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TEMPERATURE DEPENDENCE OF GALVANOMAGNETIC PROPERTIES OF UNDOPED n-TYPE GaAs/GaAs AND n-TYPE InGaAs/InP LAYERS

A. WOLKENBERG[1, 2], T. PRZESŁAWSKI[1], K. REGIŃSKI[1], J. KANIEWSKI[1]

*Institute of Electron Technology, al. Lotników 32/46, 02-668 Warsaw, Poland
** Institute of Materials Engineering, Technical University of Częstochowa,
al. Armii Krajowej 19, 42-200 Częstochowa, Poland

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ABSTRACT

The magnetoresistance (MR) and the Hall-effect measurements in undoped *n*-type GaAs/GaAs and *n*-type $In_{0.53}Ga_{0.47}As$/InP samples in the temperature range 3.5 ÷ 300 K were carried out. We have obtained magnetoresistance data on the samples of *n*-type epilayers on SI GaAs and SI InP substrates made MBE technology. Magnetoresistance by measurements in constant magnetic fields vs. temperature are completed. The measurements reveal that the magnetoresistance of the samples strongly depends on the temperature and magnetic field.

1. Introduction

The resistivity of semiconductor samples in magnetic field normally increases when temperature decreases and exhibits the change of the slope at temperatures range near 50 ÷ 120 K. In the higher temperatures the conductivity behaviour is shown to be consistent with the classical transport theory. But at the lower temperatures magnetoresistivity decreases. These phenomena are less pronounced in the samples with strongly doped layers.

In the certain samples at low temperatures we have obtained negative magnetoresistance (NMR). The decrease of the MR in low temperatures is connected with the measured increase of Hall carrier concentration. We suppose that all of the investigated layers during its epitaxial growth are unintentionally doped from substrates with Cr or Fe in the area of some first monolayers or that there exist fairly well-defined "dangling bonds" and in the lowest range of temperature, conductivity is by impurity band conduction with the electrons moving by thermally activated hopping.

In the previous papers [1–4] it has been mentioned that the semiconductors show MR effect. The origin of the MR in thin epilayers and that they can be connected with the outdiffusion of iron or chromium with *2d* unpaired electron spins from SI GaAs and SI InP agree with our understanding of the phenomenon. These spins in low temperatures and under magnetic field may form parallel configuration, which results in strong increase of the conductivity. Another interpretation base on the presence of compressive epitaxial strain in thin films with lattice mismatch [5].

In our paper we present results that on the samples from our MBE this effect occur and can be interpreted similar to n_H behaviour at low temperature.

2. Experimental

The samples investigated in this paper were grown at RIBER 32P MBE reactor. Further details regarding the fabrication are given in Ref. [6, 7]. The GaAs layers were deposited onto (001) oriented SI-GaAs at substrate temperatures T_S = 580°C and thickness 2.3 µm. The $In_{0.53}Ga_{0.47}As$ layers onto (001) SI-InP grown at T_S = 510°C with the thickness 1 ÷ 7 µm. The galvanomagnetic properties of the layers have been investigated in the magnetic field up to 1.5 T at temperatures from 3.5 to 300 K with a Van der Pauw square shape sample. Ohm contacts for the Hall and magnetoresistance measurements were made by In-Sn dots in contacts annealed in nitrogen medium at 420°C for 1.5 min. All measurements were made by average the voltage values to eliminate the thermoelectric potentials. In order to eliminate the effects due to probe misalignment, data were taken for both positive and negative magnetic fields. The samples were placed in a closed-cycle liquid helium cryostat, which was inserted into magnet with the direction of the magnetic field perpendicular to the sample plane. There were measured Hall concentration n_H vs. temperature and magneto-resistance $\Delta\rho/\rho_0$ vs. temperature and magnetic field. The $In_{0.53}Ga_{0.47}As$ layers were unintentionally doped for the concentration lower as $6.2 \cdot 10^{15}$ cm^{-3}. The samples with higher concentration were doped with Si.

