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THE ODD COMPONENTS OF NEGATIVE MAGNETORESISTANCE OF n-TYPE GERMANIUM CRYSTAL AT THREE DIFFERENT TEMPERATURES

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The transverse magnetoresistance (TMR) was measured versus the magnetic field, B, at three different temperatures (80, 100 and 130 K) for n-type germanium crystals with carrier concentration of 1.8×10^{14} cm^{-3}. These measurements were done in the case of deviating the current vector from the (100) axis of symmetry by different angles (φ), i.e. ($\varphi_{(100)}$) = 22.5°, and $\varphi_{(100)}$ = 32.5°. Many types of anomalous negative TMR were observed. The degree of variation of anomalous behaviours of negative TMR was controlled by the values of φ, T, and intravalley scattering (μB). These results show that the asymmetry variations of quantitative and qualitative effects of negative TMR are strongly dependent on the anisotropic scattering of charge carriers in k-space, due to the noncompensating relations among (φ, T), (φ, μB) and (T, μB). Also the anomalous terms $\Delta\rho/\rho_0(\mu B)$ and the normal components $\Delta\rho/\rho_0(\mu B)^2$ of TMR were calculated at different T and φ. The experimental data are illustrated and the results are discussed.

Key words.: Magnetoresistance, n-Type germanium crystal, Different temperature.

Introduction

The negative magnetoresistance (MR) at low fields was measured for compensated n-type GaAs with net donor concentration just below the metal-insulator transition [1]. The MR exhibited a quadratic field dependence for values less than 750 G. Also they found that the MR irregular dependent on the temperature. These results were explained on the bases of theories of quantum- interference effects in the variable-range-hopping regime [2-4].

Different types of anomalous effects of MR in amorphous Cu-Ti alloys were observed at low B in temperature range 0.045 - 4.25 K [5]. These data were analyzed by the use of a weak-localization theory including spin-splitting and electron-electron interaction theories [4-6]. Moreover, the anomalous of negative and positive transverse MR (TMR) were measured under B up to 25 KG and at T = 1.7 and 4.2 K in n-Ge crystal grown in the (110) direction [7]. On the other hand, a temperature-independent positive weak-field MR was observed in a high-mobility of some heterostructure semiconductors [8].

The present work includes the study of individual effects of both the temperature and the varying angle of deviation (φ) of the current vector from (100) axis of symmetry of n-Ge on the behaviours of TMR.

Experimental

The two n-Ge samples were doped with the impurity concentration of 1.8×10^{14} cm^{-3}. An ultrasonic cutter was used to cut the impurities out of the crystal grown in the (100) direction. The orientation* of the two samples are chosen so that the angles (φ_n) are different, i.e. $\varphi_{(100)}$ = 22.5x and $\varphi_{(100)}$ = 32.5°. Where φ_n is the angle of deviation of the current vector from (100) axis of symmetry. Every sample has a bridge shape with dimensions of 10 x 1.5 x 0.6 mm^3. The surfaces of the samples were polished and etched with diluted CP-4 etching solution. Thin silver wires (0.05 mm dia.) were soldered on the spots for electrodes by using silver paste. Special attention was paid so that each electrode did not spread on the contact surface into the adjacent surface. All electrodes were checked to be ohmic in contacts at the investigated temperatures (80, 100 and 130 K).

During the measurements, the following simplifications were made to minimize the rate of error in the measuring data: 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 contact-barrier resistance was much smaller than the spreading resistance, and finally the medium was homogenous and quasi-isotropic. The variation of the resistivity in different experiments at all values of φ and T were in the order of 1%. Therefore, to distinguish the normal and anomalous magnetoresistivity, it was to measure a change less than 0.1%. This was 10^{-8}V in the worst case. These measurements were carried out by the D.C. method and with the aid of high-impedance digital nanovoltameter.

For measuring the low temperatures, a certain type of cryostat was used. The measurements of ρ and magnetoresistivity ($\Delta\rho/\rho_o$) were made using a small electric current (I = 100 mA) to avoid overheating the carriers. To eliminate the thermomagnetic effect on the carriers, a small magnetic

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

field with a maximum of 13 kg was used. A calibrated gaussmeter was used to measure the steady magnetic field.

