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Heterojunction $In_{0.53}Ga_{0.47}As/InP$ magnetic field sensors fabricated by molecular beam epitaxy

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The aim of our work is to construct magnetic field sensor (MFS) and temperature sensor (TS) based on galvanomagnetic effects. Basing on the analysis of available experimental data we chose n-type $In_{0.53}Ga_{0.47}As$ on InP as a suitable material. We fabricated thin InGaAs layer ($t = 4$ μm) with electron mobility $\mu_H = 0.7\ m^2(Vs)^{-1}$ and carrier concentration $n_H = 2.25\times10^{20}\ m^{-3}$ at room temperature. The absolute sensitivity γ_0 defining maximal output voltage of the Hall sensor (HS) and the current-related sensitivity γ deduced from the measurement results are $\gamma_0 = 1.1\ VT^{-1}$ and $\gamma = 5600\ \Omega T^{-1}$, respectively. Additionally, we found magnetoresistor current sensitivity $S_I \sim 800\ \Omega T^{-1}$ and voltage sensitivity $S_V \sim 0.5\ T^{-1}$ for the layer. Similarly, in the $In_{0.53}Ga_{0.47}As/InP$ layer ~1 μm thick with $n_H = 8.5\times10^{23}\ m^{-3}$ and $\mu_H \sim 0.5\ m^2(Vs)^{-1}$ we obtained the values of the parameters: $\gamma_0 = 0.008\ VT^{-1}$, $\gamma = 40\ \Omega T^{-1}$, and $S_I \sim 1\ \Omega T^{-1}$, $S_V \sim 0.05\ T^{-1}$. The studies lead towards the construction of new magnetic field and/or temperature sensors on the basis of present and previously obtained as well as published experimental results.

1. Introduction

Electronic devices capable of sensing magnetic field strength are becoming increasingly popular and commercially important [1]–[7]. Hall effect devices give a voltage output that is more linear with magnetic field than that which can be obtained with magnetoresistors but the signal level is much lower. They are also small, require no on-chip amplifying electronics, have good noise immunity due to their low impedance, work over a relatively wide temperature range, and are speed insensitive (*i.e.*, they respond to magnetic field, not to the rate of change of magnetic field).

Magnetoresistors are simpler devices than Hall sensors, and it was quickly realised that the most sensitive MFS are those fabricated from materials with low concentration of high-mobility charge carriers, because the relative change in resistance is proportional to the square of the mobility [2], [8]. Modern technology creates a rapidly growing demand for sensors and actuators based on magnetic effects and exploiting dedicated magnetic materials. Optimisation and control of electrical characteristics of epitaxial InGaAs layers require accurate methods for the measurement of the relevant parameters. Specifically, Hall effect measurements yield information on the carrier density, whereas the mobility is indicative of the purity and the degree of perfection of the films. A systematic and thorough characterisation will also lead to better understanding of the behaviour of the electronic devices built of these materials.

2. Experimental procedures

The $In_{0.53}Ga_{0.47}As$ layers were fabricated on (001) semi-insulating (SI) InP by molecular beam epitaxy (MBE) with RIBER 32P. The layers were grown at substrate temperature T_S = 510 °C to thickness from 1 μm to 4 μm. Further details concerning the fabrication are given in [9], [10]. The galvanomagnetic properties of the layers were investigated in magnetic fields up to 1.5 T at temperatures from 3.5 K to 300 K with a Van der Pauw square shape sample. Ohmic contacts were made to In-Sn dots and annealed in nitrogen medium at 420 °C for 1.5 min. All voltages were averaged to eliminate the thermoelectric potentials. In order to eliminate the effects due to probe misalignment, all data were taken in positive and negative magnetic field directions. The samples were placed in a closed-cycle liquid helium cryostat which was inserted into the magnet and oriented so that the magnetic field was perpendicular to the sample plane. The Hall concentration n_H *vs.* temperature and magnetoresistance $\Delta\rho/\rho_0$ *vs.* temperature and magnetic field were measured. The $In_{0.53}Ga_{0.47}As$ layers were always characterised by unintentional doping concentration lower than 6.2×10^{21} m^{-3}. The samples with higher concentration were doped with Si.

