YU ISSN 0015—3206
FZKAAA 23 (3): 211 (1991)

EFFECT OF DEVIATIONS OF THE CURRENT VECTORS FROM (100) AXIS OF n-TYPES SILICON BY DIFFERENT ANGLES ON THE MAGNETORESISTANCE AT 300 K

MOHAMED S. ZAGHLOUL

Dept. of Physics, Faculty of Science, Al Azhar University, Nasr City, Cairo, Egypt

Received 10 February 1989

Revised manuscript received 6 May 1991

UDC 538.935

Original scientific paper

The transverse magnetoresistance (TMR) was measured as a function of rotational angle Θ between the directions of both magnetic field (B) and current (I) at several values of B in n-type silicon crystals with carrier concentration of 10^{16} cm^{-3} at 300 K. The orientation of the samples are chosen so that the angles (φ_n) among the current vectors and (100) crystallographic axis are 10°, 30° and 40°, respectively. These measurements were done under in low electric and magnetic fields. Many types of anomalous effects of TMR were observed at the two opposite directions of B. Sharp variations in anomalous TMR with different intensities were found when $\varphi_{(100)} = 10°$. Also the negative effects of $\Theta - \Delta\varrho/\varrho_0$ relationships were detected at low B, but as B increases the negative MR vanishes. This shows that the anomalous and negative behaviours of TMR are strongly dependent upon the value of deviation angle of current from (100) axis of symmetry. The experimental data are illustrated and the results are discussed.

1. *Introduction*

Impurity levels and electron scattering mechanisms in some single crystals were investigated by means of resistivity and Hall coefficient measurements in the 30—500 K temperature range$^{1)}$. It was found that the lattice scattering is predominant in this range and the temperature dependence of electron mobility. Theoretical and experimental studies were made of the magnetic field (B) dependence of the Hall coefficient at 77 and 300 K, and of the temperature dependence of Hall effects in the range 77—260 K on the p-type germanium[2]. These results may be attributed to the scattering by ionized impurities, and by the acoustic phonons mechanisms.

The transverse and longitudinal magnetoresistance (LMR and TMR) as a function of rotational angle Θ between B and current (I) under relatively high B at low temperature were studied[3] for p-type (001) Si on sapphire (1—2 μm thickness). The appearance of anisotropy behaviours of MR may be due to the deformation-potential-constant formalism.

The aim of this work is to study the effect of deviations of the current vectors from (100) axis of n-Si crystals by different angles (φ_n) on the TMR under weak electric and magnetic fields at 300 K.

2. *Experimental details*

The n-type silicon samples were doped with the same impurity concentration of 10^{16} cm^{-3}. An ultrasonic cutter was used to cut the impurities out of crystals grown in (100) direction. The orientations* of the samples are chosen so that the angles φ_n among the current vectors and (100) axis are 10°, 30° and 40,° respectively, i. e. $\varphi_{(100)} = 10°, 30°$ and 40°. Every sample has a bridge shape with dimensions of $10 \times 1.5 \times 0.6\,\text{mm}^3$. The surfaces of the samples were polished and etched before making electrical contacts. Thin silver wires were shouldered on the spots for electrodes by using silver paste. A special attention was paid so that each electrode did not spread out of the contact surface into adjacent surfaces. All the electrodes were checked to be ohmic in contact at the investigated temperature ($T = 300$ K). Also the homogeneity of every sample was checked by comparing the values of resistivity and Hall coefficient obtained on the two sets of the side arms of the sample at $T = 300$ K.

During the measurements, the following simplifications were made; the diameter of the circular disk of the contact was much smaller than the smallest linear dimension of the sample, the resistivity ϱ and carrier mobility μ of the contact material were much smaller than those of the material under examination, the finally the medium was homogenous and quasi-isotropic.