Results and Discussion

The dependence of TMR on the intravalley scattering μB (μ is the mobility of charge carriers) at different temperatures when $\varphi_{(100)} = 22.5°$ and $\varphi_{(100)} = 32.5°$ are shown in Figs. 1 and 2. All μB-$\Delta\rho/\rho_o$ relationships are exhibiting different types of anomalous negative MR. Acording to these measurements (Figs. 1 and 2), it is interesting to analyse these experimental data which can be characterized with the following fundamental features;

(i). A steep increase was found in the negative MR for low values of μB at T = 80 K in Figs. 1 and 2, on the other hand as the μB increases, the negative MR tend to decrease when $\varphi_{(100)}$=22.5°, which is in contrast to the behaviour shown when $\varphi_{(100)}$=32.5°, where the negative MR seems to be constant at high values of μB. This indicates that the dependence or independence of negative MR on μB may be due to the asymmetry scattering of the motion of charge carriers in k-space. These effects are controlled by the non-compensating relation between φ and μB at any value of T.

(ii). At T = 100 K (Fig. 1) the increasing rate of negative MR is paprabolic dependent upon μB, but in Fig. 2 ($\varphi_{(100)}$ = 32.5°) many skew behaviours were observed for different values of μB. The appearance of different anomalous effects of negative MR at T=80 and 100K for the same values of φ, show that the non-compensating relations among φ, T, and μB are strongly affecting on the type and intensity of the scattering processes of charge carriers in k-space.

(iii). A striking negative anomalous effects in the quality and quantity of TMR were found at T = 130 K (Figs. 1 and 2). For $\varphi_{(100)}$=22.5°, the shape of negative TMR as can be seen from Fig. 1 is characterized by what is called inverse-hump. Where a sharp increase in the negative TMR was observed as μB increases up to definite value of μB. Afterward, the above process repeated itself again but in opposite direction with different rates. The separating value of μB between the increasing and decreasing rates of negative TMR may be called critical value of intravalley scattering, $(\mu B)_{crit}$=0.16, (the point c in Fig.1). This means that before and after a point c there are two asymmetrical types of scattering mechanisms. Also the physical meaning of $(\mu B)_{crit}$ is that the field causing impurity breakdown due to the asymmetry of the direction of the motion

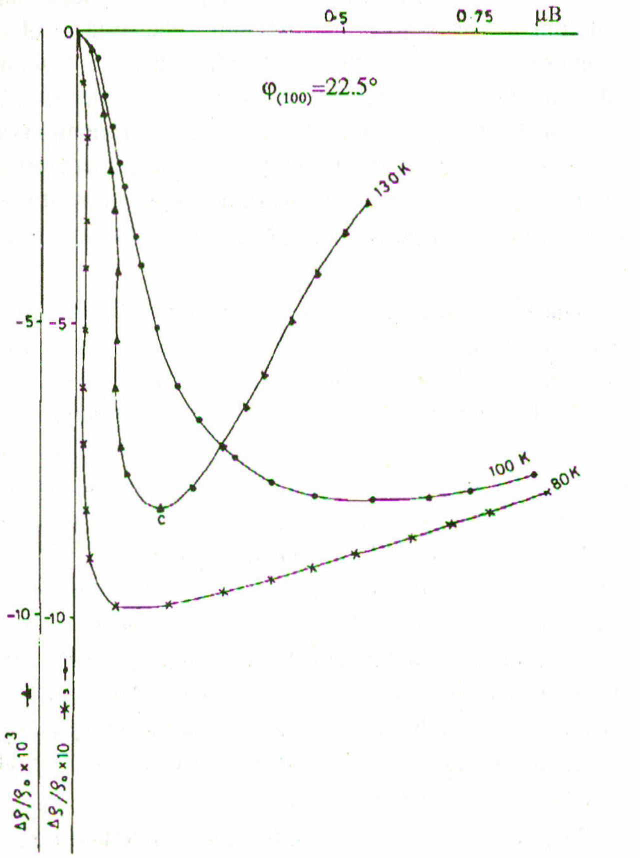

Fig. 1. Dependence of transverse magnetoresistivity $\Delta\rho/\rho_o$ on intravalley scattering μB for n-Ge sample (n=1.8 x 10^{14}cm^{-3}) when the deviation angle of current from (100) axis of symmetry is 22.5°, i.e. $\varphi_{(100)}$=22.5° at T=80, 100 and 130 K.