3. Results and discussion

Figure 1 shows a plot of $\Delta\rho/\rho_0$ vs. temperature for three magnetic fields 0.02 T, 0.6 T and 1.4 T for a 2.3 μm thick layer of GaAs/GaAs SI with n_H = = $9.1 \cdot 10^{15}$ cm^{-3} at 300 K.

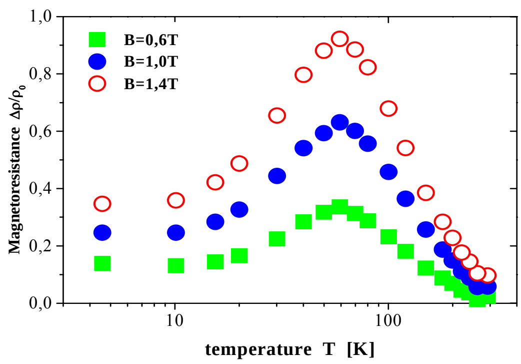

Fig. 1. Magnetoresistance vs. temperature for the sample GaAs/SI GaAs, $n_H = 9.1 \cdot 10^{15}$ cm^{-3}.

Hall concentration vs. temperature taken at magnetic fields B = 0.6 T are shown in Fig. 2 for the mentioned sample.

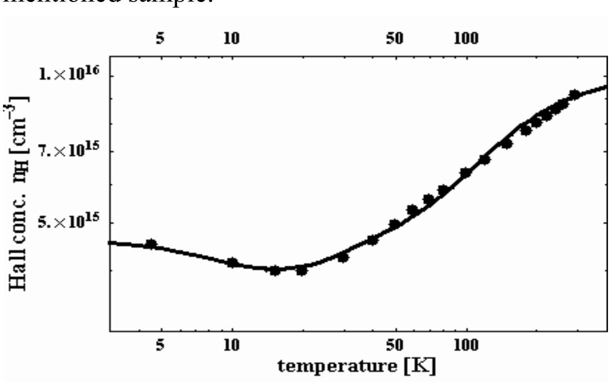

Fig. 2. Hall concentration vs. temperature for the sample as in Fig. 1, • experimental points, — fit calculated from the neutrality equation using the following parameters: N_A = = $9.0 \cdot 10^{14}$ cm^{-3}, E_A = 0.003 eV; main donor atoms concentration $N_D = 8.0 \cdot 10^{15}$ cm^{-3}, E_D = 0.0015 eV; deep donor concentration $N_{D1} = 3.5 \cdot 10^{15}$ cm^{-3}, E_{D1} = 0.025 eV, additional unknown atoms or charged dislocations: neutral X = $4.6 \cdot 10^{15}$ cm^{-3}, charged $X_{ch} = 1.23 \cdot 10^{15}$ cm^{-3}, E_X = 0.00065 eV.

Similar investigation were performed on $In_{0.53}Ga_{0.47}As$ layers deposited on InP SI 7 μm thick, and with $n_H = 2.25 \cdot 10^{14}$ cm^{-3} at 300 K. The temperature dependence of MR at 0.6 T, 1.0 T and 1.4 T are plotted in Fig. 3.

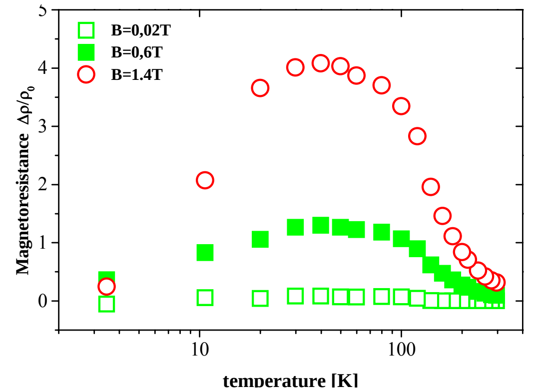

Fig. 3. Magnetoresistance vs. temperature for the sample $In_{0.53}Ga_{0.47}As$/SI InP $n_H = 2.25 \cdot 10^{14}$ cm^{-3}.

