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Magnetic field sensors based on undoped $In_{0.53}Ga_{0.47}As/InP$ heterostructures fabricated by molecular beam epitaxy and metalorganic chemical vapor deposition

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In this paper we, describe the design and fabrication process of Hall and magnetoresistor cross-shaped sensors using $In_{0.53}Ga_{0.47}As/InP$ layer structures as active media. The influence of geometric correction factor G_H on sensitivity parameters of these devices has been investigated. The results have been used in order to optimize the structure design behavior at temperatures ranging from 3 to 300 K. The large changes of the galvanomagnetic parameters *vs*. magnetic field and temperature allow these devices to be used as signal and measurement magnetic field sensors.

Keywords: Hall sensors, magnetoresistors, InGaAs/InP heterostructures, electronic transport, geometric correction factor, molecular beam epitaxy (MBE), metalorganic chemical vapor deposition (MOCVD).

1. Introduction

Semiconductor magnetic field-sensors such as Hall devices and magnetoresistors are widely used in many industrial and domestic applications [1–3]. Most of them are based on the galvanomagnetic effects due to the Lorentz force on the charge carriers [4–6]. Recently, III-V semiconductors, especially the AlGaAs/GaAs and InGaAs/InP material systems, have gained importance in optoelectronics and in high speed electronics. A key parameter for such devices which determines their sensitivity to a magnetic field is a high electron mobility, which is crucial for high output signal. The high room-temperature electron mobility of *n*-type InGaAs has created new interest in Hall sensors made from these materials. With the development of growth techniques, it is now possible to fabricate high-quality III-V heterostructures. Optimization and control of electrical characteristics of epitaxial InGaAs layers require accurate methods for measurement of the carrier density, whereas the mobility is indicative of the purity and the degree of perfection of the films.

In this paper we, propose a device structure and fabrication procedure of the sensors. We describe and compare Hall devices and magnetoresistors fabricated with undoped $In_{0.53}Ga_{0.47}As/InP$ heterostructures grown by molecular beam epitaxy (MBE) and metalorganic chemical vapor deposition (MOCVD) technology. This could open a wide range of applications the construction of Hall or magnetoresistor sensors used as signal or measurement devices.

2. Device structure and fabrication

The geometry and structure of the fabricated devices is shown in Fig. 1. One can observe here the layout of the mask (Fig. 1**a**) and sensor after technological processes (Fig. 1**b**). The epitaxial structures were grown by means of MBE and MOCVD techniques. Details of the growth of lattice-matched $In_{0.53}Ga_{0.47}As/InP$ structures have been given elsewhere [7–11]. The galvanomagnetic methods were used for the characterization of materials for sensors. The temperature-controlled Van-der-Pauw and Hall measurements were performed in a closed-cycle He cryostat in the dark [8, 10]. Basic properties of the samples studied are listed in Tab. 1. Cross-shaped InGaAs Hall elements with a leg length l = 1 mm and a width w = 2 mm (Fig. 1), were fabricated on the active layers with mesa etching by the lift-off technique. Four ohmic electrodes were formed on the ends of each crossbar by alloying evaporated AuGe-Ni. The chips of a size of 4×4 mm were mounted and bonded on a non-magnetic chip

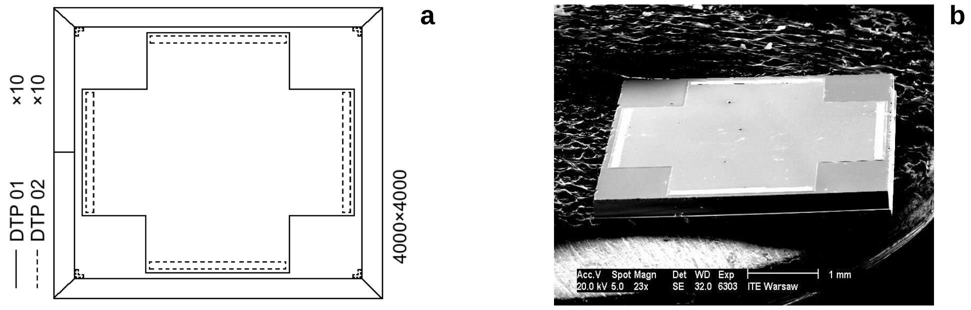

Fig. 1. View of the Hall sensor: mask layout for cross-shaped sensor (**a**), the sensor structure after etching (**b**).

Table 1. Basic properties of the samples at T = 293 K, B = 0.6 T.