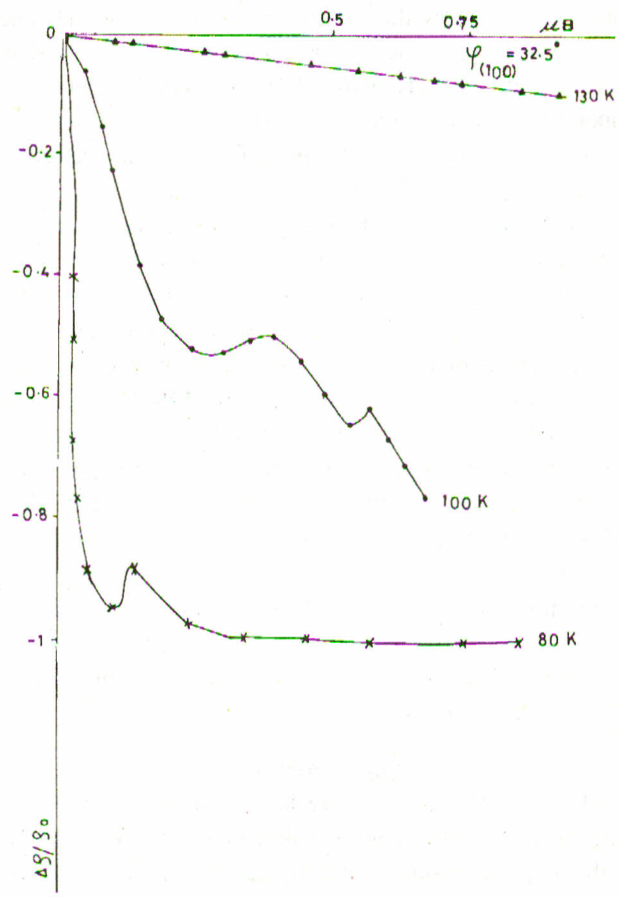

Fig. 2. Dependence of $\Delta\rho/\rho_o$ on μB when $\varphi_{(100)}$=32.5° at T=80, 100 and 130 K.

of charge carriers in k-space as a result of deviation angle of current from (100) axis of symmetry. This behaviour is in contrast to what was observed for $\varphi_{(100)} = 32.5°$ at the same temperature (Fig. 2) where the negative TMR seems to linear dependent upon μB. Also the relative changes in $\Delta\rho/\rho_o$ at T = 130 K for two deviation angles of current φ_n are many times smaller than at other investigated temperatures;

$$(-\Delta\rho/\rho_o\ \mu B)\ \varphi_{(100)} = 22.5° \neq (-\Delta\rho/\rho_o\ \mu B)\ _{(100)} = 32.5° \quad \text{for T = constant.}$$

Individually and severally, it can be seen that the negative anomalous effects of TMR (Figs. 1 and 2) are not suitable with the variation of temperatures at constancy of φ. This indicates that, in the case of deviating the current vector from the axis of symmetry by different angles, there are different types of asymmetry scattering mechanisms. The degree of anomaly of quantitative and qualitative effects of these mechanisms is strongly dependent on any small and large variations in the values of T and μB for constancy of φ. Consequently, the appearance of negative MR at relatively modest temperatures, (where the negative MR was considered low temperature phenomenon), may be readily understood if taken into account the effect of deviation of current vectors from (100) axis of symmetry by different angles φ_n [9-13];

$$(-\Delta\rho/\rho_o\mu B)T{=}80_K \neq (-\Delta\rho/\rho_o\mu B)\ T{=}100_K \neq (-\Delta\rho/\rho_o\mu B)T{=}130_K \quad \text{for } \varphi_{(100)} = \text{constant}$$

The effect of non-compensating relations among φ, T, and μB on the asymmetry scattering of charge carriers in k-space, may be shown in Fig. 1 at T = 130 K for $\varphi_{(100)} = 22.5°$ it was found that there is direct relation between the increasing rate of conductivity (σ) of carrier concentration in the impurity band and the low values of μB up to $\mu B = 0.16$. After this value the conductivity start to decrease as the μB increases, i.e. there is inverse relation between σ and μB. This shows that the intensity and directions of charge carriers (n) in k-space are asymmetrical which are characterized by a different compensating values of No. F 1/2 (η)~n along the whole scale of μB.

On the other hand it was observed that when $\varphi_{(100)} = 32.5°$ at the same above temperature (T = 130 K) the linear dependence of negative MR on μB may be attributed to the fact that the compensating value of Nc. F 1/2 (η) is directly proportional with μB. In general, the irregular distributions of anomalous effects of negative MR at constancy of T or φ may be due to the increase or decrease of binding energy of bound states of the donor level in different rates according to the non-compensating relations of (φ.T) and (φ. μB). This indicates that the anomalous MR is strongly temperature and weak magnetic field dependent when the current does not flow along the axis of symmetry.