In Fig. 4 we have plotted carrier concentration vs. temperature for the same sample (Fig. 3) at B = 0.6 T. The next figures presents magnetoresistance maximum in dependence from carrier concentration (Fig. 5). These maximum values happen at different

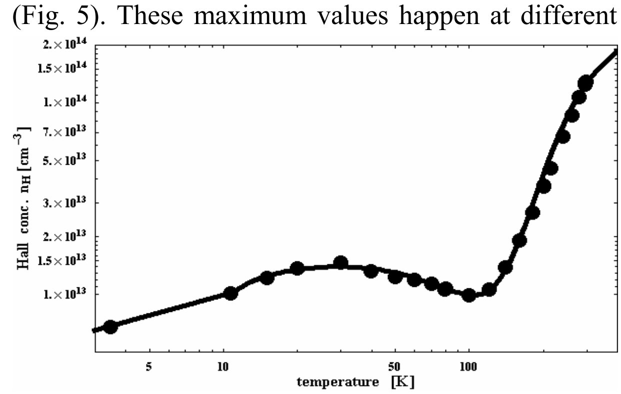

Fig. 4. Hall concentration vs. temperature for the sample as in Fig. 3, • experimental points, — fit calculated from the neutrality equation using the following parameters: N_A = = $1.65 \cdot 10^{14}$ cm^{-3}, E_A = 0.015 eV; main donor atoms concentration $N_D = 1.795 \cdot 10^{14}$ cm^{-3}, E_D = 0.0025 eV; deep donor concentration $N_{D1} = 2.7 \cdot 10^{14}$ cm^{-3}, E_{D1} = 0.09 eV additional unknown atoms or charged dislocations: neutral $X = 1.8 \cdot 10^{15}$ cm^{-3}, charged $X_{ch} = 6.5 \cdot 10^{12}$ cm^{-3}, E_X = 0.018 eV.

temperatures. On the samples with higher doping level we can observe the maximal magnetoresistance values, which are lower in comparison with that from Fig. 3. In the samples in which the outdiffusion of X atoms [8] probably is more significant negative magnetoresistance occurs (Fig. 6). The sample with Hall carrier concentration with $n_H = 2.2 \cdot 10^{15}$ cm^{-3} at 300 K vs. temperature for 1 μm thick are shown in Fig. 7. Magnetoresistance values as a function of B direction for the sample as in Fig. 6 we plot in Fig. 8.

In the investigated samples of GaAs and $In_{0.53}Ga_{0.47}As$ layers we observe two phenomena, Hall concentration increase and magnetoresistance decrease in low temperatures (lower as approx. 100 K) (see Figs. 2, 4, 7 and Figs. 1, 3, 6). These two properties suggest some discrepancies between

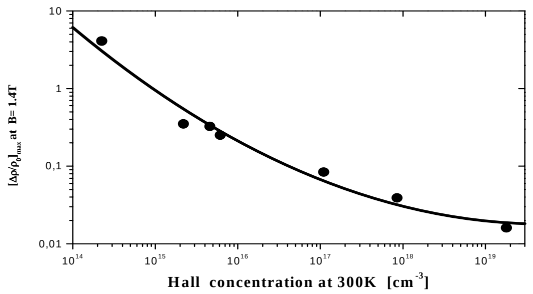

Fig. 5. $\Delta\rho/\rho_0$ in maximum vs. majority carrier concen- tration.

