Review of Scientific instruments

InAs/$Al_{0.2}Ga_{0.8}Sb$ Quantum Well Hall Sensors with improved temperature stability

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Cross-shaped Hall sensors with high sensitivity and excellent temperature stability were fabricated from quantum wells based on an InAs/$Al_{0.2}Ga_{0.8}Sb$ heterostructure. The layers were grown on semiinsulating GaAs substrates by Molecular Beam Epitaxy. Maximum Hall mobilities of 215,000 cm^2/Vs with sheet carrier concentrations of $9x10^{11}$ cm^{-2} were measured at 4.2 K for an undoped quantum well structure. These transport properties result in sensitivities as high as 3 T^{-1} (for voltage drive) and 650 Ω/T (for current drive). Additional Si δ-doping in the middle of the InAs quantum well leads to a highly improved temperature stability of the sensitivities.

I. Introduction

Hall effect devices are by far the most widely used magnetic sensors today. Their future mainly depends on whether means will be developed to enhance their sensitivity and improve their temperature stability.

Some low temperature applications in fundamental research might include the use of a Hall sensor: as a simple magnetic field sensor; for the calibration of coils or permanent magnets, or to measure remanent fields; for magnetization measurements by depositing superconducting material[1-3], ferromagnetic films[4] or clusters on top of the sensitive area of the Hall sensor, for development of Hall probes for a Scanning Hall Probe Microscope[5]; and for measuring field distribution at the side of a superconductor by attaching an array of Hall sensors to a superconductor crystal[6,7]. Also at higher temperatures, Hall sensors are used for research, as well as industrial applications such as magnetic read-out sensors, brushless motors.

The Hall voltage built up at the sides of a rectangular plate with length L, width W, electron sheet carrier concentration n_s and mobility μ can be expressed in the following way for current and voltage drive respectively:

Current drive : $$V_H = \frac{I_D B}{n_s e} \qquad (1)$$

Voltage drive : $$V_H = V_D B \mu \frac{W}{L} \qquad (2)$$

Especially for high performance Hall sensors the following requirements have to be met: a) high carrier mobility for high sensitivity in voltage drive, b) low carrier concentration for high sensitivity in current drive. In general, voltage and current sensitivities of a rectangular Hall sensor can be expressed as follows:

$$S_V = \frac{1}{V_D}\frac{dV_H}{dB} \cong \mu \frac{W}{L} \qquad \left(T^{-1}\right) \qquad (3)$$

$$S_I = \frac{1}{I_D}\frac{dV_H}{dB} \cong \frac{1}{n_s e} \qquad (\Omega/T) \qquad (4)$$

Since mobility and sheet carrier concentration can be optimized in the MBE growth of materials containing a two dimensional electron gas (2DEG), they proved to be the most appropriate for the fabrication of Hall sensors[8]. Sandwiched between AlGaSb layers, thin InAs layers form a quantum well structure that exhibits a high conduction band offset and a low effective mass for the electrons in the InAs quantum well. This results in a good confinement of the two dimensional electron gas with high mobilities of around 30,000 cm^2/Vs at room temperature[9].

In this paper we report on a comparative study on the sensing performance and temperature stability of undoped and doped $InAs/Al_{0.2}Ga_{0.8}Sb$ quantum well structures for application in Hall sensors at temperatures from 4.2 K up to 200 K. Results and discussion for these sensors in the temperature range between –100 °C and +150 °C have been presented elsewhere[10].

II. Epitaxial growth and device fabrication

Three different layer types were grown and processed. The first one is a nominally undoped $InAs/Al_{0.2}Ga_{0.8}Sb$ structure with an InAs quantum well thickness of 15 nm (undoped sample A). The second sample consists of a 20 nm thick InAs quantum well with insertion of a low Si δ-doping of nominally $3x10^{12}$ cm^{-2} in the middle of the InAs quantum well (lowly doped sample B). The layer structure of the last sample differs from the previous only by a higher central Si δ-doping of nominally $9x10^{12}$ cm^{-2} (highly doped sample C). Hall mobilities and carrier concentrations were determined using the Van der Pauw method. Details on growth and characterization of these layers can be found elsewhere[11]. We developed a technology for the fabrication of $InAs/Al_{0.2}Ga_{0.8}Sb$ Hall sensors with cross geometry ranging from 80 µm down to 1 µm in size. Single devices were defined by standard optical lithography. Wet chemical and reactive ion etching techniques were used for mesa isolation. Afterwards, ohmic contacts were made using TiW/Au metallization. Finally, the samples were diced and individual chips were bonded for testing.

III. Results and discussion

Hall sensors with cross geometry of 80 x 80 μm^2 were fabricated from the undoped and doped InAs/$Al_{0.2}Ga_{0.8}Sb$ heterostructures (see Fig. 1). The results presented here were obtained by measuring these 80 μm Hall crosses.