For measuring the rotational angle Θ between the directions of both B and current (I), the sample was put in cryostat. The strength of the D. C. electromagnet was measured by a calibrated gaussmeter. The measurements of electrical resistivity and magnetoresistivity were carried out at weak electric current ($I =$ $= 100$ mA), where the carriers do not become hot and at low magnetic field up to 1.2 T to avoid the thermomagnetic effect.

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* The samples had been grown in the Department of Semiconductor Physics of Leningrad State University.

3. Results

The TMR of n-Si samples were measured as a function of rotational angle Θ between the normal direction of B and I at $T = 300$ K for different values of B, when $\varphi_{(100)} = 10°$, 30° and 40°, respectively as shown in Figs. 1, 2 and 3.

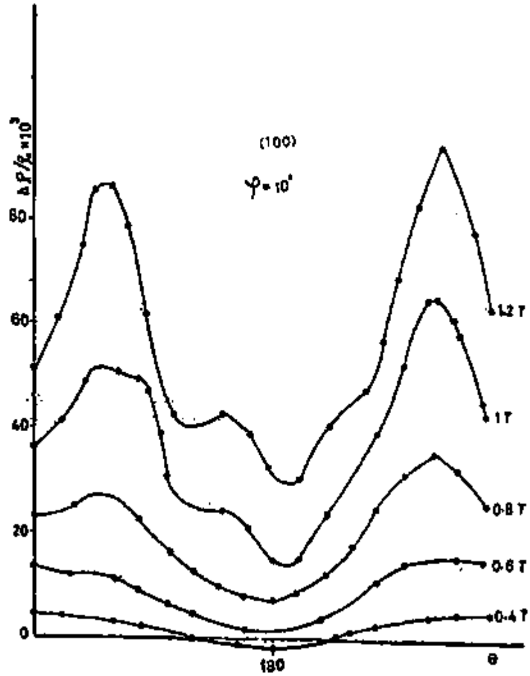

Fig. 1. The dependence of transverse magnetoresistivity $\Delta\varrho/\varrho_0$ on the rotational angle Θ for n-Si sample ($n = 10^{16}$ cm^{-3}) at several values of B, when the deviation angle φ of the current vector from (100) crystallographic axis is 10° ($\varphi_{(100)} = 10°$) at $T = 300$ K.

According to these measurements which were done at low electric and magnetic fields (Figs. 1, 2 and 3), it is interesting to analyse these experimental data, which can be characterized with the following fundamental features.

In Fig. 1, it was found that the TMR exhibits any types of anomalous effects, for $B = 0.4$ T the TMR is positive at $\Theta = 0°$ and becomes negative at $\Theta = 180°$. This means that at $\varphi_{(100)} = 10°$ the TMR depends on the polarity of B ($+\Theta_B$, $-\Theta_B$). On the other hand, the TMR tends to be positive at higher values of B with different intensities, i. e. the anomalous MR is strongly dependent on the value of B, especially at any two opposite angles. Moreover it was found that the increase of the anomalous MR with B would be accompanied by a sharp decrease in the negative MR.

From Figs. 1, 2 and 3 it can be seen that the transformation of TMR from positive to negative values at some angles is strongly dependent on the orientation of weak B. Thereafter, as B increases, the negative MR vanishes. This indicates

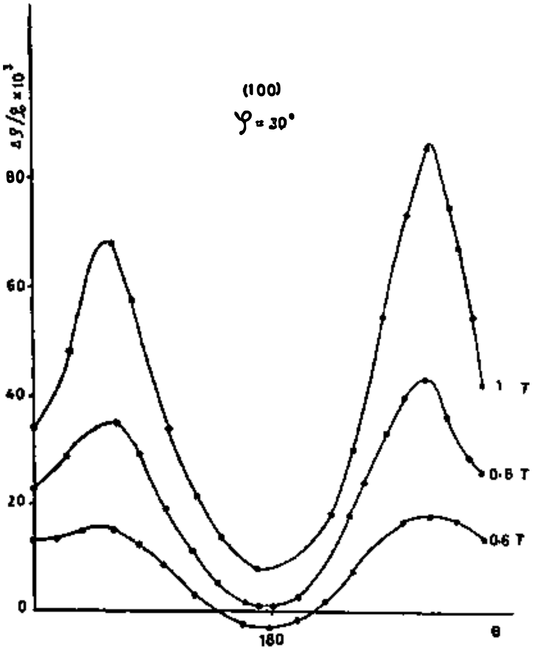

Fig. 2. The dependence of $\Delta\varrho/\varrho_0$ on Θ at several values of B, when $\varphi_{(100)} = 30°$ at $T = 300$ K.

