High-sensitivity Hall sensors using GaInAs/AlInAspseudomorphic heterostructures

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S. Del Medico [a], T. Benyattou [a], G. Guillot [a], M. Gendry [b], M. Oustric [b], T. Venet [b],
J. Tardy [b], G. Hollinger [b], A. Chovet [c], N. Mathieu [c]

[a] *LPM (URA CNRS n°358), INSA de Lyon Bât 502, 69621 Villeurbanne Cedex, France*
[b] *LEAME (URA CNRS n°848), Ecole Centrale de Lyon, BP 163, 69131 Ecully Cedex, France*
[c] *LPCS (URA CNRS n°840), ENSERG, BP 257, 38016 Grenoble Cedex, France*

Abstract

In this work, we propose solutions based on band-gap engineering of III–V heterostructures to develop new types of magnetic sensors using the properties of a two-dimensional electron gas and the benefit of strain in pseudomorphic channels. First, the optimization of the growth of pseudomorphic $In_{0.75}Ga_{0.25}As/In_{0.52}Al_{0.48}As$ heterostructures by molecular beam epitaxy is described. A low sheet electron density of 9.84×10^{11} cm^{-2} and a high mobility of 13 000 cm^2 V^{-1} s^{-1} at room temperature have been obtained. A physical model of the structure including a self-consistent description of the coupled Schrödinger and Poisson equations has been developed for a better understanding of the influence of the heterostructure design on its electronic properties. A sensitivity of 580 V A^{-1} T^{-1} with a temperature coefficient of -550 ppm °C^{-1} between -80 and 85 °C is obtained. High signal-to-noise ratios corresponding to minimal detectable fields of 350 nT Hz$^{-1/2}$ at 100 Hz and 120 nT Hz$^{-1/2}$ at 1 kHz have been measured.

Keywords: Hall sensors; Pseudomorphic heterostructures

1. Introduction

In the search for new microelectronic components, sensors play an important role because they are primordial in many fields such as measurement, detection, checking, etc. Lots of studies are being carried out to produce low-cost and easily reproducible devices, with conventional microelectronic technologies and with the aim of making intelligent sensors (i.e., detection and processing signal on the same chip). Hall semiconductor magnetic microsensors can be used in practical applications: Earth's magnetic field measurement, reading of magnetic tapes and disks, contactless switches, displacement detection or domestic energy meters [1].

The use of two-dimensional electron gas (2DEG) III–V pseudomorphic heterostructures seems to be an interesting way to obtain both a high mobility and a low sheet electron density [2,3]. These conditions are essential to get a good sensitivity. In fact, we take advantage of the 2DEG mobility properties due to the transfer of doped barrier-layer electrons to the non-doped small gap channel. The scattering of free carriers by ionized donors is reduced because of their spatial separation and thus leads to an increase of the mobility.

In this paper, we report on the fabrication and characterization of high-sensitivity Hall sensors based on the use of a GaInAs/AlInAs pseudomorphic heterostructure.

2. Device structure and fabrication

The samples were grown using a Riber 2300 MBE system. The substrates were semi-insulating (001) oriented 'epi-ready' InP wafers from Crismatec-Inpact. An optimized procedure with indium stabilization of the InP surface for a few seconds at 565 °C is used for the oxide desorption [4]. Two pseudomorphic $In_{0.52}Al_{0.48}As/In_{0.75}Ga_{0.25}As$ heterostructures, E508 and E750, with an indium composition of 0.75 in the InGaAs channel were realized with different layer thicknesses and different Si doping. A cross-sectional view of the structure is schematically shown in Fig. 1. The growth conditions were the following: a V/III beam equivalent-pressure ratio of 25 and a growth rate of ≈ 1 µm h^{-1} for each material. The growth temperature was 500 °C

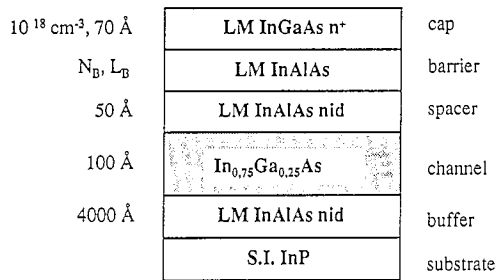| 10^{18} cm^{-3}, 70 Å | LM InGaAs n$^+$ | cap |
N_B, L_B	LM InAlAs	barrier
50 Å	LM InAlAs nid	spacer
100 Å	In$_{0.75}$Ga$_{0.25}$As	channel
4000 Å	LM InAlAs nid	buffer
	S.I. InP	substrate

Fig. 1. Cross-sectional view of the structure (L_B, barrier thickness; N_B, barrier doping level; LM, lattice matched).