Sample number	Thickness t [μm]	Concentration n_H [m^{-3}]	Mobility μ_H [m^2/Vs]	Resistivity ρ_0 [Ωm]	Resistivity ρ_B [Ωm]	Product $n_H t$ [m^{-2}]
273MBE	7.0	1.8×10^{20}	0.7	0.048	0.052	1.26×10^{15}
3017MOCVD	3.0	1.6×10^{21}	1.1	0.0035	0.0037	4.8×10^{15}

carrier. Although theoretically the input power related efficiency of the Hall voltage shows a maximum for $l/w = 0.36$, a ratio of $l/w = 0.5$ was chosen. For our geometry structures the geometry dependence of the Hall voltage as a function of the Hall angle Θ ($\tan\Theta = \mu_H B$) can be obtained by solving the potential problem [12–14].

To measure the exact Hall voltage U_H, the relation l/w should have the value of more than 4, then $U_H \rightarrow U_{H\infty}$. The relation between $U_H / U_{H\infty}$ is defined as the geometrical correction factor for the Hall effect in the rectangular device:

$$G_H = \frac{U_H}{U_{H\infty}} = \frac{E_H}{E_{H\infty}} \tag{1}$$

where U_H is the measured Hall voltage and $U_{H\infty}$ is the Hall voltage measured in a rectangle with $l = \infty$ ($G_H = 1$). The second part of Eq. (1) is only valid for devices with constant dimensions in y-direction. It is important to note that G_H is a ratio of Hall voltages and thus not dependent on the thickness of the device, it is used upon [15–17]. The transfer of this geometry factor of rectangular-shaped elements to equivalent cross-shaped elements is done with the method of conformal mapping. Calculation of the geometrical correction factor for the Hall effect in a cross-shaped device (Fig. 2) is possible using the Haeusler–Lippmann procedure [14]:

$$G_H = \left[1 - \exp\left(-\frac{\pi}{2}\frac{l}{w}\right)\frac{\Theta}{\tan\Theta}\right]\left[1 - \frac{2}{\pi}\frac{s}{w}\frac{\Theta}{\tan\Theta}\right] \tag{2}$$

where $\tan\Theta = \mu_H B$ is the Hall angle, s – voltage electrode width and $l/w = 1.7$ for our cross structure with $a/b = 0.5$. On applying the nomogram in Fig. 2 to obtain G_H for a cross-shaped structure, we first take $a/b = 0.5$ ($a = 1$ mm, $b = 2$ mm) and then

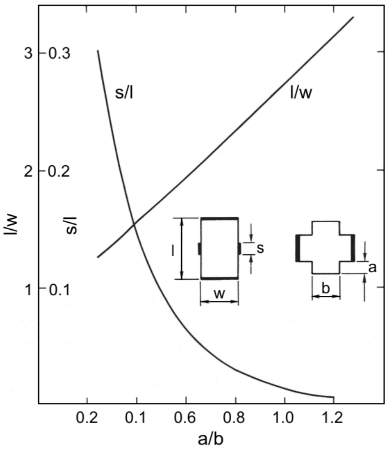

Fig. 2. Comparison between equivalent G_H for a rectangular and cross-shaped device [14].

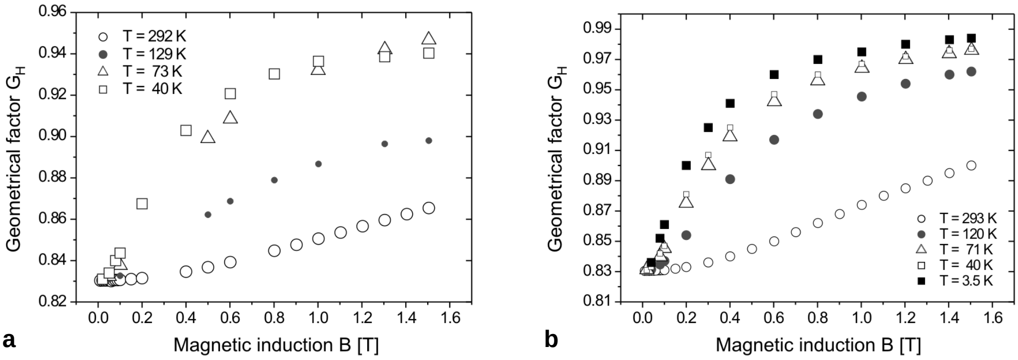

Fig. 3. Geometrical correction factor G_H *vs.* magnetic induction B for: 273MBE (**a**) and 3017MOCVD (**b**).