The measured magnetoresistivity could be expanded in powers of μB to calculate the contributions of TMR at different T for φ_1 and φ_2 as shown from the empirical formula;

$$\Delta\rho/\rho_o\ (\mu B, T)\ \varphi{=}\text{constant} = a_o + a_1 (\mu B)^1 + a_2 (\mu B)^2 + ...$$

where the first-order term represents the anomalous non-parabolic dependence $\Delta\rho/\rho_o \sim(\mu B)^1$ (odd power of μB), and the second-order term describes the normal positive dependence $\Delta\rho/\rho_o \sim(\mu B)^2$ (even power of μB). The constants a_0, a_1 and a_2 depend on the temperature and the geometry of the sample (orientation). This formula was fitted to the experimental data at different temperatures when $\varphi_{(100)} = 22.5°$ and $\varphi_{(100)} = 32.5°$ for calculating the constants of the two contributions of TMR as shown in Table 1.

The calculated constants a_1 and a_2 at all temperatures for φ_1 and φ_2 are really represented the odd anomalous terms $\Delta\rho/\rho_o$ (μB) and even normal components $\Delta\rho/\rho_o$ $(\mu B)^2$ of TMR respectively. From Table 1 it can be seen that all the odd terms of TMR are negative and have different values according to the value of both T and φ. For $\varphi_{(100)} = 22.5°$, the constant a_1 at T = 80 K is many hundredfold times larger than at T = 130 K. The negative odd component of TMR at T = 80 K when $\varphi_{(100)} = 22.5°$ is three and half times bigger than at $\varphi_{(100)} = 32.5°$, but at T = 130 K when $\varphi_{(100)} = 22.5°$ the non-parabolic component of TMR is half time smaller than at $\varphi_{(100)} = 32.5°$. This means that the rate of asymmetry variations of anomalous terms are controlled by the values of φ and T.

TABLE 1. VALUES OF THE CONSTANTS a_1, a_2 AND THE RATIO OF ERRORS IN THESE CALCULATION(E) AT T=80, 100, AND 130 K, WHEN $\varphi_{(100)}$=22.5° (φ_1) AND $\varphi_{(100)}$=32.5° (φ_2).

T, K	$\varphi_{(100)} = 22.5° = (\varphi_1)$			$\varphi_{(100)} = 32.5° = (\varphi_2)$			$a_1\varphi_1/a_1\varphi_2$	$a_2\varphi_1/a_2\varphi_2$
	a_1	a_2	E	a_1	a_2	E		
80	-31.689048	+217.63646	±0.0005	-9.0316	+18.043679	±0.0103	3.51	12.06
100	-3.6356005	+4.1063162	±0.0025	-2.5025543	+2.3872849	±0.0203	1.45	1.72
130	-0.05770662	+0.10647074	±0.0022	-0.09749361	+0.03901894	±0.0002	0.58	2.73

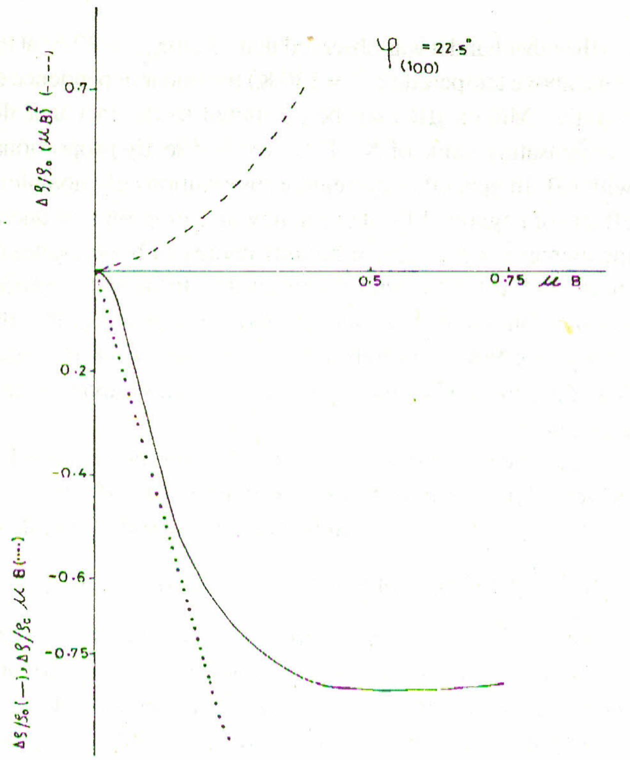

Fig. 3. Dependence of the measured $\Delta\rho/\rho_o$ (—) on the μB at T=130 K when $\varphi_{(100)}$=22.5°. The calculated odd term $\Delta\rho/\rho_o$ μB and even term $\Delta\rho/\rho_o$ $(\mu B)^2$ of TMR are represented by symbols (.....) and (----) respectively.

