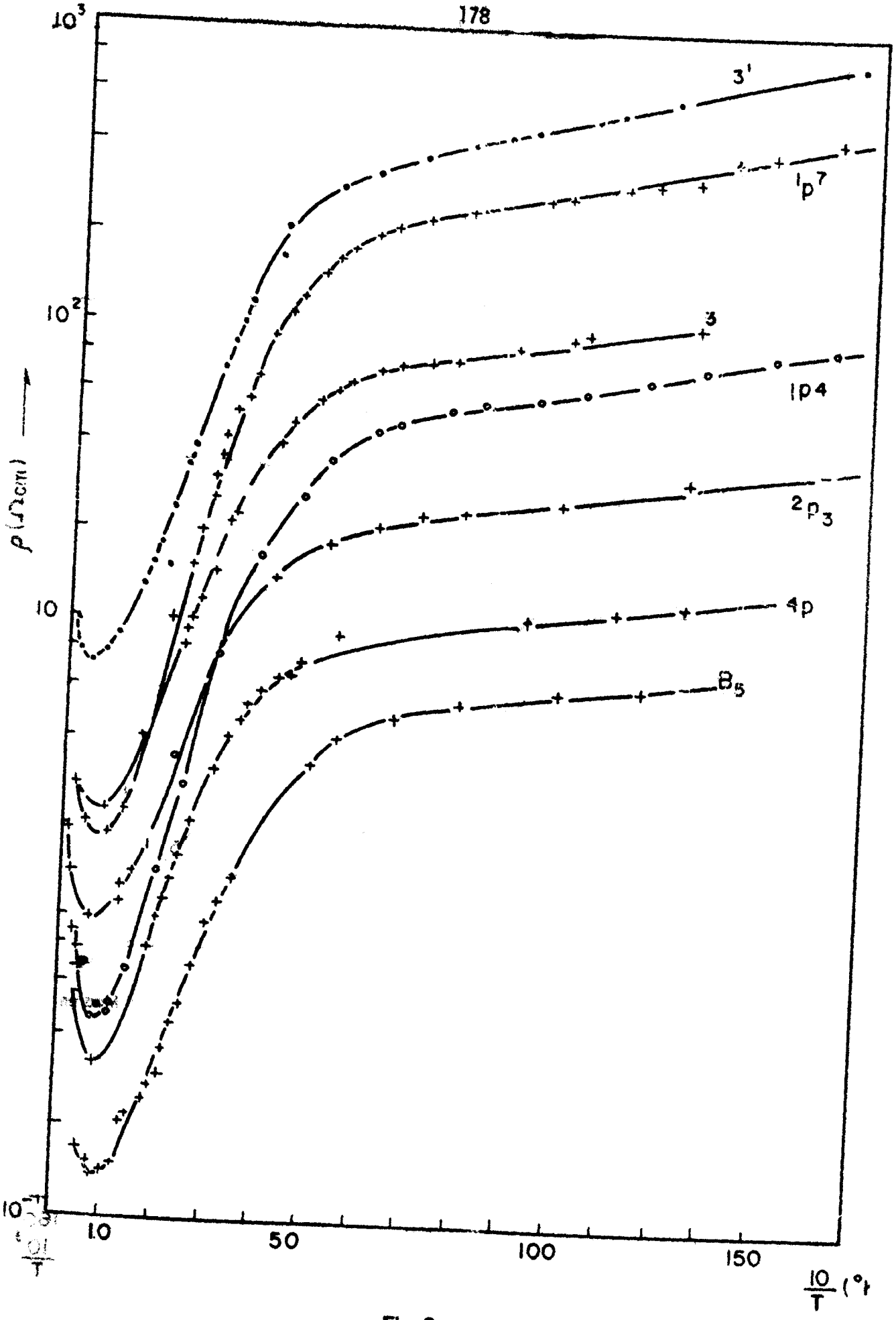
10^3
10^2
10
1.0
ρ (Ωcm) ⟶
3'
$^1p^7$
3
$^1p^4$
$^2p_3$
4p
B_5
50
100
150
$\frac{10}{T}$ (°k
$\frac{10}{T}$