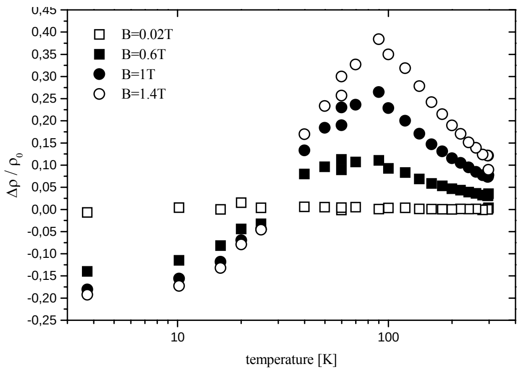

Fig. 6. Magnetoresistance vs. temperature for the sample $In_{0.53}Ga_{0.47}As$/SI InP $n_H = 2.2\cdot10^{15}$ cm^{-3}.

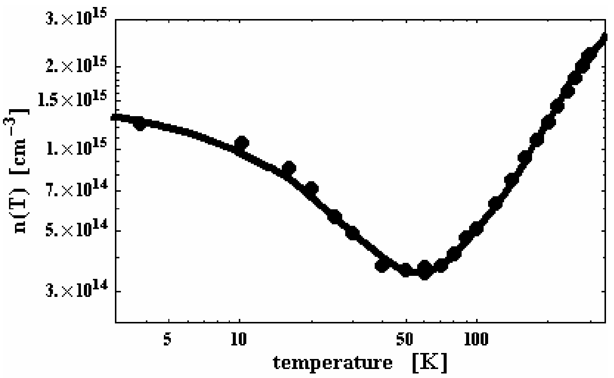

Fig. 7. Hall concentration vs. temperature for the sample as in Fig. 6, • experimental points, — fit calculated from the neutrality equation using the following parameters: N_A = $1.0\cdot10^{17}$ cm^{-3}, $E_A = 0.001$ eV; main donor atoms concentration N_D = $1.049\cdot10^{17}$ cm^{-3}, E_D = = 0.0012 eV; deep donor concentration $N_{D1} = 1.875\cdot10^{14}$ cm^{-3}, $E_{D1} = 0.08$ eV additional unknown atoms or charged dislocations: neutral $X = 1.55\cdot10^{15}$ cm^{-3}, charg-ed $X_{ch} = 1.7\cdot10^{14}$ cm^{-3} , E_X = 0.025 eV.

classical transport model for the semiconductors and our results. They seem to be connected with semi-conductor layers in which are contained such elements as: Ga, As and In with outdiffusing species from supporting SI wafer (Cr from GaAs, Fe from InP).

The maximum values of magnetoresistance were obtained at most pure samples (see Figs. 3 and 5) but the shape of the dependence is similar in GaAs and $In_{0.53}Ga_{0.47}As$ layers. This suggests that crystallo-graphic and transport properties in the epitaxial MBE layers are more complicated as in the normal bulk

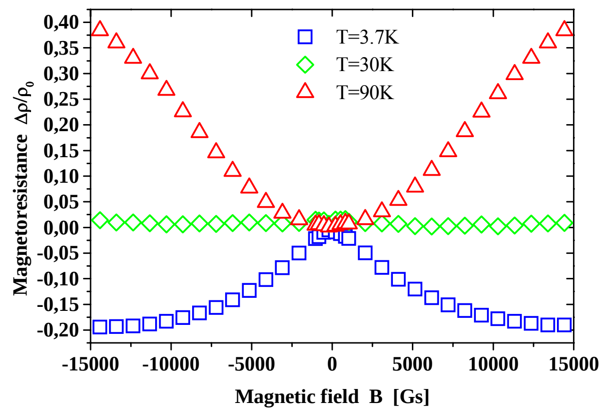

Fig. 8. Magnetoresistance values vs. magnetic field direction taken at different temperatures for the sample as in Fig. 6.