The Hall voltage as a function of the applied magnetic field for current and voltage drive of the undoped structure A at 4.2 K are displayed in Fig. 2 and 3 respectively. The output characteristics for current drive show excellent linearity up to 0.8 T. For the voltage drive case, magnetoresistive effects are detectable in the small non-linearity of the curves. At temperatures around room temperature, these magnetoresistive effects do not appear.

We investigated the dependence of the sensitivity as a function of the applied drive current and voltage. This has been done with a fixed magnetic field.

At 4.2 K, the undoped Hall sensor exhibits high sensitivities (650 Ω/T for current drive and 3 T^{-1} for voltage drive) over a wide range of drive currents and voltages. A decrease in sensitivity can be noticed only at high currents ($I_D > 5$ mA) and voltages ($V_D > 3$ V). This decrease is caused by heat generation due to high current densities in the device. A higher operation temperature implies an increase in sheet carrier concentration and a decrease in mobility, which in return results in a drop of sensitivities. However, the results show that our Hall device can be operated over a wide range of drive currents and voltages with maximal sensitivity.

In a variety of practical low temperature laboratory applications, sufficient temperature stability of the sensitivities of the Hall sensor is required. Therefore, we investigated and compared the temperature characteristics of the three different types of InAs quantum well structures referred to as A, B and C. The two doped layers differ from the nominally undoped structure A by insertion of a low (B) and high (C) Si δ-doping in the middle of the InAs quantum well. Figs. 4 and 5 show the temperature dependence of the sensitivities for the three Hall sensors in the temperature range of 4.2 K up to 200 K. Generally, all three sensors exhibit stable temperature characteristics.

An intrinsic and undoped InAs quantum well Hall sensor gives the highest voltage and current sensitivities over the entire temperature range. But doping of the InAs quantum well can lead to improved temperature characteristics at the cost of lower current and voltage sensitivities. The temperature dependence of the sensitivities for current and voltage drive basically reflects the temperature dependence of the sheet carrier concentration and the carrier mobility in the InAs quantum well.

As the temperature goes down to 4.2 K, there is a transition from increasing sensitivities to plateaus of constant sensitivity (below 40 K). These plateaus result from the constant sheet carrier concentration and carrier mobility at low temperatures. Ionized impurity scattering becomes the dominant scattering mechanism, which gives rise to a temperature independent mobility. Besides that, the freeze-out of intrinsic carriers at low temperatures, leads to a constant extrinsic sheet carrier concentration.

Generally, interface, background and remote impurity scattering are the dominant scattering mechanisms at low temperatures for a two dimensional electron gas. At higher temperatures, phonon scattering takes over as the limiting scattering mechanism. Extrinsic doping of the InAs quantum well to a level higher than the intrinsic concentration will overweight the strong temperature dependence of intrinsic carrier generation and freeze-out. From Fig. 4 it is seen that the higher sheet carrier concentration for the extrinsically doped InAs quantum wells reduces the current sensitivity on one hand, but on the other hand improves the temperature stability significantly.

Furthermore, Si δ-doping of the InAs quantum well enhances background impurity scattering, which can decrease the mobility for high concentrations also at higher temperatures. Hence, lower voltage sensitivities can be observed in Fig. 5 for the two doped InAs quantum wells compared to the undoped structure. At the same time the temperature stability of the voltage sensitivity improves significantly.

Table 1 summarizes the results on the three types of Hall sensors. As indicated in bold in this table, the best sensor choice for a low temperature application can be as follows: For temperatures below 40 K, the undoped InAs Hall sensor is most sensitive and most temperature stable if used in voltage drive. For temperatures between 77 K and 300 K, one might prefer to use a highly doped InAs Hall sensor with a higher temperature stability in voltage drive, at the cost of a lower sensitivity (but still high enough to detect sub-Gauss changes in magnetic field with e.g. lock-in techniques). In case one intends to use the Hall sensor in applications with a magnetic field higher than about 50 mT, it is best to use the sensors in current drive, to eliminate non-linearity effects due to magneto-resistance which appear in voltage drive at higher fields and lower temperatures. If temperature stability is not the main concern, it is clear that the undoped sensor - with its highest sensitivity - is the most suitable sensor.

The input resistance of the sensors can be written as follows (with $R_{\square}$ the sheet resistance):

$$R = R_{\square}\frac{L}{W} = \frac{1}{n_s e\mu}\frac{L}{W} = \frac{S_I}{S_V}\,. \tag{5}$$

Fig. 6 displays the temperature dependence of the input resistance for all three sensors. A calculated input resistance, obtained by dividing the current sensitivity by the voltage sensitivity, agrees well with the measured resistance.

