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Temperature Dependence of Galvanomagnetic Properties for Lightly Doped N-Type Si

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Abstract

The temperature dependence of Hall and magnetoresistance effects in n-type Si having a resistivity of 1400 Ω cm at room temperature is studied in the temperature range of 210-320 K. The variation of transverse magnetoresistance as a function of temperature is similar to the longitudinal magnetoresistance variation in $< 001 >$ and $< 1\bar{1}0 >$n-Si the samples. It is observed that, in $< 001 >$ sample, the transverse and longitudinal magnetoresistance variation is greater than that in the $< 1\bar{1}0 >$ sample. In both samples, the temperature dependences of magnetoresistance is in accordance to double space anisotropy parameters. In both samples, the transverse and longitudinal magnetoresistance coefficents increase with increasing temperature in the temperature range 210-240 K and decrease with increasing temperature in the temperature range 240-320 K. The carrier concentration increases with increasing temperature and Hall mobility increases with temperature up to 260 K and decreases with increasing temperature above 260 K.

1. Introduction

Single crystal silicon (Si) is one of the most important materials of present microelectronic technology. A lot of information can be obtained about semiconductors by characterizating their electrical and optical properties. Two of these characterization methods are Hall and magnetoresistance tehcniques. Magnetoresistance measurements provide information about constant energy surfaces and unknown magnetic field measurments, white Hall measurements provide information about carrier concentration, type and Hall mobility of the same meterials [1].

The form of the energy bands are important for theoretical magnetoresistance coefficents, as well as the values of the band parameters and their anisotropy that effect their formation. In cubic symmetry, the three independent magnetoresistance coefficients can be calculated from magnetoresistance measurements [2]. Magnetoresistance effects have been studied by Long and Myers [3] in highly doped p-type Si in the temperature range 77 to 350 K. They demonstrated that there is an increase in magnetoresistance coefficients with increase in resistivity and an inverse dependence on temperature. The tempereture dependence of transverse magnetoresistance in high resistivity p-type Si is studied in the range from 120 to 290 K [4].The magnetoresistance coefficients for the samples increase with decreasing sample temperature in the range from 290 to 160 K; however, this behavior is reversed below 160 K. It is proposed that this reversal is due to the double injection effect [4]. Temperature and magnetic field dependence of electrical resistivity and Hall effect in several p-type Si samples have been investigated [5]. The relative directions of current, magnetic field and crystallographic axes dependence of the magnetoresistance has been studied at 77 and 300 K as a function of the field strength with particular emphasis on obtaining accurate values of the various coefficients which are required for a complete charactarization of the magnetoresistance in the limit of zero field. The main features of these results are the relatively large observed values of longitudinal magnetoresistance which, in the same cases, are nearly as large as the transverse effects [5]. The effect of impurity concentration, temperature and orientation on the magnetoresistance coefficents have been reported by Nakagawa and Zukotnyski [6]. Their experimental results for the magnetoresistance coefficents increased with decreasing impurity concentrations. The drift, Hall mobility and Hall coefficient have also been calculated by Nakagawa and Zukotnyski using the Kane band model. The results agree with experimental results for both Si and Ge [7].

The anisotropy parameters in higly doped p-type Si have been reported by Long [3]. He found m=1.02, n= 0.17 (77 K) and m=1.35, n=0.39 (300 K) and the rate of anisotropy parameters (m/n) was found to be 0.17 (77 K) and 0.29 (300 K), respectively.

Three coefficents β, γ, δ defined by Seitz [8] which characterize the change in conductivity of cubic crystals in weak magnetic field are used in their theoretical calculations. The values of the Hall mobility at 300 K were found from the usual relation [9] μ_H=σR, and lie between 360 cm^2/Volt-sec and 390 cm^2/Volt-sec for p-type samples.

In this article, the temperature dependence of transverse, longitudinal magnetoresistance coefficients Hall mobility and anisotropy parameters have been measured having magnetic field perpendicular and parallel to [001] and [1$\bar{1}$0] for high resistivity n-Si in the temperature range 210-320 K. To the best of our knowledge this is the first time that anisotropy parameters as a function temperature have been investigated in high resistivity n-type Si.