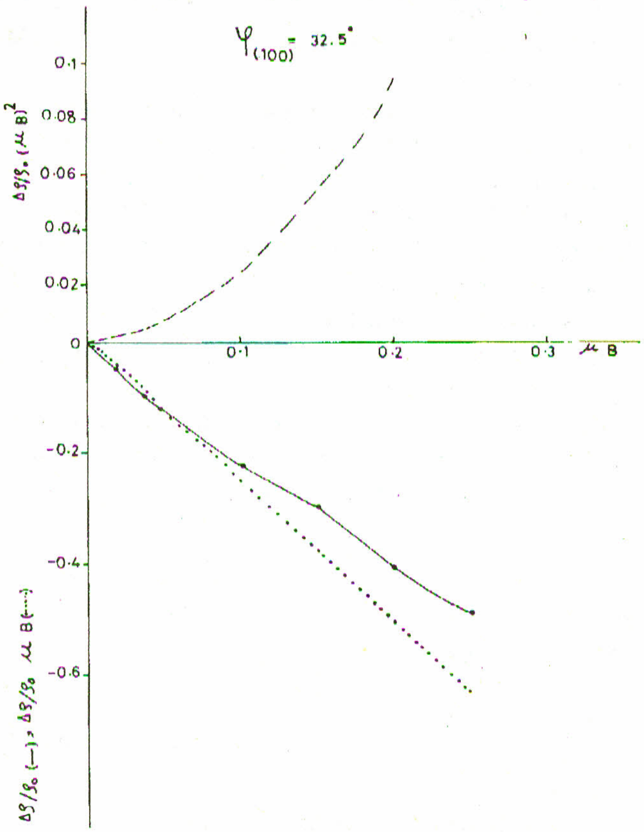

Fig. 4. Dependence of the measured $\Delta\rho/\rho_o$ (—) on the μB at T=100 K when $\varphi_{(100)}$=32.5°. The calculated odd term $\Delta\rho/\rho_o$ μB and even term $\Delta\rho/\rho_o$ $(\mu B)^2$ of TMR are represented by symbols (.....) and (----) respectively.

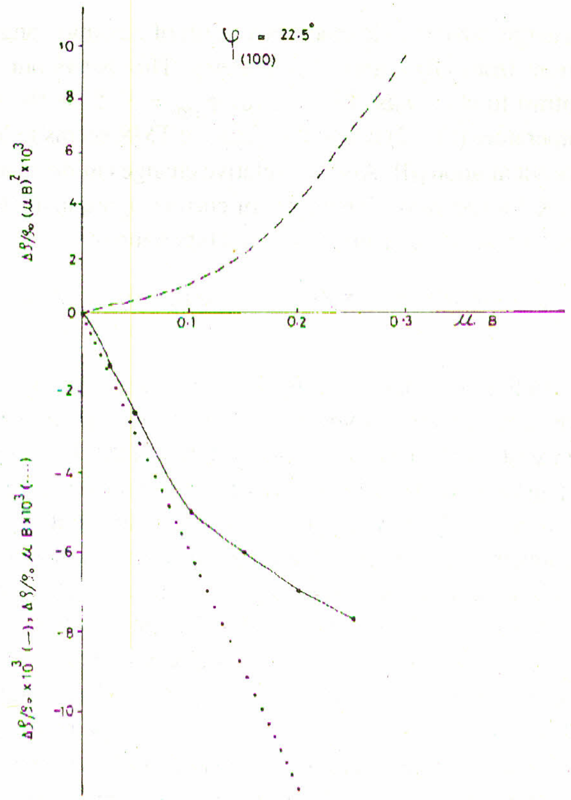

Fig. 5. Dependence of the measured $\Delta\rho/\rho_o$ (—) on the μB at T=130 K when $\varphi_{(100)}$=22.5°. The calculated odd term $\Delta\rho/\rho_o$ μB and even term $\Delta\rho/\rho_o$ $(\mu B)^2$ of TMR are represented by symbols (.....) and (----) respectively.

