Reprinted from

The Journal of PHYSICS and CHEMISTRY OF SOLIDS

An International Journal

PERGAMON PRESS

OXFORD · LONDON · NEW YORK · PARIS

J. Phys. Chem. Solids Pergamon Press 1963. Vol. 24, pp. 1539–1542. Printed in Great Britain.

TEMPERATURE DEPENDENCE OF HALL MOBILITY AND μ_H/μ_D FOR Si

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(*Received* 19 *April* 1963; *revised* 8 *July* 1963)

Abstract—The temperature dependence of the Hall mobilities has been determined as $6{\cdot}4 \times 10^9$ $T^{-2{\cdot}91}$ and $2{\cdot}4 \times 10^8$ $T^{-2{\cdot}06}$ for holes and electrons respectively. Using for the drift mobilities the expression found by LUDWIG and WATTERS, $2{\cdot}3 \times 10^9$ $T^{-2{\cdot}7}$ and $2{\cdot}1 \times 10^9$ $T^{-2{\cdot}5}$ for holes and electrons, we have calculated the temperature dependence of $\mu_H/\mu_D = r$, and found it coherent with the observed variation of the Hall coefficient. At 300°K, for holes $\mu_H = 398$ cm^2 $(V_s)^{-1}$ and $r_p = 0{\cdot}84$ and for electrons $\mu_H = 1880$ cm^2 $(V_s)^{-1}$ and $r_n = 1{\cdot}31$.

1. INTRODUCTION

THE determination of the density carrier in Si through measurements of Hall coefficient, $R_H = hV/BI$,† implies knowing the value of the ratio $\mu_H/\mu_D = r$. There exists a certain dispersion in the results obtained by other investigators (1, ..., 15) for the values of the drift mobility, μ_D, Hall mobility, $\mu_H = R_{H\sigma}$, and consequently $\mu_H/\mu_D = r$. We have determined, by using high purity, floating zone refined Si, the temperature dependence of the Hall mobility. Using the results of LUDWIG and WATTERS(1) (from here on we shall refer to their paper as 1) for the values of the drift mobilities, μ_D, we have calculated the temperature dependence of the ratio μ_H/μ_D, and compared it with that of R_H.

2. EXPERIMENTAL TECHNIQUES

The facilities in the laboratory allow us to measure Hall effect and resistivity between 320 and 100°K, the temperature homogeneity of the studied sample being 0·1°.

The magnetic field is generated by a Varian electromagnet which allows to work with fields up to 10,000 G. The measurements of the magnetic field were done with the usual nuclear resonance equipment. The samples were normally measured in a 5,000 G field in the direction of the crystal axis (111). The linearity of the results as a function of the magnetic field was verified in several instances.

The Si samples can be measured in vacuum or in an inert atmosphere. When the contact resistance in the sample was sufficiently low, we used an opposition bridge for the measurements, otherwise, a VIBRON electrometric voltmeter.

The Si samples were cut with an ultra-sonic drill in the shape shown in Fig. 1. The dimensions were chosen so as to reduce as much as possible the effects of geometry and injection of minority carrier by the contacts.

During the measurements, the electric field E in the Si was never superior to 400 mV/cm and the linearity of the Hall effect as a function of E was in all cases verified.

The sparking technique(16) was used for the formation of the contacts, with Au–Sb for Si–*n* and Al for Si–*p*. To make sure that the irregularity of the contacts did not affect the measurements, an electrical analogy for the sample was made. It was verified that the influence of the current injecting contacts completely disappeared before reaching the nearest pair of arms.

In Si–*p* and Si–*n* samples a certain dispersion in the results is observed when the abrased surface is attacked either with NO_3H or FH. This

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† h: sample thickness; I: total current; B: magnetic field; V: Hall tension.

dispersion is caused by the formation of an oxygen surface layer and was of 8, 4 and 3·5 per cent, for samples 0·5, 1 and 2 mm thick respectively. A direct relation can be found between the dispersion values and the surface–volume ratio. We have used for our measurements samples 2 mm thick which had been attacked with FH.

The homogeneity of the Si crystals used was below 1 per cent for the *p*-type Si, while for the *n*-type a gradual variation not superior to 9 per cent, was observed along the sample, in this later case a convenient average value for the Hall voltage measured on the two pairs of arms was determined. The precision for the resistivity measurements amounted to 6 per cent and for the mobility 3 per cent. The reproducibility of the results for the same sample was below 1 per cent.

Si-*p*

We have used *p*-type, floating zone refined Si with resistivities of approximately 1,000; 5,000; and 8,000 Ω cm. The Hall mobility results between 100 and 320°K are shown in Fig. 2, curve 1, they follow the law: $\mu_H = (6{\cdot}4 \pm 0{\cdot}15) \times 10^9\ T^{-2{\cdot}91}$.

In Table 1 are shown the results obtained by different authors for the Hall mobility and drift mobility at 300°K, and the coefficient α in the expression $\mu = AT^{-\alpha}$.