2. Basic Equations

The magnetoresistance coefficients in terms of measurable parameters can be written in the following form [3]:

$$M_j^B = \frac{\Delta\rho}{\rho_o B^2} = \left[\frac{V(B) - V(0)}{V(0)B^2}\right] = \left[\frac{\rho(B) - \rho(0)}{\rho(0)B^2}\right], \tag{2.1}$$

where superscript B and subscript j represent the magnetic field and current directions, respectively, and thus the difference between the resistivity with, (denoted by ρ(B$_z$)), and without (denoted by ρ(0)) the magnetic field is given by

$$\Delta\rho = \rho(B_z) - \rho(0). \tag{2.2}$$

The avarage voltage V$_x$(B) (for transverse and longitidunal magnetorsistance) is written as:

$$V_H = \frac{1}{4}\Big\{[V_{CD}(B_z) - V_{CD}(-B_z)]_{I_+} - [V_{CD}(B_z) - V_{CD}(-B_z)]_{I_-}\Big\}, \tag{2.3}$$

where I$_+$ and I$_-$ indicate positive and negative polarities of current, respectively. The voltage in zero magnetic field V$_x$(0) is given as

$$V_x(0) = \frac{1}{2}\left[V_{CD}(0)_{I_+} - V_{CD}(0)_{I_-}\right], \tag{2.4}$$

where VCD is the voltage contacts between C and D. The Hall coefficient and the Hall mobility for n-type semiconductors are
defined as

$$R_H = \frac{r_H}{ne} = \frac{V_H d}{B_z I_x} \tag{2.5}$$

and

$$\mu_H^e = r_H \mu_d^e = |R_H|\sigma, \tag{2.6}$$

where r$_H$ is the Hall coefficient factor, n the carrier concentration, e the electron charge, μ_d^e the drift mobility, σ is the electrical conductivity for electrons, d the sample thickness and I$_x$is the current through the sample.

r_H values, given by Nagakawa as a function of temperature, were used in this study [7]. The Hall voltage V_H in Equation (2.5) is given by

$$V_H = \frac{1}{4}\Big\{[V_{CD}(B_z) - V_{CD}(-B_z)]_{I_+} - [V_{CD}(B_z) - V_{CD}(-B_z)]_{I_-}\Big\}. \tag{2.7}$$

The drift mobility and carrier concentration for electrons can be experimentally obtained by using the Hall coefficient and the Hall coefficient factor which is used to examine theoretical magnetoresistance coefficients.

The weak field magnetoresistance results can be discussed conveniently in terms of the following two anisotropy parameters [10]. Magnetoresistance is, in general, very sensitive to anisotropies in the energy surface and in the scattering, and these parameters reflect this sensitivity:

$$m = (2\beta + \delta)/2\beta \tag{2.8}$$

$$n = (2\beta + 2\gamma + \delta)/2\beta \tag{2.9}$$

where β, γ, δ are small-field magnetoresistance constants, which can be expresed as

$$\begin{array}{ll} a = -\alpha\rho & b = -(\beta + \rho\alpha^2)\rho \\ c = -(\gamma - \rho\alpha^2)\rho & d = -\delta\rho. \end{array} \tag{2.10}$$

Magnetoresistance coefficients can be written as a fuction of a,b,c,d as follows:

$$M_{110}^{110} = b + c + d/2 \tag{2.11}$$

$$M_{110}^{1\bar{1}0} = b + d/2 \tag{2.12}$$

$$M_{100}^{001} = b \tag{2.13}$$

$$M_{100}^{100} = b + c + d \tag{2.14}$$

Upon obtaining a,b,c,d values , the anisotropy parameters m, n can be calculated.

3. Experimental

In the present work, Ohmic contacts for the Hall and magnetoresistance measurements were made by AuSb (1%) evaporation in a vacuum of 10^{-5} Torr. The samples (Fig. 1) were annealed in nitrogen medium at 450 $^{\circ}$ C for 3 minutes. The galvanomagnetic measurements as a function of temperature were made in a closed-cycle He cryostat. A uniform magnetic field was applied by a Varian V-2900 electromagnet and increased from 0.0 to 0.8 T in steps of 0.1T.

The current and voltage measurements were made via a current source (Hameg, Model 2112) and a digital multimeter which has input impedance 1G-Ohm (Keithley, Model 171) with a measuring accuracy of ±0.01 μA and ±0.01 nV, respectively. The current was applied between the point contacts A and B, and voltage was measured between the two point contacts C and D for both the Hall and magnetoresistance effects (Fig. 1). All the measurements were made by averaging the voltage values to eliminate the thermoelectric potentials [12].