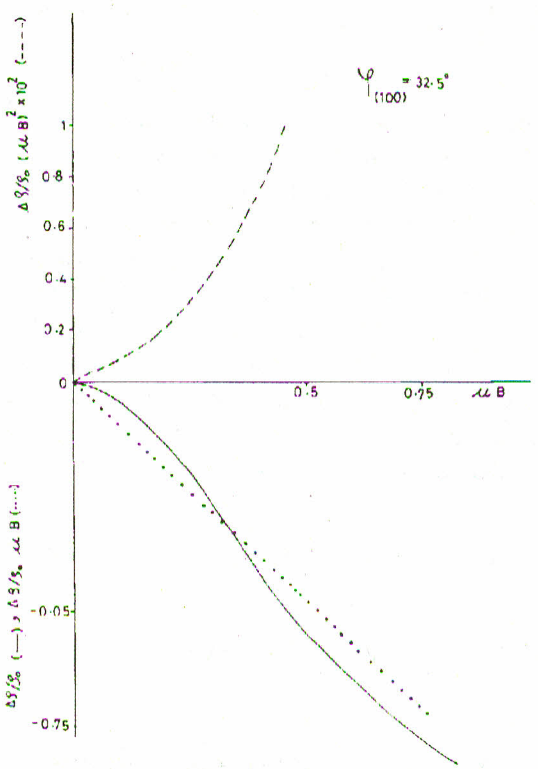

Fig. 6. Dependence of the measured $\Delta\rho/\rho_o$ (—) on the μB at T=130 K when $\varphi_{(100)}$=32.5°. The calculated odd term $\Delta\rho/\rho_o$ μB and even term $\Delta\rho/\rho_o$ $(\mu B)^2$ of TMR are represented by symbols (.....) and (----) respectively.

The presence of linear anomalous terms $\Delta\rho/\rho_o \sim (\mu B)^1$ as shown in Figs. 3-6 at different values of T and φ, indicate that the odd term of TMR is weak intravally scattering dependent phenomenon, in the case of deviating the current vector from any axis of symmetry. Moreover, it was found that at T = 80 K, the odd linear termes of TMR is nearly ten times bigger than at T = 100 K for $\varphi_{(100)} = 22.5°$ as shown in Table 1. These examples give us a good idea about the effect of non-compensating relations of φ and T on the irregular distributions of odd terms of TMR;

$$(\Delta\rho/\rho_o \sim(\mu B)^1 \varphi_{(100)} = 22.5° \neq (\Delta\rho/\rho_o \sim(\mu B)^1 \varphi_{(100)} = 32.5°$$

for T = constant;

$$(\Delta\rho/\rho_o \sim(\mu B)^1)T{=}80,\ 100\ K \gg (\Delta\rho/\rho_o \sim(\mu B)^1)\ T{=}130_K$$

for φ = constant.

If the current flows along the axis of symmetry, the anomalous effect vanishes, because in this case the general behaviour of TMR under weak fields is obeying Onsager relations [14];

$$B_{ijk} = -B_{ijk}, \quad \rho_{ijk} = -\rho_{ijk}$$

The dependence of calculated normal components of TMR on (μB) at different temperatures for $\varphi_{(100)} = 22.5°$ and $\varphi_{(100)} = 32.5°$ are shown in Table 1 and Figs. 3-6. These results show that all even positive components of TMR are quadratic dependent on μB, as well-known;

$$\Delta\rho/\rho_o \sim(\mu B)^2$$

As may be seen from Table 1, the normal components of TMR are asymmetrical at constancy of temperature for different φ and the reversal is true. Where at T=80 Kwhen $\varphi_{(100)} = 22.5°$, the even term is many times bigger than that at $\varphi_{(100)} = 32.5°$, but for $\varphi_{(100)} = 32.5°$ at T=130 K it was observed that the value of a_2 is 100th times smaller than at T=80 K for the same φ;

$$(\Delta\rho/\rho_o \sim(\mu B)^2)\varphi_{(100)} = 22.5° \neq (\Delta\rho/\rho_o \sim(\mu B)^2)\varphi_{(100)} = 32.5°$$

for T = constant;

$$(\Delta\rho/\rho_o \sim(\mu B)^2)\ T{=}80K \neq (\Delta\rho/\rho_o \sim(\mu B)^2)\ T{=}100\ K \neq (\Delta\rho/\rho_o \sim(\mu B)^2)T{=}130K$$

for φ = constant.