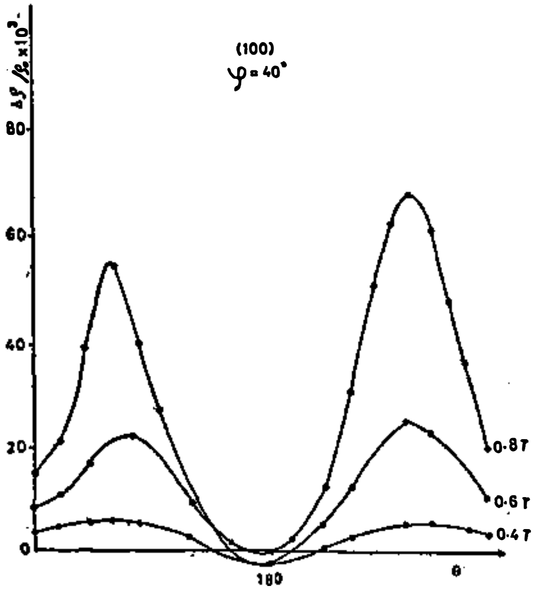

Fig. 3. The dependence of $\Delta\varrho/\varrho_0$ on Θ at several values of B, when $\varphi_{(100)} = 40°$ at $T = 300$ K.

that there is a certain relation between the value of φ_n and the intensity of negative MR at low B. Generally at constancy of low B, the relation between the value of φ_n and the degree of negative quantity of MR is complicated, i. e. at $B = 0.6$ T for $\varphi_{\langle 100 \rangle} = 10°$, the variation of TMR with Θ is positive, but for $\varphi_{\langle 100 \rangle} = 30°$, the negative MR was observed. On the other hand for $B = 0.8$ T when $\varphi_{\langle 100 \rangle} = 30°$, the $\Theta - \Delta\varrho/\varrho_0$ relationship is positive, but for $\varphi_{\langle 100 \rangle} = 40°$, a small negative area was found, while the negative areas of TMR at $B = 0.4$ for $\varphi_{\langle 100} = 40°$ and at $B = 0.6$ T for $\varphi_{\langle 100 \rangle} = 30°$ are nearly symmetrical. Afterward it was observed that the negative depth of TMR at $B = 0.4$ T for $\varphi_{\langle 100 \rangle} = 10°$ is smaller than that at $\varphi_{\langle 100 \rangle} = 40°$. This shows that the negative MR is not only low temperature as well known, but are also low B and deviation angle of current dependent phenomenon.

As may be seen from Figs. 1, 2 and 3, the TMR exhibits different types of positive anomalous effects at high values of B. The largest anomalous effects were observed at minimum deviation angle of current ($\varphi_{\langle 100 \rangle} = 10°$), but as φ_n increases the anomalous effect decreases, i. e. the anomalous character of MR is inverse function to φ_n. In order words, at any constant high value of B, the increasing or decreasing rates of anomalous MR at all values of φ_n are asymmetrical. This means that the MR is not only dependent on known parameters, but are also dependent on the current direction with respect to the type of orientation of axis of symmetry[4-14], and the value of deviation angle of current.