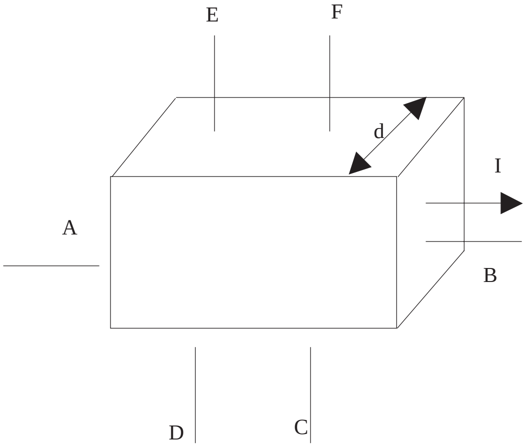

Figure 1. Hall bar geometry.

4. Results and Discussion

Figure 2 shows a plot of transverse magnetoresistance coefficents (M_T) vs. temperature. As seen in Fig. 2, in $< 001 >$ and $< 1\bar{1}0 >$ n-Si samples, (M_T) increases with increasing temperature up to 240 K and decreases in the range 240-320 K. This may result from scattering of electrons by different type of (donor and acceptor) impurities in Si. In $< 001 >$ sample, the variation of $M_T$is greater than that of $< 1\bar{1}0 >$ sample up to 270 K and is almost equal with each other above 270 K. The longitudinal magnetoresistance coefficients (M_L) in both samples increases with increasing temperature in the temperature range 210- 240 K and decreases with increasing temperature above 240 K (see Fig. 3). The (M_L) in $< 001 >$sample is greater than that of $< 1\bar{1}0 >$ sample. The (M_T) and (M_L) depend on band and scattering anisotropy of the sample [4]. So we can say that both of our samples have a strong band anisotropy. The variations of the (M_T) and (M_L) as a function of temperature are in agreement with theoretical studies of Nakagawa and Zukotynski [6] in the sample temperature range of 240-300 K, but disagree below 240 K. We proposed that this disagreement is due to the double injection effect. Double injection covers the cases when injected carriers of both types play a role in determining the conductivity mechanism, even if the current is carried by only one type of carrier. Hall [12] and Okazaki et al. [13]have pointed out that injection and recombination of electrons and holes occur in the intrinsic region of a thin p-i-n structure. In the case of silicon, double injection has been observed in samples with doping concentration of 10^{11} to 10^{13}cm^{-3}[14]. We could not perform any measurements below 210 K due to high resistivity (below this temperature), instabilities and oscillations.

Also in p-type Si, which has high resistivity, we could not make any measurements below 120 K due to instabilities and oscillations [4]. In $< 1\bar{1}0 >$ samples, the (M_L) and (M_T) values as a function of temperature are smaller than those of$< 001 >$ samples. The reason is that, although band anisotropy in $[1\bar{1}0]$ direction is greater than that of [001] direction, the scattering anisotropy is smaller than that in the [001] direction.

In isotropic media, anisotropy parameters are m=1 and n=0. Deviation of experimental values of m and n from above values is then indicative of a deviation from isotropy either of energy surface or of the scattering or of both [5]. As seen in Fig. 4 and Fig. 5, it is easily observed that the values of m and n are different from above values. So we can say that our samples have anisotropic scattering and band structure. Deviation from isotropy of anisotropy parameters (m and n) in the [001] direction is greater than that of the $[1\bar{1}0]$ direction in the temperature range of 200 to 280 K. This is an unexpected result, because Si has the highest rotational symetry in the [001] direction. We can say that the scattering anisotropy in the [001] direction is greater than that of $[1\bar{1}0]$ direction. Deviation from isotropy of anisotropy parameters increases with decreasing temperature in the range of 320 to 240 K, but decreases below 240 K. This result is in agreement with the values of the magnetoresistance coefficents and the mobilities.