Table 1
Characteristics of the structures

Structure	L_B (Å)	N_B (cm^{-3})	μ_H (300 K) (cm^2 V^{-1} s^{-1})	n_s (300 K) (cm^{-2})
E508	580	8×10^{17}	13100	1.76×10^{12}
E750	400	6×10^{17}	9380	9.84×10^{11}

for the two pseudomorphic heterostructures. A growth interruption procedure already established [5] to get a smooth channel interface and low impurity incorporation was achieved by closing the main shutter for 5 s, allowing a surface reconstruction from a (2×1) As-stabilized surface to a (4×1) cation-stabilized surface.

Hall measurements were carried out on square samples using the van der Pauw technique to measure electron concentration and mobility. The characteristics of the structures are listed in Table 1. The growth of an InAlAs buffer on the semi-insulating InP substrate is necessary to get good-quality materials and interfaces. An In$_{0.75}$Ga$_{0.25}$As channel is then inserted. This layer contains a 2DEG with a high mobility at the InAlAs barrier/InGaAs hetero-interface. The spacer increases the spatial separation between donors and electrons. The barrier layer is doped so as to provide electrons in the channel. The InGaAs lattice matched cap layer is highly doped to have good ohmic contacts.

Two sorts of Greek-cross Hall devices were fabricated by photolithography. The dimensions of the Hall element are either 600 μm in length and 200 μm in width ($L/W = 3$) or 1000 μm and 200 μm ($L/W = 5$). The ohmic contacts were made by alloying evaporated AuGe/Ni/Au.

3. Heterostructure modelling

For a better understanding of the influence of the heterostructure design on its electronic properties, a model involving the self-consistent resolution of Schrödinger and Poisson equations using Fermi–Dirac statistics has been developed. This allows us to determine the conduction-band structure, the energy levels in the

channel as well as the wave functions (Fig. 2). We can in this way visualize the localization of the electrons and check the possible parasitic parallel conduction in the barrier. This conduction occurs when, for example, due to a too wide barrier, a non-depleted zone remains in this layer. Then conduction takes place in two 'channels': the 2DEG of the well and the non-depleted zone of the barrier. We have also studied the influence of several factors on the sheet carrier density (doping level of barrier, spacer and channel thicknesses) (Fig. 3). The Fermi-level pinning at the GaInAs surface was considered as a boundary condition and estimated at 0.3 eV from the bottom of the conduction band. We have then simulated the E750 structure in order to reduce the sheet electron density n_s and parallel conduction and to have the best carrier confinement in the channel. The first electron level is located at 60 meV below the Fermi level, which corresponds to an electron population of 9.4×10^{11} cm^{-2}. The second level is situated 106 meV above the Fermi level and is nearly empty. The E508 structure was not an optimized one with regards to such a physical modelling.
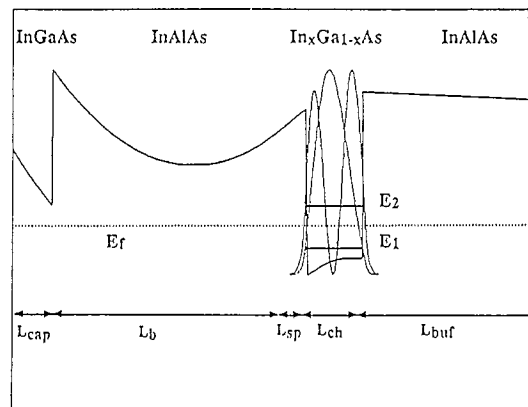

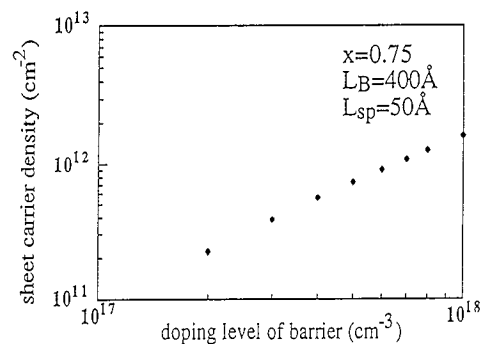Fig. 2. Band diagram of the InGaAs/InAlAs structure (E750) at 300 K.

Fig. 3. Simulated behaviour of the sheet carrier density vs. barrier doping level (L_{sp}, spacer thickness).