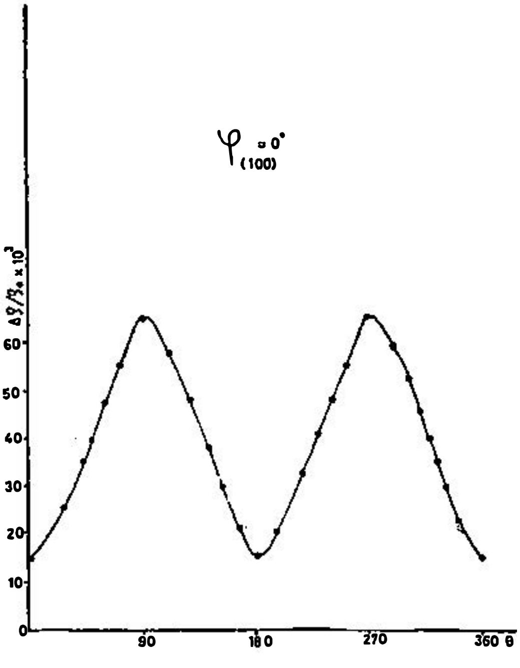

Fig. 4. The dependence of $\Delta\varrho/\varrho_0$ on Θ, in the case of current flowing along $\langle 100 \rangle$ axis of symmetry ($\varphi_{\langle 100 \rangle} = 0°$) for $B = 0.8$ T at $T = 300$ K.

In Figs. 2 and 3 it was found that as the magnetic field increases, the relative change in resistivity shows the tendency of normal effect more and more, which are in contrast to the behaviours shown in Fig. 1, at $\varphi_{(100)} = 10°$. As shown in these figures, the most important effective periodical angle on the behaviour of MR is at $\Theta = 180°$, where the MR is changeable from negative to positive and finally the relative change of $\Delta\varrho/\varrho_0$ is nearly equal zero at $\Theta = 180°$. These processes repeated they self many times in different rates at different values of both B and φ_n. This result means that there is a definite relation between the effective rotational angle and the deviation angle of current φ_n due to the elliptic structure of energy surfaces.

From the above mentioned it can be seen that at any φ_n the negative, positive and asymmetry behaviours of TMR are controlled by the values and directions of low B. These data are not readily understod unless taken into account the magnitudes of φ_n as effective parameters on the behaviours of MR:

$(\Delta\varrho/\varrho_0\Theta)_T \neq (\Delta\varrho/\varrho_0\,(\Theta + \pi))_T$ for constancy of both B and φ_n;

$(\Delta\varrho/\varrho_0\Theta)\,\varphi_{(100)} = 10°$, $30°$ and $40° \neq$ constant for constancy of both T and B.

If the current flows along the (100) axis of symmetry, i. e. $\varphi_{(100)} = 0°$, the anomalous behaviour of MR vanishes as shown in Fig. 4, where $T = 300$ K and $B = 0.8$ T, i. e. in the case of flowing the current along the axis of symmetry, the Θ — TMR curve is positive and $\cos 2\Theta$ dependent, or the variations of TMR with Θ at any two opposite directions of B are symmetrical. This indicates that the general behaviour of TMR under weak fields is obeying Onsager relation's[15].

4. *Discussion*

The appearance of negative and anomalous effects of TMR under weak fields at relatively high temperature ($T = 300$ K), may be attributed to the different asymmetry scattering of charge carriers in $\vec{k}$-space due to the deviation of current vector from (100) axis of symmetry by different angles φ_n, i. e. there are many different types of anomalous scattering in the directions and the distributions of the charge carriers in $\vec{k}$-space. These processes are controlled by the individual effects of non-compensating relations among (φ_n, T), (φ_n, B) and (φ_n, Θ).

According to the above assumption, this arrangement has created a certain type of asymmetry of electric potential gradient (E). The intensity of the asymmetry of E is controlled by the value of deviation angle of current φ_n. This means that the magnetic field points in a direction that is not a symmetry direction for the axis of symmetry, so one may expect a deviation of the induced Hall field E_H from the direction perpendicular to B as shown in Fig. 5. Therefore, it is clear that two effects may occur; the effective masses m^* of change carriers are asymmetrical, and due to the anomalous variation of the direction of E_H according to the value of φ, the directions of the motion of charge carriers in $\vec{k}$-space have different asymmetry scattering as shown in Fig. 6.