3. Results and discussion

The magnetic field density and temperature dependence of the Hall voltage and resistance were carefully observed while investigating the electrical characteristics of the Hall generators. Figure 1 shows the dependence of Hall voltage U_H on magnetic induction B in the range 0.025–1.4 T determined at different temperatures for four fixed values of the control current. Some of the relevant electrical parameters of the samples are presented in the Table. Figure 2 presents the current sensitivity *vs.* temperature dependence at low and high fields. As can be noticed in Fig. 2 the maximum sensitivity rises rapidly as temperature decreases in the range from 300 to 120 K and then slowly decreases with temperature reaching a minimum at 30 K. However, a slight increase of sensitivity takes place on a further decrease in temperature below 20 K. Figure 3 shows magnetoresistance $\Delta\rho/\rho_0$ dependence on

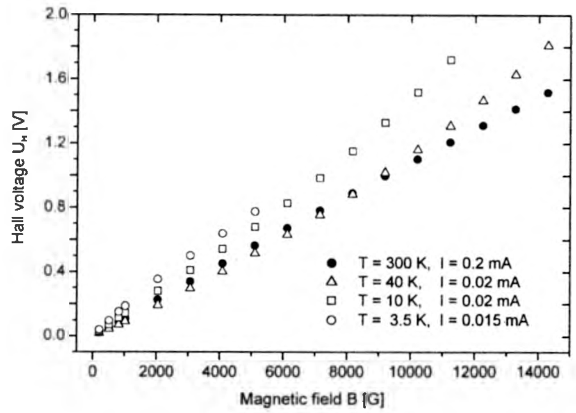

Fig. 1. Static sensitivity characteristics for $In_{0.53}Ga_{0.47}As/InP$ with $n_H = 2.25\times10^{20}$ m^{-3}.

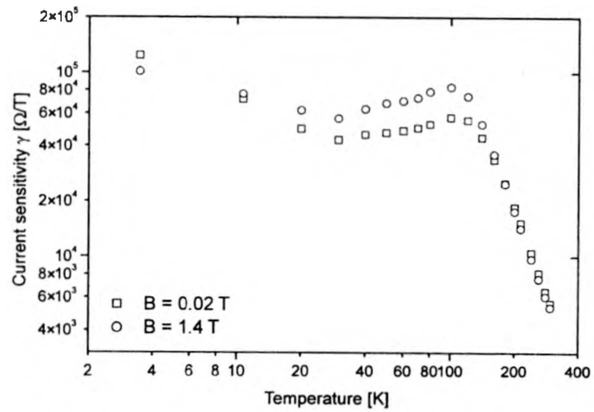

Fig. 2. Current sensitivity *vs.* temperature for the sample as in Fig. 1.

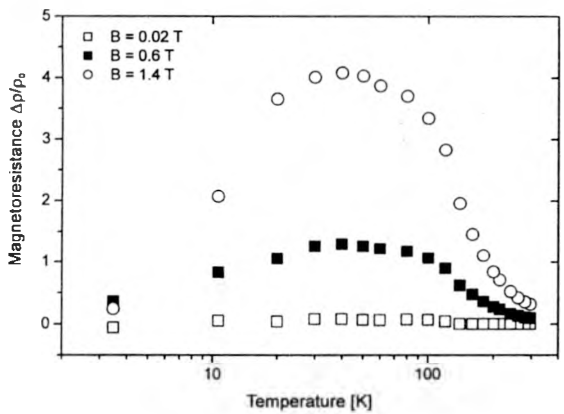

Fig. 3. Magnetoresistance *vs.* temperature for the sample as in Fig. 1.

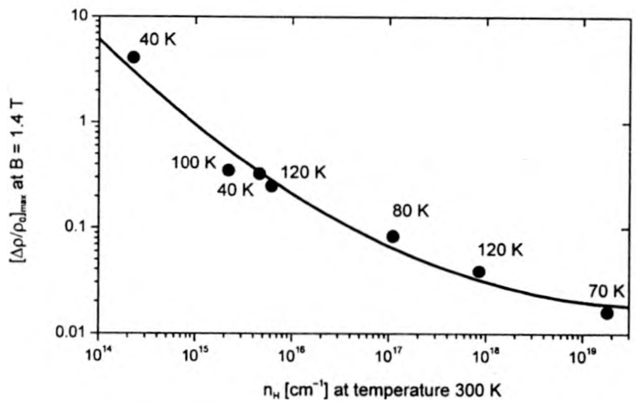

Fig. 4. Maximum magnetoresistance *vs.* Hall concentration.