Generally, all three sensors exhibit a good temperature stability of the input resistance. This could already be expected from the stable temperature characteristics from the single sensitivities. The temperature characteristics of the undoped InAs quantum well with intrinsic conduction can be explained by an increase of the sheet carrier concentration and a decrease of the carrier mobility with increasing temperature. These two effects compensate for each other to generate a less temperature dependent resistance, especially at low temperatures ($T < 75$ K).

IV. Summary and conclusion

In summary, our results on the InAs/$Al_{0.2}Ga_{0.8}Sb$ Hall elements demonstrate the potential of this semiconductor device for a wide range of magnetic sensing applications in which the combination of high sensitivity and good temperature stability is required. Si δ-doping of the InAs quantum well results in excellent temperature stabilities of the output characteristics at reduced sensitivities.

Acknowledgements

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FIG. 1. SEM picture of a cross-shaped Hall element (80 µm wide bars).
At the ends of the cross, the contacts are shown as white stripes.

FIG. 2. Hall voltage as a function of the applied magnetic induction for current drive (for sample A: undoped InAs/$Al_{0.2}Ga_{0.8}Sb$ quantum well).

FIG. 3. Hall voltage as a function of the applied magnetic induction for voltage drive (for sample A: undoped InAs/$Al_{0.2}Ga_{0.8}Sb$ quantum well).

FIG. 4. Current sensitivity versus temperature for the three InAs/$Al_{0.2}Ga_{0.8}Sb$ sensors (at 100 mT and 1 mA drive).

FIG. 5. Voltage sensitivity versus temperature for the three InAs/$Al_{0.2}Ga_{0.8}Sb$ sensors (at 50 mT and 1 V drive).

FIG. 6. Temperature dependence of the input resistance for the undoped and doped InAs/$Al_{0.2}Ga_{0.8}Sb$ sensors

FIG. 1. J. Bekaert Review of Scientific Instruments

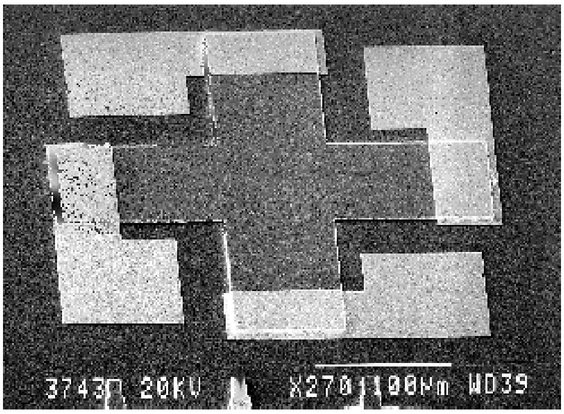
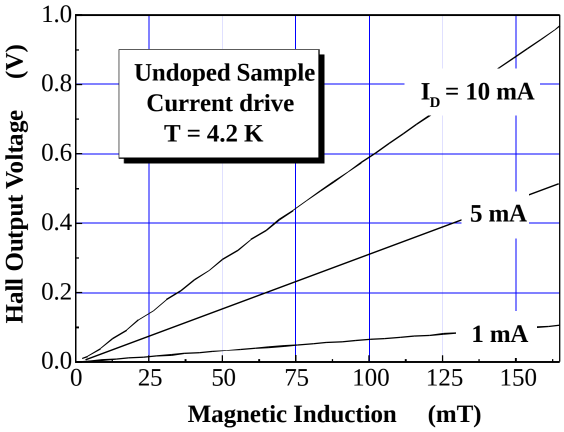


FIG. 2. J. Bekaert Review of Scientific Instruments



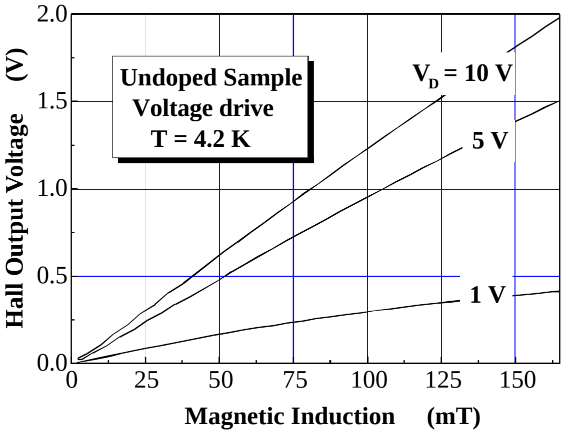
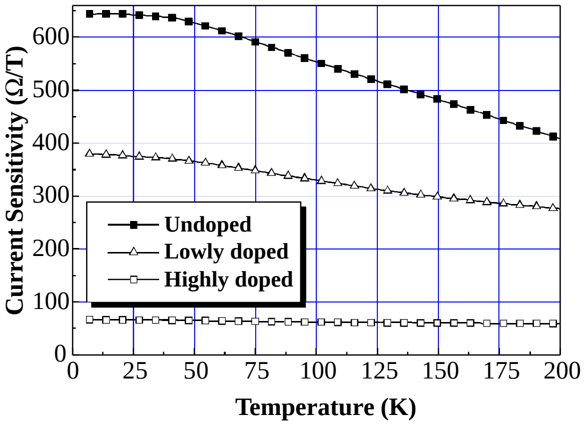