The different anomalous effects of parapolic and non-parapolic terms of TMR as shown in Figs. 3-6 may be attributed to the depend of a_1's and a_2's on the non-componsating relations among φ, T, and μB. In the same way, it may be observed from Table 1, the constants (a_1 and a_2) are strongly dependent on the lowered values of T at every φ but as T increases, the values of a_1 and a_2 decrease. This indicates that the magnetic field modifies the direction of the motion of the charge carriers in k-space according to the magnitudes of the above relations. Also Figs. 3-6 show that the MR is not only dependent on the even power of μB, but also on the odd power of μB.

From the fundamental basis of theoretical calculations [15-17] for the relation between the MR and the power series of B, it was found that the MR depends only on even power of B. This means that the Onsager symmetry [14] is automatically contained in the solutions of Boltzmann equation [18] i.e. the Boltzmann equation does not explain the odd terms, where the calculations of the two contributions of MR as shown in Table 1 and Figs. 3-6, show that the odd terms of the TMR are in good agreement with $(\mu B)^1$.

In n-Ge (1.8 x $10^{14}cm^{-3}$) crystals, it was found that the measured TMR at different φ and T is nearly equal to the sum of two components, one of them is positive normal term and the other is negative anomalous linear one. This assumption was examined for the two deviation angles of current from (100) axis of symmetry at T=100 K and T=130 K as shown in Figs. 3-6. Firstly, when T=constant = 100 K, it was found that the normal positive component of TMR for $\varphi_{(100)} = 22.5°$ (Fig. 3) is many times bigger than for $\varphi_{(100)} = 32.5°$ (Fig. 4). On the other hand at T=130 K for $\varphi_{(100)} = 22.5°$ (Fig. 5), the odd term of TMR is smaller than for $\varphi_{(100)} = 32.5°$. Secondly, when φ=constant = $\varphi_{(100)} = 22.5°$, it was observed that the two contributions of TMR at T=130 K (Fig. 5) are smaller than that

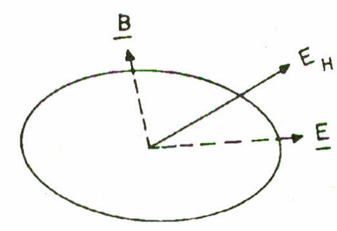

Fig. 7. Direction of induced Hall field (E_H) as a result of application of weak electric (E) and magnetic (B) fields.

at T=100 K (Fig. 3). Moreover, for $\varphi_{(100)} = 32.5°$ at T=100 and 130 K, the distributions of the two components of negative TMR are asymmetrical. In this arrangement (Figs. 3-6) it could be seen that the above concept of MR summation remains same and the variation of the odd term position is due the change of φ and T.

From the above mentioned facts, it was observed that the most important concept used to describe these results is the deviation of the current direction from the axis of symmetry. This means that the anomalous behaviours of MR are not only dependent on known parameters but are also dependent on the magnitudes of the angle of deviation of current φ_n with respect to the type of orientation of the axis of symmetry [19-27].

The above results may be attributed to the different asymmetry scattering of both the intensity and directions of charge carriers during the actual motion in k-space. This phenomenon is due to the deviation of current vectors from (100) axis of n-Ge by different angles (φ_n). When the magnetic field points in a direction that is not a symmetry direction for the axis of symmetry of n-Ge crystal, one may expect a deivation of the induced Hall field E_H from the direction perpendicular to B as shown in Fig. 7. Also, the change in the angle of deviation of the current from (100) axis of symmetry created a certain type of asymmetry of electric potential gradient (E). The intensity of E is controlled by the non-compensating values of (φ_n.T), (φ_n.μB) and (T.μB). Moreover the measurements of TMR at low fields means that the population of current density (J) is the same in each ellipsoid having different effective masses (m*). That is the charge carriers during the scattering remain on the same kind of energy ellipsoids, in the k-space, this is the intravalley scattering (μB), so the contribution of J of the i-th energy ellipsoid is defind as the following;

$$J^{(i)} = (\Sigma_i \sigma^{(i)})\, E \sim (\Sigma_i\, m^{*-1})\, E;$$

$$\frac{\Delta\rho}{\rho_o} = \frac{J_{(o)} - J_{(B)}}{J_{(o)}}$$

This means that the anomalous effects of negative TMR may be explained, if taken into account that the variation of dynamic parameters of charge carriers in k-space such as, mobility (μ), m*, conductivity (σ), relaxation time φ, mean free path (1),... etc., are strongly dependent on the values of φ, T, and μB;

$$m^{*-1}_{ij} = h^{-2} \frac{\partial^2 E}{\partial k_i \partial k_j}$$

$$1 = 1_0(1 + \mu^2 B^2)^{-1};$$

$$\therefore\ (m^*)\ \varphi_{(100)} = 22.5° \neq (m^*)\ \varphi_{(100)} = 32.5° \text{ for } T=\text{constant}.$$