Moreover the measurement of TMR at low fields means that the population of current density (J) is the same in each ellipsoids having different m^*. That is,

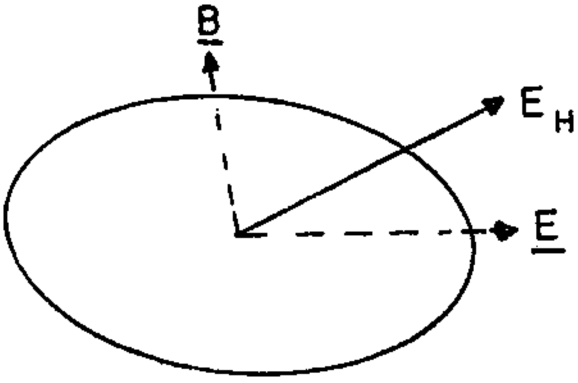

Fig. 5. Direction of induced Hall field E_H as a result of application of weak electric (E) and magnetic (B) fields.

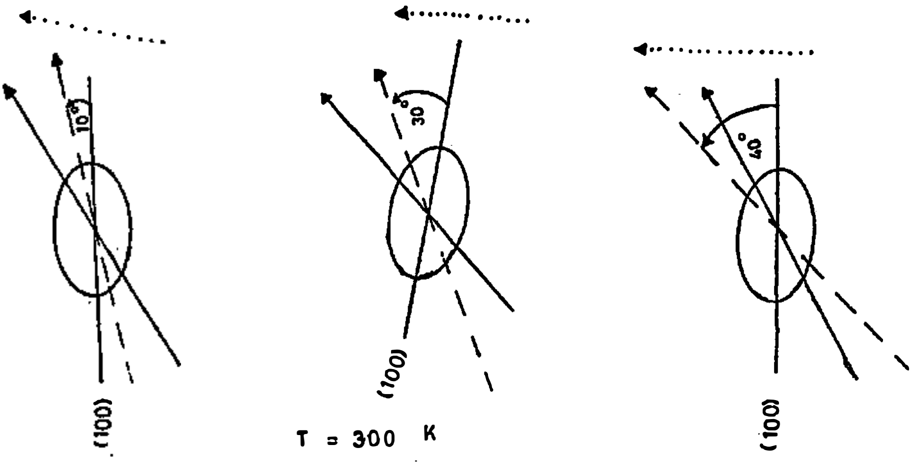

Fig. 6. Effect of the drifting field for the carriers at (100) axis of symmetry under a different deviation angles of current vectors at $T = 300$ K. ---▶ applied E, ···▶ Hall field and —▶ direction of carrier motion along the ellipsoids.

the charge carriers during the scattering remain on the same kind of energy ellipsoids in the $\vec{k}$-space. This is the intravalley scattering:

$$J = \sum_i J^{(i)} = (\Sigma_i \sigma^{(i)}) E$$

$$J \sim (\sum_i m^{*-1}) E$$

where $J^{(i)}$ is the current distribution of the i-th energy ellipsoid and $\sigma^{(i)}$ is the contribution of the i-th ellipsoid to the conductivity tensor.

From these measurements, it can be seen that the most important concept used to describe these results is the deviation of the current vector from the axis of symmetry. This means that the Hall mobility μ_H depends on the polarity of weak B at any Θ. So the induced E_H at the two opposite directions of $\vec{B}$ are not symmetrical as shown in Fig. 7. In this case the conductivity or the specific resistivity are dependent on the direction of $\vec{B}$. The relation among $\Delta\varrho/\varrho_0$, σ, J and m^* are given as follows:

$$\Delta\varrho/\varrho_0 = \frac{\sigma(0) - \sigma(B)}{\sigma(B)} = \frac{J(0) - J(B)}{J(0)} \sim m_j^*(B) - m_j^*(0).$$