samples. Some of the $In_{0.53}Ga_{0.47}As$ samples having thickness of 1 µm exhibit negative magnetoresistance (Fig. 6). For this sample are presented MR values at three temperatures: 3.7 K, 30 K and 90 K (Fig. 8). The activation temperature for negative magneto-resistance seems to be appr. 30 K, i.e. 2.6 meV. We suppose after MOTT [9] that there exist fairly well defined "dangling bonds" and in the lowest range of temperature, conductivity is due to impurity band conduction, i. e. the electron moving by thermally activated hopping. If it is a correct explanation, we should expect a plot of ln ρ vs. $T^{-1/4}$ to give a straight line. The Mott formula for temperature dependence of resistivity due to variable-range hopping is:

$$\rho = \rho_0 \exp[(T_0/T)^{1/4}] \qquad (1)$$

where ρ_0 is the resistivity value for a perfect struc-ture, and T_0 is the temperature, which is also the gradient of the Mott (1) plot.

In Fig. 9 are shown the curves for the sample from Fig. 6. The straight lines represent the fits to the Mott law (Eq. (1)) in the three observed regions *A*, *B* and *C*.

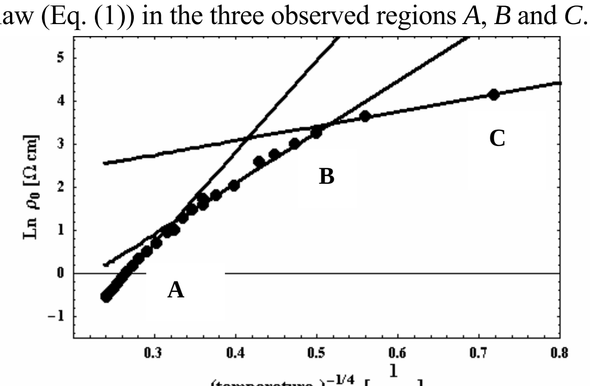

Fig. 9. *A* – ln ρ against $1/T^{1/4}$ at T = 300 ÷ 70 K; $\rho_0 = 0.0035$ Ω·cm, $T_0 = 2\cdot10^5$ K; *B* – ln ρ against $1/T^{1/4}$ at T = 70 ÷ 12 K; $\rho_0 = 0.07$ Ω·cm, $T_0 = 2\cdot10^4$ K; *C* – ln ρ against $1/T^{1/4}$ at T = 12 ÷ 3.7 K; $\rho_0 = 5.8$ Ω·cm, T_0 = = $1.2\cdot10^2$ K.

According to SASAKI [10] comparing Hall concentration and the resistivity variations vs. temperature (Fig. 7 and 9) we observed that three

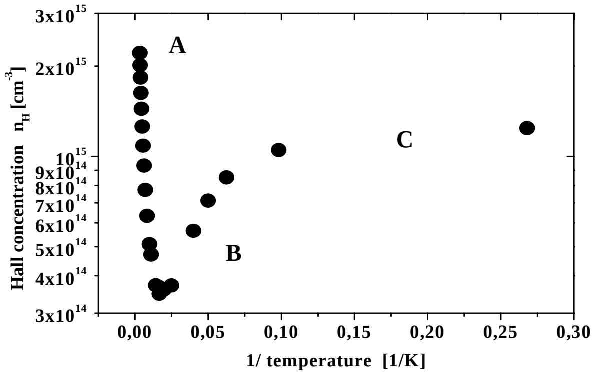

Fig. 10. Arrhenius plot for the sample as Fig. 6, 7.

temperature regimes could be assigned (from high to low temperature). The Mott's law seems to apply to these regimes satisfactory but with different parameters as ρ_0 and T_0. We find activation energy for this regions from Arrhenius plot of ln n_H against $1/T$ (Fig. 10).

They are localised vs. bottom of the conduction band as in Fig. 11. The band gap for $In_{0.53}Ga_{0.47}As$ against temperature was calculated after SAJAL ET AL. [11] from their (Eq. 4).