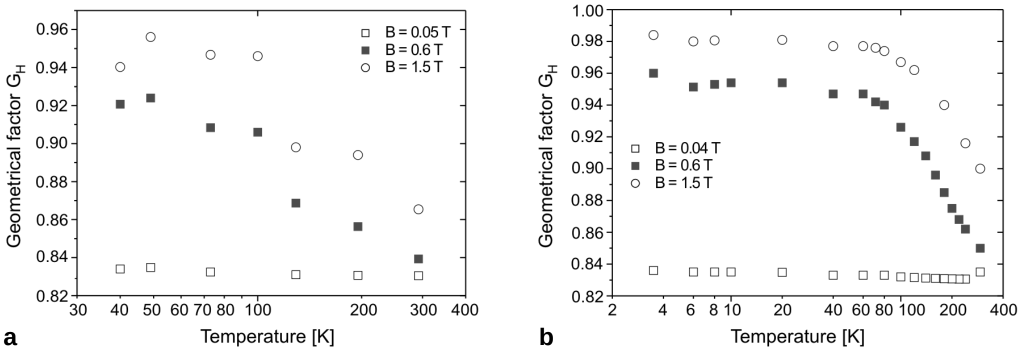

Fig. 4. Geometrical correction factor G_H *vs.* temperature T for: 273MBE (**a**) and 3017MOCVD (**b**).

$l/w = 1.71$ and $l = 1.71w$. For $s/l = 0.1$ we obtain $s/0.71w = 0.1$ and $s/w = 0.171$. Thereafter, having all parameters, we can determine the value of G_H for our cross-shaped structure (see Fig. 1). The geometrical correction factor of the sensitivity for cross-shaped elements with $l/w = 0.5$ and a magnetic field strength B, computed using Eq. (2), is presented in Fig. 3.

The G_H at three different magnetic fields is plotted as a function of temperature in Fig. 4.

3. Characteristic parameters of Hall and Gauss devices

One of the most important characteristics of a Hall effect magnetic field sensor is the supply-current related sensitivity γ. A feature of a Hall sensor is a linear response of the Hall voltage U_H to the bias current I and perpendicular magnetic field B:

$$U_H = \gamma I B = \frac{r_n}{e n_H t} G_H I B \tag{3}$$

Table 2. Electrical parameters of sensors built from 273MBE working as a Hall and Gauss device.

T [K]	B [T]	I [μA]	P_X [μW]	R_X [Ω]	R_H [m^3C^{-1}]	γ_0 [VT^{-1}]	γ [ΩT^{-1}]	S_I [ΩT^{-1}]	S_V [T^{-1}]	$\Delta\rho/\rho_0$ [%]	$\mu_H B$	η_{teoret} [%]
293	0.6	17	2	6970	0.0345	0.085	4140	765	0.13	7	0.425	1.5
	1.5				0.032	0.068	4000	1682	0.73	26	0.997	8.4
129	0.6	12	1.3	8804	0.11	0.186	13576	15630	0.84	42	1.07	10
	1.5				0.074	0.095	9547	10631	1.4	105	1.82	80
73	0.6	10	1.0	10387	0.26	0.32	33637	37017	3.0	45	2.14	40
	1.5				0.21	0.15	28888	30518	0.85	168	4.42	—
49	0.6	10	0.7	7353	0.24	0.32	31720	34324	2.5	80	2.8	66
	1.5				0.19	0.15	25951	27146	0.8	250	5.5	—
40	0.6	14	3.0	15057	0.2	0.27	26556	28840	2.6	130	2.64	60
	1.5				0.13	0.12	15730	16727	0.88	240	3.85	—

Table 3. Electrical parameters of sensors built from 3017MOCVD working as a Hall and Gauss device.

T [K]	B [T]	I [μA]	P_X [μW]	R_X [Ω]	R_H [m^3C^{-1}]	γ_0 [VT^{-1}]	γ [ΩT^{-1}]	S_I [ΩT^{-1}]	S_V [T^{-1}]	$\Delta\rho/\rho_0$ [%]	$\mu_H B$	η_{teoret} [%]
293	0.6	30	1.0	1164	0.004	0.04	1128	332	0.342	5.0	0.68	4.0
	1.5				0.0045	0.04	1287	1430	1.36	18	1.85	30
120	0.6	30	0.35	384	0.0047	0.05	1453	1585	2.7	30	2.48	50
	1.5				0.005	0.048	1623	1687	0.78	58	6.6	—
71	0.6	30	0.2	243	0.0049	0.052	1526	1620	2.2	36	4.0	—
	1.5				0.005	0.5	1684	1725	0.73	70	10.7	—
40	0.6	30	0.2	206	0.0044	0.05	1441	1522	2.12	24	4.4	—
	1.5				0.0047	0.047	1543	1580	0.73	64	11.5	—
3.5	0.6	30	0.2	207	0.0063	0.066	2027	2112	2.0	70	6.13	—
	1.5				0.007	0.62	2260	2295	0.7	160	16.7	—