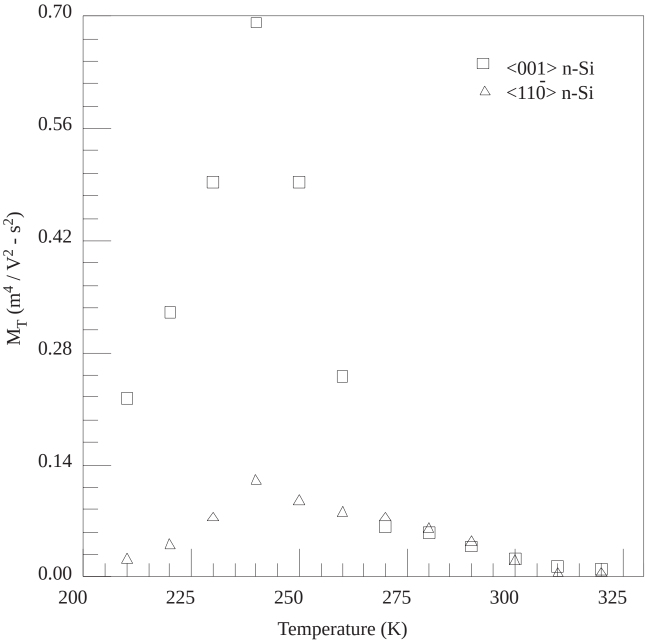

Figure 2. Transverse magnetoresistance coefficient as a function of sample temperature.

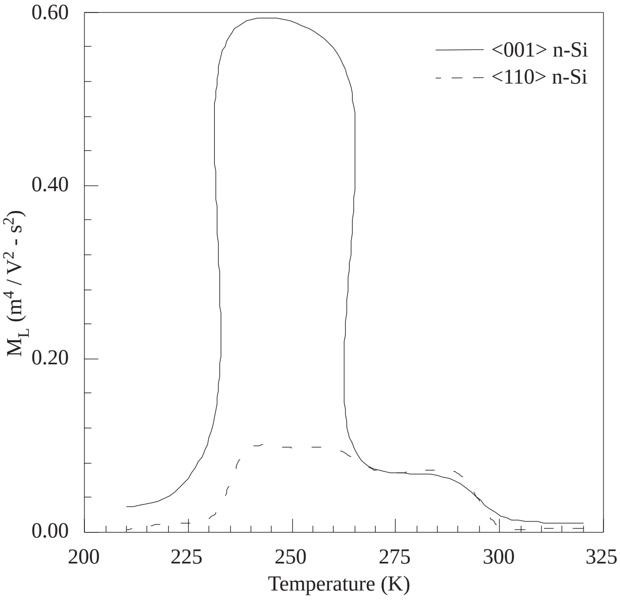

Figure 3. Longitidunal magnetoresistance coefficient as a function of sample temperature.

As seen in Fig 6, the Hall mobility increases with increasing temperature in the temperature range 210- 260 K and decreases with increasing temperature in the temperature range 260- 320 K. The change of Hall mobility as a function of temperature (260- 320 K) is in agreement with theoretical calculations [7]. The different behavior of Hall mobility in the range 210- 260 K arises from the different type of ionized impurities in Si sample. Although the lattice scattering is dominant at the range 260- 320 K, below 260 K ionized impurity scattering is more dominant [15].

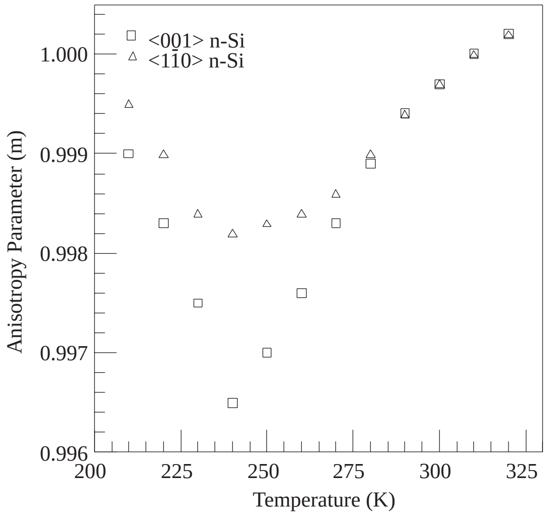

Figure 4. Anisotropy parameter (m) as a function of sample temperature.