4. Results

4.1. Product sensitivity, temperature coefficient

One of the most important characteristics of a Hall-effect device is the 'supply-current-related sensitivity' defined theoretically by Popovic [6]:

$$K_H = \left(\frac{1}{I} \frac{\partial V_H}{\partial B} \right) = G \frac{r_H}{q n_s}$$

where I is the supply current, V_H the Hall voltage, r_H the Hall scattering factor of the majority carriers and G the geometrical correction factor. The Hall factor is considered as $r_H \approx 1$ for degenerate carriers. The geometrical factor represents the diminution of the Hall voltage due to a non-perfect current confinement in a finite-length Hall device. In our devices we can consider that $G \approx 1$.

The output Hall voltage for the E750 device with a length to width ratio of five is shown in Fig. 4. The devices show a good linearity versus the magnetic field in the investigated range (5.6 mT, 0.8 T). Our result for the best configuration is a product sensitivity K_H of 580 V A^{-1} T^{-1}. All the results are summarized in Table 2. K_H is inversely proportional to n_s, which explains the difference between the E508 and the E750 device sensitivities. K_H was also extracted at various temperatures between -80 and 85 °C. The value of $(1/K_H)(dK_H/dT)$ is situated between -230 and -550 ppm °C^{-1} for the different devices. In fact, K_H varies only from -100 ppm °C^{-1} between -80 and 25 °C, but the temperature coefficient increases at higher temperature.

4.2. Noise spectrum

Voltage fluctuations across the Hall electrodes H$_1$ and H$_2$ were measured at zero magnetic field as a function of frequency. Fig. 5 shows the noise power spectral density S_v of the Hall voltage for the sample E508 on a device characterized by $L/W = 3$. A $1/f$ behaviour is clearly observed. For frequencies above ≈ 80 kHz, the noise spectrum reaches the thermal noise, which is 3×10^{-9} V Hz$^{-1/2}$. The theoretical value for thermal noise is $4kTR$. For this device $R = 395$ Ω; then the calculated thermal noise is 2.5×10^{-9} V Hz$^{-1/2}$, which is in good agreement with the observed value. The minimum magnetic field B_{min} that can be detected by the sensor for a S/N ratio equal to one is determined by the sensitivity of the Hall device and its measured noise. At 1 kHz and 100 Hz, the estimated B_{min} values are 120 and 350 nT Hz$^{-1/2}$, respectively.

Table 2
Values of the magnetic sensitivity at 300 K and of the temperature coefficient obtained on the two materials and for different geometries between -80 and 85 °C

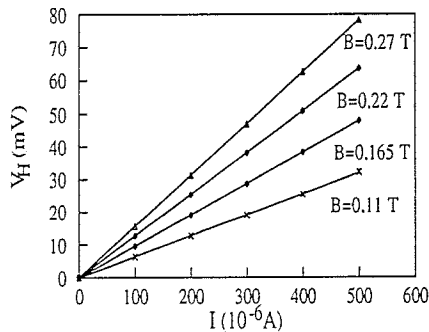| Structure	E508 $L/W = 3$	E508 $L/W = 5$	E750 $L/W = 3$	E750 $L/W = 5$
K_H (V A^{-1} T^{-1})	346	325	550	580
$\frac{1}{K_H} \frac{dK_H}{dT}$ (ppm °C^{-1})	-230	-360	-500	-550

Fig. 4. Hall voltage as a function of magnetic field for different values of the bias current for the $L/W = 5$ device of sample E750.
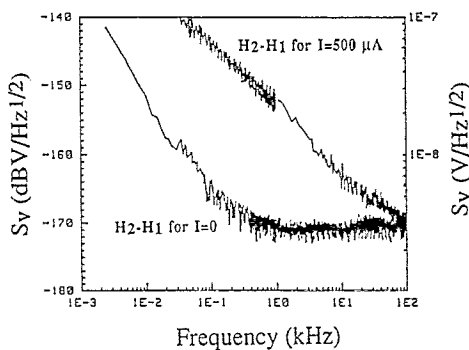

Fig. 5. Hall-voltage noise spectrum of the $L/W = 3$ device of sample E508. H$_2$–H$_1$ represents the voltage fluctuations between the two Hall contacts H$_1$ and H$_2$.

5. Conclusions

Highly sensitive InGaAs-2DEG Hall devices have been fabricated from a high-mobility In$_{0.75}$Ga$_{0.25}$As/In$_{0.52}$Al$_{0.48}$As pseudomorphic heterostructure grown by MBE. The Hall devices have a product sensitivity of 580 V A^{-1} T^{-1} with a small temperature coefficient of -550 ppm °C^{-1} and high magnetic resolutions of 350 nT Hz$^{-1/2}$ at 100 Hz and 120 nT Hz$^{-1/2}$ at 1 kHz. These devices also show excellent linearity.

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