T a b l e. Electrical characteristics of $In_{0.53}Ga_{0.47}As$ Hall elements (T – temperature, J – input current, P_X – input power, γ_0 – absolute sensitivity, γ – current sensitivity, R_X – input resistance, μ_H – Hall mobility, R_H – Hall coefficient, η – nominal efficiency for B = 0.1 T and B = 1.4 T).

T [K]	J [mA]	P_X [mW]	γ_0 [VT^{-1}]	γ [ΩT^{-1}]	R_X [Ω]	μ_H [m^2(Vs)$^{-1}$]	R_H [m^{3}C^{-1}]	η [%]
295	0.2	0.4	1.1	5600	9925	0.73	0.029	0.05
			(1.06)	(5300)		(0.70)	(0.028)	(8.4)
40	0.02	0.007	0.092	46000	18337	3.27	0.24	0.9
			(1.27)	(63400)		(4.50)	(0.33)	(35)
10	0.02	0.025	1.44	71810	61425	1.52	0.37	0.2
			1.53*	76710*		1.62*	0.40*	28*
3.5	0.015	0.037	1.86	123850	166500	0.97	0.64	0.08
			1.52**	101650**		0.80**	0.53**	1.4**

* at B = 1.12 T, ** at B = 0.5 T

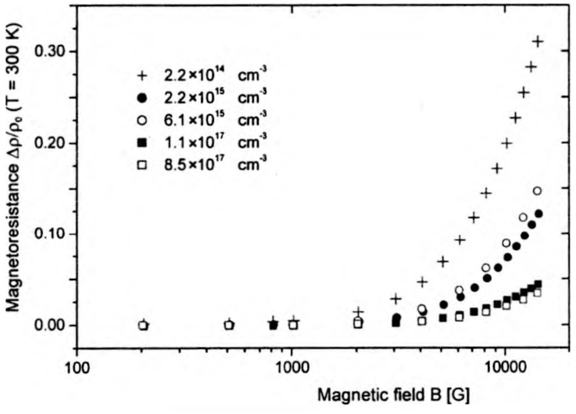

Fig. 5. Magnetoresistance *vs.* magnetic field for different samples.

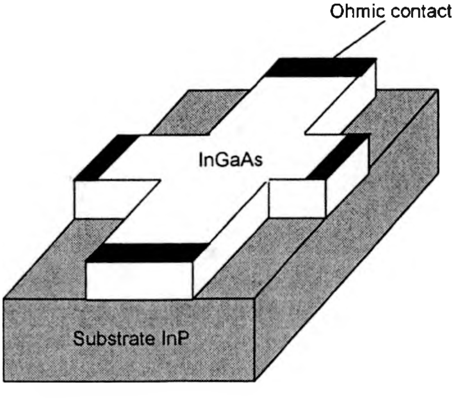

Fig. 6. Schematic diagram of the MFS.

temperature at low, middle and high field. It is evident that between 30–50 K a maximum of magnetoresistivity appears, which could be exploited in sensor construction. In Figure 4 the maximum values of magnetoresistivity at 1.4 T for different doping values are presented. It can be seen, that the best material for sensor construction is the sample with limited doping which at 40 K exhibits 7 times higher resistivity in the applied field than the highly doped samples. At 300 K the magnetoresistivity values are highest in samples with low doping (see Fig. 5). The proposed structure for a MFS sensor is presented in Fig. 6. We anticipate that such a structure will allow simultaneous measurement of the magnetic field and temperature with a simple sensor.

4. Conclusion

The results presented above should be considered as preliminary, because the complexity of the problem requires performing other series of experiments, including application of different measurement techniques. The obtained results indicate that the electrical transport properties of the $In_{0.53}Ga_{0.47}As/InP$ thin layers are indicative of a considerable potential for application in producing galvanomagnetic devices, which is demonstrated by electron mobility and its temperature dependence. Magnetic sensors made of these materials would be endowed with a high sensitivity.

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