So the induced E_H modifies the direction of the motion of charge carriers according to the value of T when φ is constant (Fig. 8) and the value of φ when T is constant (Fig. 9). This means that the conductivity or the specific resistivity have a dependence on the direction of B. The relation between them are given as follows;

$$\frac{\Delta\rho}{\rho_o} = \frac{\rho_{(B)} - \rho_{(o)}}{\rho_{(o)}} \sim m^*_j(B) - m^*_j(o)$$

Conclusion

The appearance of negative TMR at relatively modest temperatures (80, 100 and 130 K) and the different anomalous odd terms of TMR show that the two non-compensating relations between (φ_n.T) and (φ_n.μB) are considered effective parameters on the behaviour of MR. This indicates that the anomalous directions of the motion of charge carriers in k-space under weak fields are strongly dependent on the value of φ.

$$\Delta\rho/\rho_o = f\,(T, \mu B, n, \varphi_n)$$

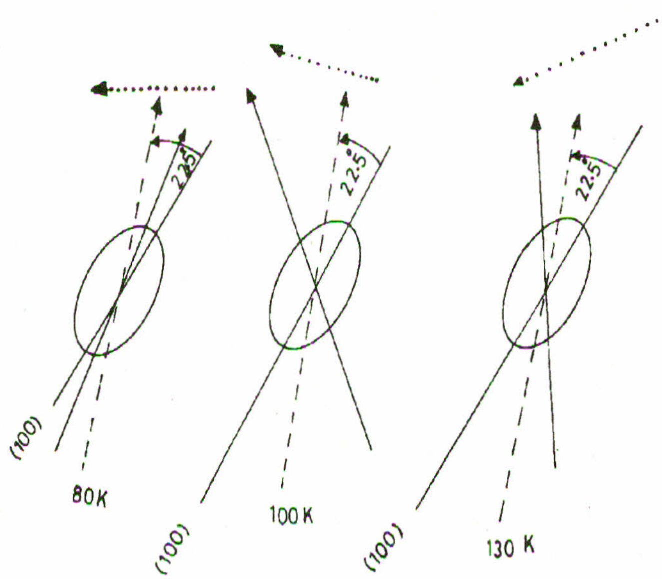

Fig.8. The effect of the drifting fields for carriers under constant deviation angle of current vectors at different temperature s→ current direction,→Hall field (E_H) and → direction of carriers motion along the ellipsoids.

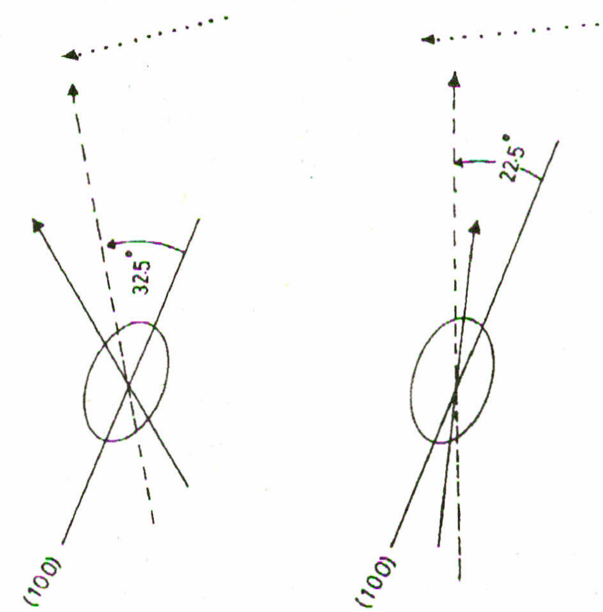

Fig. 9. The different directions of charge carriers under different deviation angles of current vectors at constant temperature with the same above symbols in Fig. 8.

In the case of flowing the current direction along any axis of symmetry ($\varphi = 0°$), the anomalous MR vanishes due to the symmetry relations;

$$\Delta\rho/\rho_o = f\,(T, \mu B, n).$$

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