Undoped Sample
Voltage drive
T = 4.2 K
V_D = 10 V
5 V
1 V
Hall Output Voltage (V)
2.0
1.5
1.0
0.5
0.0
0
25
50
75
100
125
150
Magnetic Induction (mT)

FIG. 4. J. Bekaert Review of Scientific Instruments



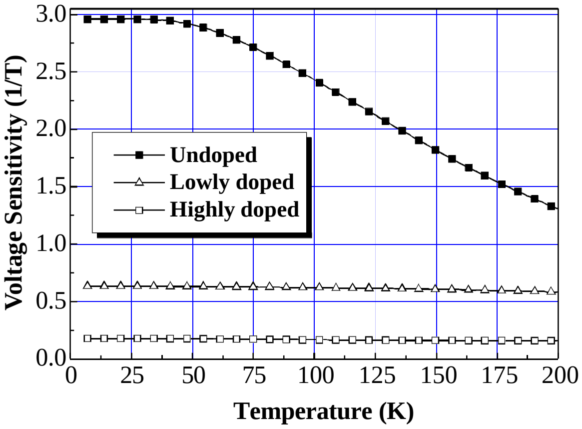

Voltage Sensitivity (1/T)
Temperature (K)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0
25
50
75
100
125
150
175
200
Undoped
Lowly doped
Highly doped

FIG. 6.

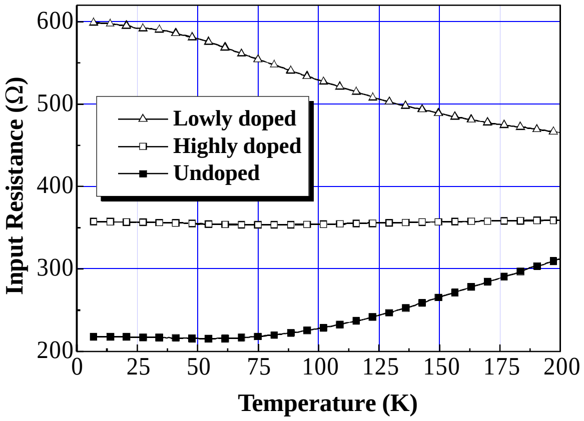

Input Resistance (Ω)
600
500
400
300
200
Lowly doped
Highly doped
Undoped
0
25
50
75
100
125
150
175
200
Temperature (K)

TABLE I. Hall data, input resistances, sensitivities at 4.2 K, 77 K and 300 K and their temperature coefficients for three types of InAs/$Al_{0.2}Ga_{0.8}Sb$ quantum well Hall sensors.

Sample		A : Undoped	B : Lowly doped	C : Highly doped
Si-δ-doping in 2DEG (cm^{-2})		none	$3x10^{12}$	$9x10^{12}$
	4.2 K	214600		
Mobility (cm^2/Vs)	77 K	193400	21960	6710
	300 K	33600	19120	6420
	4.2 K	$9.13x10^{11}$	$1.65x10^{12}$	$9.41x10^{12}$
Sheet Carrier Concentration (cm^{-2})	77 K	$1.06x10^{12}$	$1.81x10^{12}$	$9.93x10^{12}$
	300 K	$2.00x10^{12}$	$2.65x10^{12}$	$1.16x10^{13}$
	4.2 K	644	379	66.4
Current Sensitivity (Ω/T)	77 K	587	346	62.9
	300K	302	236	54
Temperature Coefficient (%/K)	4.2 K - 40 K	**-0.028**	-0.064	-0.04
	77 K - 300 K	-0.22	-0.14	**-0.063**
	4.2 K	2.96	0.633	0.18
Voltage Sensitivity (1/T)	77 K	2.68	0.626	0.171
	300K	0.9	0.514	0.162
Temperature Coefficient (%/K)	4.2 K - 40 K	**-0.011**	-0.0088	-0.031
	77 K - 300 K	-0.29	-0.08	**-0.024**
	4.2 K	218	598	357
Input Resistance (Ω) *	77 K	219	551	353
	300 K	350	457	359

* Since the ratio W/L is 1/3 for our sensors, the sheet resistance is three times smaller than the input resistance.