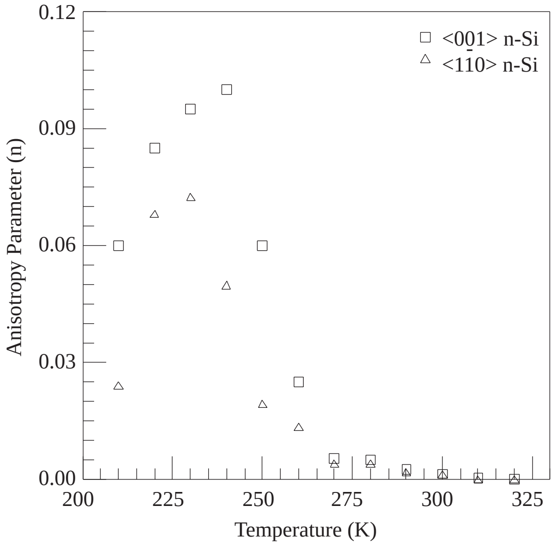

Figure 5. Anisotropy parameter (n) as a function of sample temperature.

In Fig. 7, we plotted the carrier concentration as a function of temperature in the range 210- 320 K. The carrier concentration increases with increasing temperature in the temperature range 210- 270 K, decreases with increasing temperature in the temperature range 270- 290 K, and again increases with increasing temperature above 290 K. In these graphs the estimated error bars are smaler than the size of the centred symbols. In semiconductors, carrier concentration increases with increasing temperature [16]. The behavior of carrier concentration in both samples at 270-290K is due to compensation.

Deviation from isotropy of anisotropy parameters increases with decreasing temperature in the range of 320 to 240 K, but decreases below 240 K. This result is in agreement with the values of the magnetoresistance coefficents and the mobilities. In conclusion, this paper reports the transverse and longitudinal magnetoresistance and anisotropy parameters as a function of temperature in high resistivity n-Si. The transverse and longitudinal magnetoresistance effects show that the shape of the constant-energy bands surfaces is nonspherical.

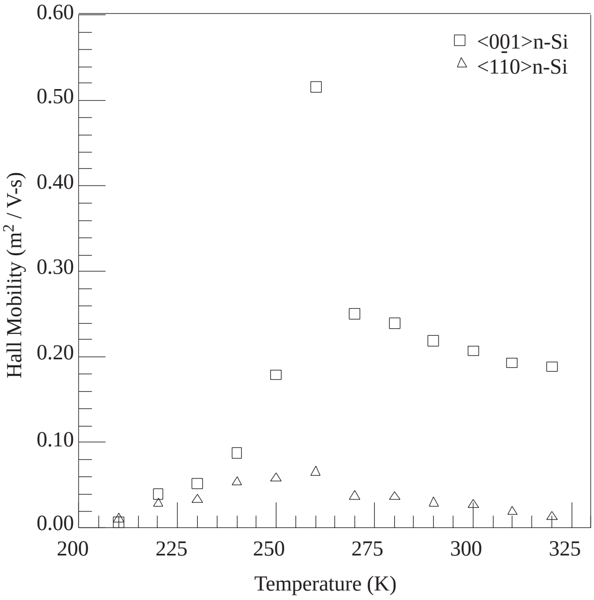

Figure 6. Hall mobility as a function of sample temperature.

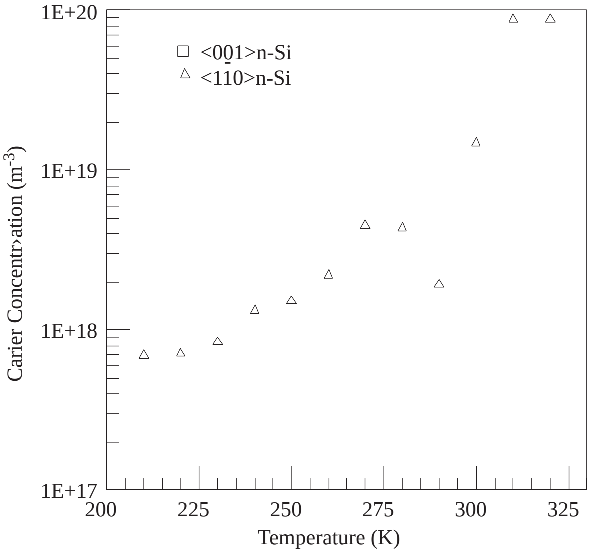

Figure 7. Carrier concetration as a function of sample temperature.

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