Fig 2

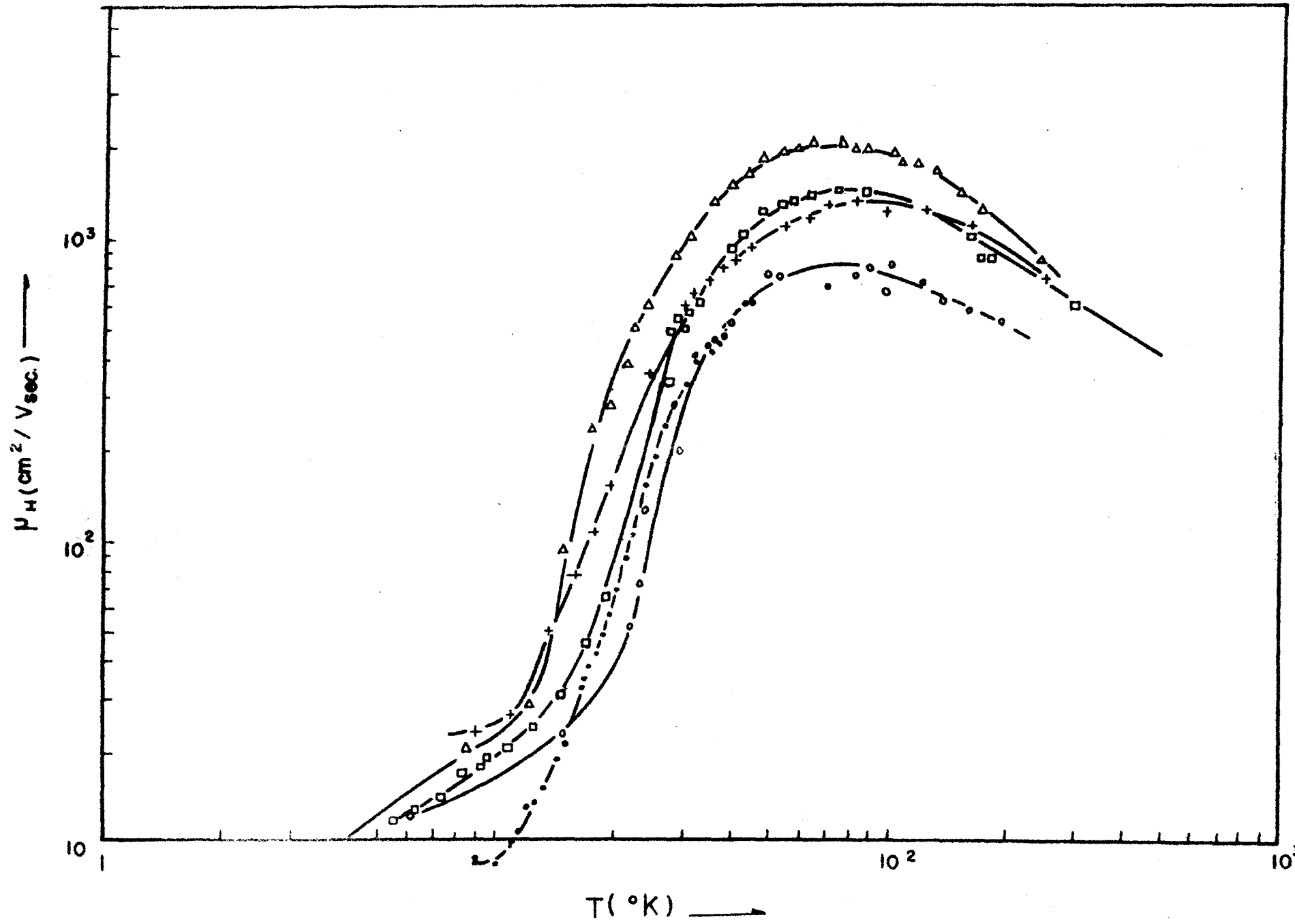

Fig. 3

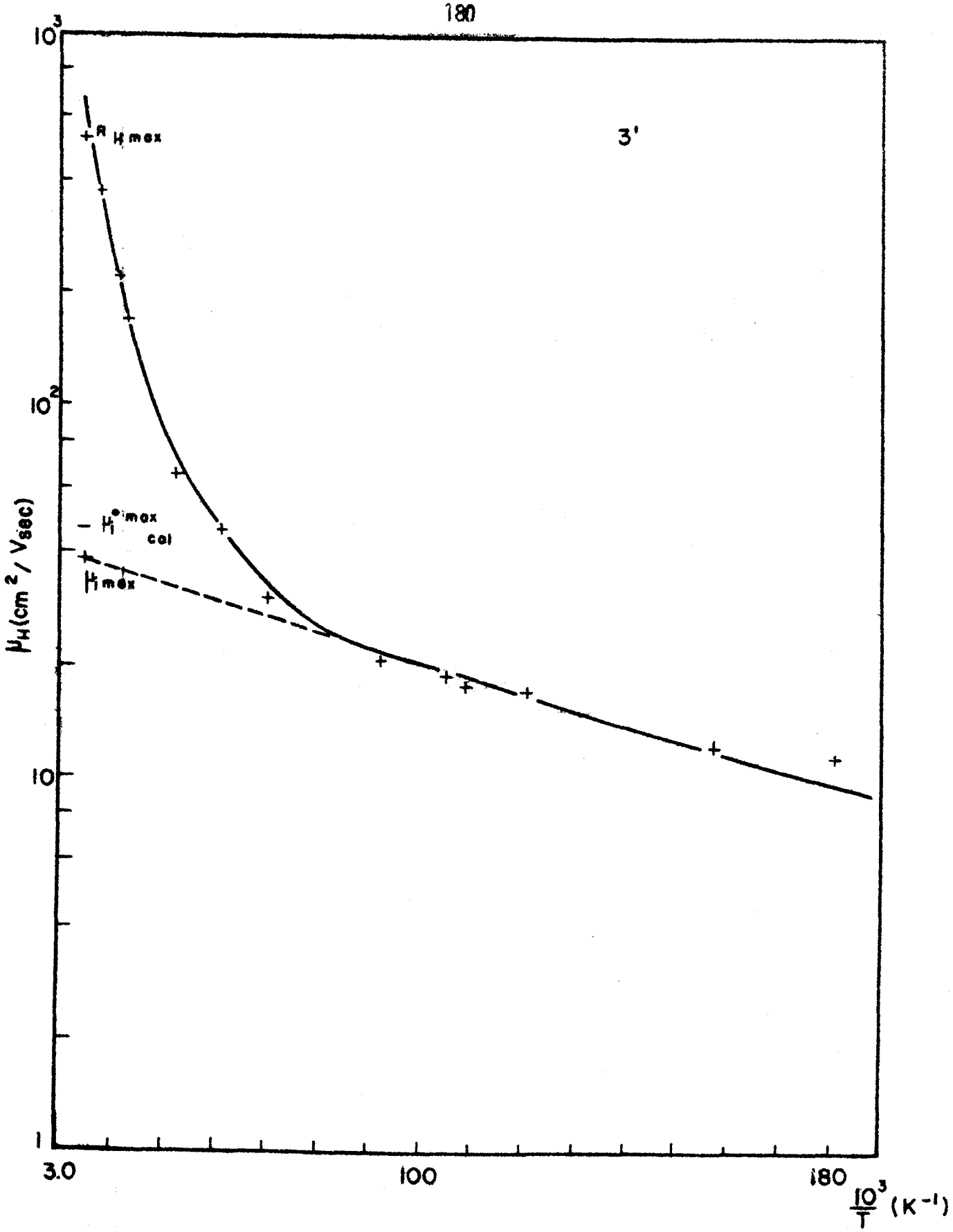

Fig 4

h^H(cw ^{sec}) ——→

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