There is a good agreement between the mobility values of Refs 2, 4, 5, 6, 7 and 8 and our results. We can find no explanation for the difference with the value given by Ref. 3. Nothing can be said with respect to coefficient α since there is a large dispersion in the results.

Using the results of (1) for the drift mobility of holes we have calculated the absolute value and the temperature dependence of the ratio $r_p = \mu_H/\mu_D$. This ratio can be approximately represented between 300 and 150°K by the $2{\cdot}8\ T^{-0{\cdot}21}$ law. In Fig. 2, curve 2 are represented the experimental

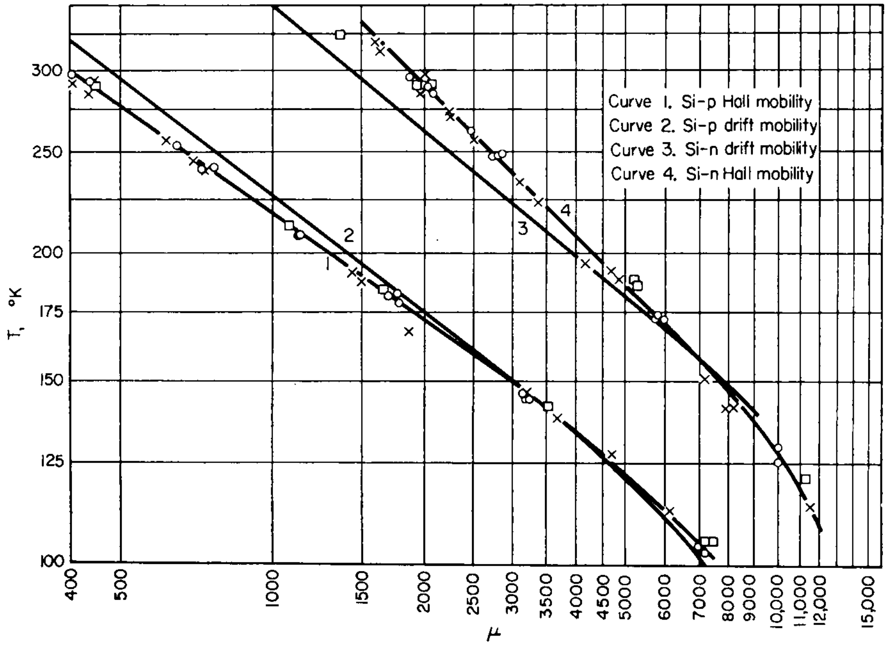

FIG. 2. Curve 1: $\mu_{Hp} = f(T)$, ○ 1440 Ω-cm Si-*p*
× 7700 Ω-cm Si-*p* (authors)
□ 6200 Ω-cm Si-*p*.
Curve 2: $\mu_{Dp} = f(T)$, Ref. (1)
Curve 3: $\mu_{Dn} = f(T)$, Ref. (1)
Curve 4: $\mu_{Hn} = f(T)$, ○ 900 Ω-cm Si-*n*
× 800 Ω-cm Si-*n* (authors)
□ 1400 Ω-cm Si-*n*.

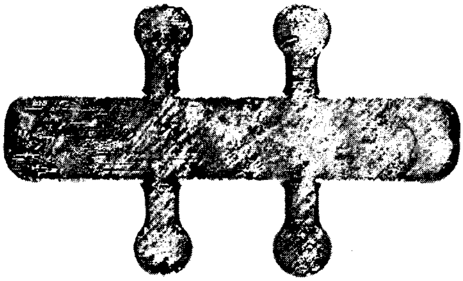

FIG. 1. Photograph of a Si sample (dimensions of the body: 16 × 3 mm).

Table 1. Si–*p*

Reference		(3)	(2)	(4)	(5)	(6)	(7)	(1)	(13)	(8)	Authors
$T = 300°K$	μ_H	619	350	350	404	375	370			399	398
$T = 300°K$	μ_D				356			475	495	504	
	α_H	2·7		2·36			2·9				2·9
(Ω-cm)	α_D	5000	33	50	110	85	115	180		1000	8000

results of (1), with their highest resistivity Si–*n* sample. In Fig. 3, curve 1, the value of r_p is shown as a function of T. If the carrier density were constant with T, then the variation of R_H with T should be equal to the variation of r_p. In Fig. 3, curve 2, we have plotted the variation of R_H with temperature, normalized to the value of r_p at 300°K. Our results for the temperature dependence of r_p agree, as can be seen in Fig. 3, with the Hall coefficient variation observed by LONG(6) for samples of 35 Ω-cm. The difference between curves 1 and 2 can be explained by a small variation in the carrier density as a function of the temperature ($1–2\times 10^{11}$ for a $\Delta T = 200°$). It can be rightly supposed that this effect is due to a change in the charge state of the dislocations, or other crystal imperfections and which will be more noticeable in a high resistivity sample than on a low resistivity one as can be seen for the sample of 35 Ω-cm of Long. It is on account of this that we can conclude that our results for μ_H and those of μ_D obtained by (1) are coherent and curve 1 represents the correct variation of r_p with the T.