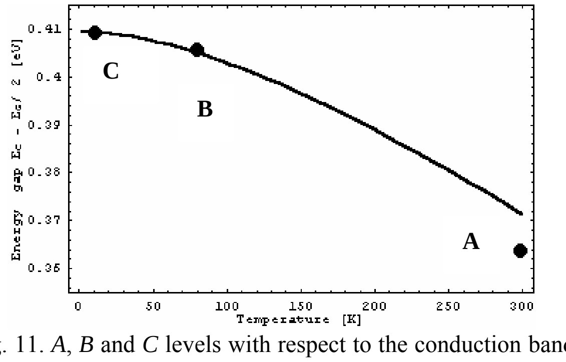

Fig. 11. *A*, *B* and *C* levels with respect to the conduction band edge as function of temperature: 300 K and lower + 16 meV, 80 K and lower – 1.26 meV, 10 K and lower – 0.09 meV.

The main level (*A*) at 300 K is localised under the bottom of the conduction band. Two next (*B* and *C*) are above and consequently merged to the conduction process in lower temperatures. We believe that the doping elements, which allow establish such strange properties may be outdiffused from supporting semi-insulating wafers or due to variable – range hopping.

Plain dependence from magnetic field intensity suggest also some spin ordering valve phenomena, which show such elements as Fe or Cr.

4. Conclusion

The MBE layers of GaAs and $In_{0.53}Ga_{0.47}As$ present the examples of very complicated behaviour of the charge carrier transport [12, 13]. All layers at the low temperature exhibit magnetoresistivity decrease and connected with it increase of the Hall carrier concentration. The samples in which negative magnetoresistance exists fulfil Mott's law, which is connected with the presence of crystal defects.

REFERENCES

1. S. A. ALLIEV, F. P. KESAMANLY, S. LAGUNOVA, D. N. NASLEDOV, *phys. stat. sol.*, 1966, **17,** 105–108.
2. Ch. YAMANOUCHI, K. MIZUGUCHI, W.SASAKI, *J. Phys. Soc. Japan*, 1967, **22**, 859–864.
3. T. M. PEKAREK, B. C. CROOKER, S. LI, M. MCELFRESH, J. C. P. CHANG, D. MCINTURFF, E. S. HARMON, M. R. MELLOCH, J. M. WOODALL, *J. Appl. Phys.*, 1997, **81**, 4869–4871.
4. Z. DZIUBA, T. PRZESŁAWSKI, K. DYBKO, M. GÓRSKA, J. MARCZEWSKI, K. REGINSKI, *Appl. Phys*., 1999, **85**, 6619–6624.
5. J. P. LOCQUET, J. PERRET, J. FOMPEYRINE, E. MÄCHLER, J. W. SEO, G. VAN TENDELOO, *Nature*,1998, **394**, 453–458.
6. V. V. PREOBRAZENSKII, D. I. LUBYSHEV, K. REGIŃSKI, J. MUSZALSKI, *Thin Solid Films*, 1995, **267**, 51–53.
7. J. KANIEWSKI, Z. ORMAN, J. PIOTROWSKI, K. REGIŃSKI, M. ROMANIS, *Proc. SPIE*, 2000, **4130**, 749–759.
8. T. PRZESŁAWSKI, A. WOLKENBERG, K. REGIŃSKI, J. KANIEWSKI, J. BĄK-MISIUK, *Thin Solid Films*, 2000, **367**, 232–234.
9. N. F. MOTT, *Phil. Mag*., 1969, **19**, 835–852.
10. W. SASAKI, *Phil. Mag*., 1985, **B52**, 427–435.
11. P. SAJAL, J. B. ROY, P. K. BASU, *J. Appl. Phys*., 1991, **69**, 827–829.
12. A. WOLKENBERG, T. PRZESŁAWSKI, K. REGIŃSKI, J. KANIEWSKI, *Mater. Sci. a. Eng*., 2002, **B90**, 176–179.
13. A. WOLKENBERG, T. PRZESŁAWSKI, K. REGIŃSKI, J. KANIEWSKI, *J. Phys.&Chem. Solids*, in press.