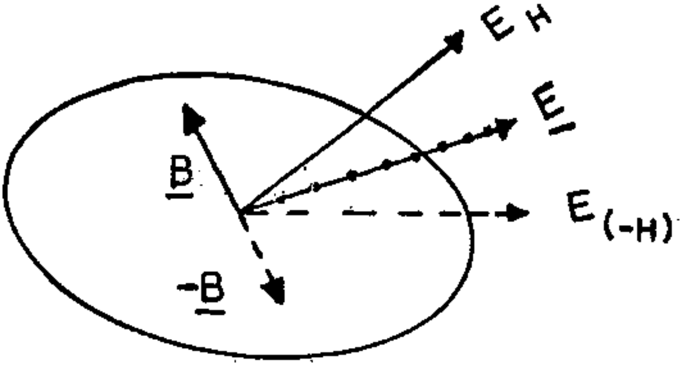

Fig. 7. The asymmetry relation between the induced E_H at the two opposite directions of B.

Also when the direction of the carrier motion is close to a symmetry axis, (Fig. 1, when $\varphi_{(100)} = 10°$), then even a low B, called $B_{crit.}$, can cause the carriers move into a symmetry direction. Further increasing of B, also acts so that he bisection of drifting field with the ellipsoid starts to decrease once more, and

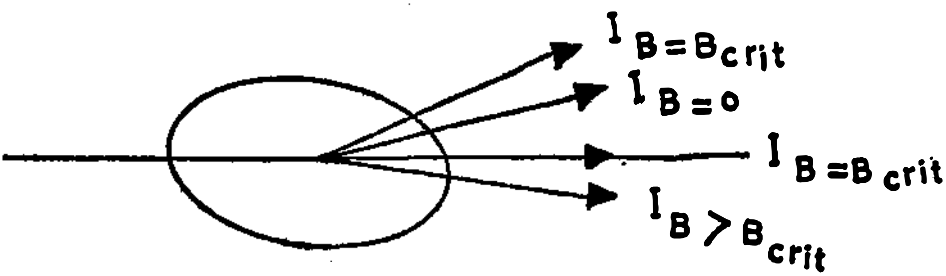

Fig. 8. Illustration of the decrease of the bisection due to the increase of B above B_{crit}.

the trend in the mobility μ variation turns to be normal as given in Fig. 8. So the magnetic field modifies the direction of the motion of charge carriers in $\vec{k}$-space,

$$\mu\varphi_{(100)} = 10° \neq \mu\varphi_{(100)} = 30° \neq \mu\varphi_{(100)} = 40° \quad \text{for } T = \text{constant}.$$

5. Conclusions

From these results it was found that the effect of deviation of the current vector from (100) axis of symmetry by different angles φ_n is considered one of the most important parameters for the appearance of anomalous behaviours of MR,

$$\Delta\varrho/\varrho_0 = f(B, T, \Theta, n, \varphi_n)$$

but if the current flows along any of the symmetry axes related to the set of ellipsoids, the anomalous MR vanishes due to the symmetry relations; i. e. $\varphi = 0°$,

$$\Delta\varrho/\varrho_0 = f(B, T, \Theta, n).$$

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EFEKT ODSTUPANJA VEKTORA STRUJE OD (100) OSI U n-TIPU SILICIJA NA MAGNETOOTPOR PRI 300 K

MOHAMED S. ZAGHLOUL

Dept. of Physics, Faculty of Science, Al Azhar University, Nasr City, Cairo, Egypt

UDK 538.935

Originalni znanstveni rad

Mjerena je ovisnost transverzalnog magnetootpora o rotacionom kutu između smjerova magnetskog polja i struje za nekoliko vrijednosti magnetskog polja u n-tipu silicija s koncentracijom nosilaca naboja od 10^{16} cm^{-3} na 300 K. Pokazano je da je anomalno ponašanje transverzalnog magnetootpora jako ovisno o vrijednosti kuta devijacije struje od (100) osi simetrije.