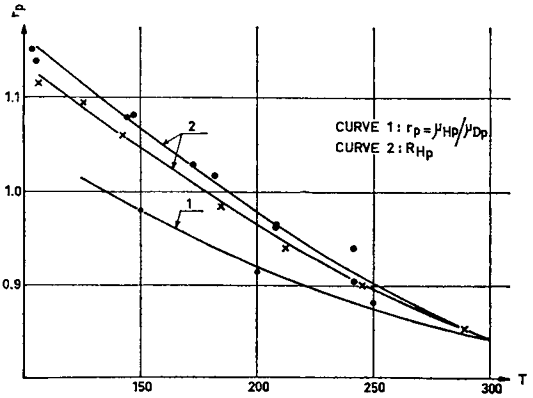

FIG. 3. Curve 1: $r_p = f(T)$ (authors).
● R_H values for 35 Ω-cm Si–*p* obtained by LONG.(6)
Curve 2: $R_H = f(T)$, × 6200 Ω-cm Si–*p* (authors)
○ 1400 Ω-cm Si–*p*.

Si–*n*

We have used Si–*n* of a resistivity superior to 500 Ω-cm purified by floating-zone. The Hall mobility results between 100 and 320°K, are shown in Fig. 2, curve 4. Between 150 and 300°K they follow the law $\mu_H = (2{\cdot}4 \pm 0{\cdot}04)\times 10^8\, T^{-2{\cdot}06}$. For temperatures lower than 170°K the measured Hall mobilities are smaller than the values given by the above law.

In Table 2 are given the results of μ_H and μ_D at 300°K, together with the value of α, from the $\mu = AT^{-\alpha}$ law.

Our value of μ_H at 300°K is slightly higher than those given by Refs 4, 8, 5 and 9. This could be explained by the fact that we have used a higher

Table 2. Si–*n*

Reference		(3)	(4)	(5)	(9)	(8)	(1)	(13)	Authors
$T = 300°K$	μ_H	1345	1740	1830	1770	1810			1880
$T = 300°K$	μ_D			1590		1345	1335	1485	
	α_H	2	2·04						2·06
	α_D						2·5		
ρ(Ω-cm)		1800	27	94	27	300	120		800

resistivity Si, however we cannot explain the low value obtained at the same temperature by Putley and Mitchell,⁽³⁾ although they have also worked with high resistivity Si. The coefficient α is also slightly higher, although a better agreement is found for this case than for the Si–*p*.

Using as drift mobility value that given by Ludwig for their higher resistivity samples, we have calculated the variation of r_n with temperature. In Fig. 2, curve 3, are shown the results of Ludwig for the drift mobility of electrons. In Fig. 4, curve 1, are represented the calculated values of r_n, which between 300°K and 150°K approximately follow the $0{\cdot}11\ T^{0{\cdot}44}$ law.

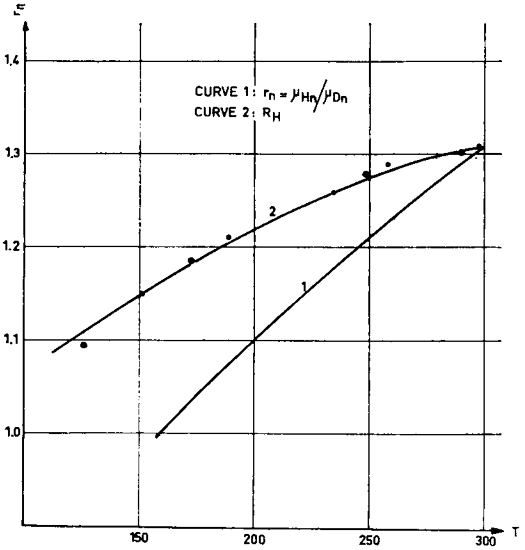

Fig. 4. Curve 1: $r_p \;=f(T)$ (authors)
Curve 2: $R_H \;=f(T)$ ● 900 Ω-cm Si–*n* (authors)
⊙ 800 Ω-cm Si–*n*.

In Fig. 4, curve 2, is given the variation of R_H with T, normalized at 300°K for the corresponding value of r_n. The decrease of R_H with T can only be explained if r_n is temperature dependent. The difference in Fig. 4, between curves 1 and 2 may be related to an effective diminution with T of the carrier density. Nevertheless, if we accept curve 1 as correct, curve 2 implies a 10 per cent variation in the carrier density for a temperature change from 300 to 170°K, variation which is approximately independent from the resistivity of the sample.

It seems that a carrier density variation with T that could be caused by levels due to lattice imperfection would lead to a smaller relative variation in the low resistivity crystals, a fact which is contrary to our experimental results. It is on account of this that a more likely value of α for the electrons drift mobility would be 2·4 instead of 2·5.

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