where $\gamma = (R_H/t)G_H$ is the supply current related sensitivity, R_H is the Hall constant, t is the thickness of the active semiconductor layer, I is the bias current and B is the magnetic induction, n_H is the Hall carrier concentration, r_n is the Hall scattering factor of the majority carriers, e is the electron charge. The slope of the Hall voltage plotted against magnetic induction B is the absolute sensitivity γ_0 connected with the maximum output voltage [3, 17–19]

$$\gamma_0 = \frac{U_{H,\,\max}}{B} \quad \left[\frac{\mathrm{V}}{\mathrm{T}}\right]. \tag{4}$$

The input power of the Hall sensor can be described by the expression [20]:

$$P_X = I_X^2 R_X = I_X^2 \rho \frac{l}{wt} \tag{5}$$

where I_X is the input current of Hall generator, R_X is the input resistance, ρ is the resistivity.

The theoretical efficiency (for scattering on thermal vibrations of crystal lattice) of the device is given by [20]:

$$\eta = \frac{R_H^2 B^2}{4\rho^2 \zeta} = 0.34 \cdot 10^{-16} \frac{\mu_H^2 B^2}{\zeta} \tag{6}$$

where ζ is the coefficient connected with spreading current between the Hall electrodes, practically $\zeta = 2$–5.

We now proceed to describe the galvanomagnetic properties of our structure working as a Gauss device (magnetoresistors). Another key characteristics for magnetoresistive sensors made from these heteroepitaxial films of high mobility are current sensitivity S_I and voltage sensitivity S_V. Of practical value in the design of magnetoresistors are the approximate analytical expressions made with $l/w \geq 0.4$ for weak and strong magnetic field [4, 10]. The basic electrical parameters of the sensor built from 273MBE are presented in Tab. 2 and of that from 3017MOCVD in Tab. 3.

4. Results and discussion

The results of electrical characterization of two cross-shaped galvanomagnetic sensor structures 273MBE with $n_H = 1.8\times10^{20}$ m^{-3} and 3017MOCVD with $n_H = 1.6\times10^{21}$ m^{-3} are presented here. Depending on the type of connection they can work as a Hall or a magnetoresistor device. It was found that the geometrical function G_H for the Hall device depends on carrier concentration, magnetic field and temperature (Figs. 3, 4.). It enables us to determine, from Eq. (3), the supply current related sensitivity γ varies with a change in temperature in the following way for current drive $U_H(T) \sim R_H(T)$. Therefore, γ is inversely proportional to the product of carrier density and the thickness of the plate. This product denotes the surface charge carrier density in the plate, so that to obtain a high γ, it is necessary to have a low sheet carrier density (see Tabs. 1–3). If a Hall device is biased by a constant voltage $U_H(T) \sim \mu_H(T)$, the electron mobility has only second-order effects. This dependence is usually much stronger than the previous one.

Magnetoresistive behavior of our cross-shaped sensors is presented in Tabs. 2 and 3. According to these results, the current sensitivity S_I exhibits better values for the 273MBE layer which is more pure than 3017MOCVD. In order to calculate voltage sensitivity $S_V \sim \mu_H B$, we need an equation both for the case of weak ($\mu_H B < 1$) and strong ($\mu_H B > 1$) magnetic field. However, in strong magnetic field some difference arises due to the Hall mobility dependence on magnetic field. In these cases the S_V depends on Hall mobility which leads to higher values for 3017MOCVD than that of 273MBE layers (see Tabs. 2 and 3). Such behavior confirms our previous assumption that for galvanomagnetic sensors the purest $In_{0.53}Ga_{0.47}As$ layers (273MBE) are more useful for γ and S_I sensitivities than 3017MOCVD. As expected, the 3017MOCVD devices have better S_V sensitivity than the 273MBE ones. On the basis of the obtained results for galvanomagnetic and temperature properties of InGaAs thin films it can be concluded that these materials can be successfully used as Hall and magnetoresistive sensors with high performance.

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