Investigation of semiconducting materials for magnetic field sensors in strong magnetic fields under cryogenic temperatures

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Abstract. Influence of strong magnetic fields $B > 3$ T under cryogenic temperatures ($1.5 \div 4.2$ K) on the signals of Hall sensors based on single-crystal whiskers (InSb, InAs) and nano-sized heterostructures (InSb/i-GaAs, InAs/i-GaAs) have been investigated. There are distinct Shubnikov – de Haas oscillations for whisker-based sensors, whereas heterostructures-based sensors demonstrate the linear field dependence of the output signal. This difference explained by the higher concentration of structure defects in the heterostructures. The derived results confirm the operability of Hall sensors based on indicated heterostructures for the magnetic fields diagnostics in the temperature and field conditions of modern particle accelerators and fusion reactors.

1. Introduction

Modern charged particle accelerators and plasma confinement systems of experimental fusion reactors like JET, ITER, DEMO tokamaks and W7-X stellarator, etc. as well, call for highly accurate magnetic field measurements.

Reaching this goal for such applications is complicated by the extreme operating conditions including strong magnetic fields ($1 \div 8$ T), wide temperature range ($4.2 \div 600$ K), and irradiation by fluxes of high energy neutrons, electrons and gamma quanta.

The authors have already developed the radiation resistant semiconductor materials for the magnetic field sensors, whose workability were demonstrated in the hard radiation environment of the neutron irradiation up to fluxes of $F = 10^{18}$ n·cm$^{-2}$ [1]. The studies have revealed that such indium containing III-V semiconducting compounds as indium antimonide (InSb) and indium arsenide (InAs) show great promise for application in magnetic field sensors intended for operation at high neutron fluxes. The methods for enhancing their radiation resistance including the metallurgical doping during the material growth, as well as the directed radiation modification, were studied. These methods allow
one to obtain the semiconductor materials featuring the minimal drift of the sensors characteristics during neutron irradiation, and this drift can be easily corrected by the control electronics.

However, the use of such materials for the high-precision magnetic field measurements in fusion reactors and particle accelerators establishes new requirements for the sensor materials, particularly, the linearity of output signals at the strong magnetic fields and the cryogenic temperatures as well, while maintaining the sufficient magnetic sensitivity.

It is known that the semiconductor materials with the degenerate electron gas and high mobility of charge carriers demonstrate the oscillations of various thermodynamic and kinetic coefficients (conductivity, heat capacity, Hall constant etc.) at the strong magnetic fields and low temperatures. The output signal nonlinearity due to the quantum Shubnikov – de Haas oscillations, limit the accuracy of the magnetic field measurement by the Hall effect sensors based on such materials.

This paper describes the results of the studies on quantum oscillations in indium antimonide and indium arsenide. The samples for investigation were prepared in two different forms with different degrees of structural perfection: the micro-sized monocrystalline InSb and InAs whiskers, and nanosized thin film InSb/i-GaAs and InAs/i-GaAs heterostructures. Also, the samples featured the different degrees of doping, and the corresponding charge carriers concentrations were in the range of \( n = (10^{16} \div 10^{19}) \text{ cm}^{-3} \).

2. Sample fabrication and experiment procedure

The Shubnikov – de Haas oscillations in the field dependences of Hall effect coefficient in InSb are well known [2, 3]. These studies were carried out on the bulk single crystals.

The goal of this study was to investigate such oscillations in the InAs and InSb thin films that were grown in the heterostructure composition on the semidielectric GaAs substrate to determine the materials parameters at which the quantum oscillations reduce to zero. Moreover, thus, to provide the high accuracy of magnetic field measurements with the help of sensors based on those materials.

In this work the quantum oscillations in single-crystal whiskers of InSb and InAs were studied as well to detect the influence of the structure imperfection degree on the amplitude of those oscillations.

The microcrystalline InSb and InAs whiskers were obtained by the deposition from the gas phase by the chemical transport reactions method. The whiskers were grown by free crystallization from the gas phase without any substrate influence, and, therefore, they are characterized by the perfection of the crystalline structure [3, 4]. The mechanical strength of whiskers is close to the theoretical values arising from the interatomic bonds. The formation of crystals with low defects content is also facilitated because they grow at the temperatures well below the melting point. This factor also determines the possibility of the self-cleaning process during the crystal growth. The sizes of whiskers are following: the thickness is \((10 \div 20) \mu\text{m}\), the width is \((40 \div 60) \mu\text{m}\), and the length ranges from one to a few millimeters.

The InSb and InAs whiskers under investigation were plate shaped, and grown along the \(<100>\) axis direction, with the side faces indices of \{100\} and \{110\}. The electrophysical parameters of InSb whiskers are shown in table 1, while those for InAs whiskers – in table 2. The concentration of charge carriers was targeted by the level of tin doping during whiskers growth.

| Table 1. Parameters of InSb whiskers and InSb/i-GaAs heterostructures |
|-------------------------------------------------|
| Sample No. | Structure | Concentration, \( n \) \( \text{cm}^{-3} \) | Mobility, \( \mu \) \( \text{cm}^{2}\text{V}^{-1}\text{s} \) | Resistivity, \( \rho \) \( \text{Ohm}\cdot\text{cm} \) |
| 22 | whisker | \( 2.8 \cdot 10^{17} \) | 18000 | 22 \( \cdot 10^{4} \) |
| 14 | heterostructure | \( 1.4 \cdot 10^{17} \) | 16000 | 26 \( \cdot 10^{4} \) |

Thin film heterostructures of InSb/i-GaAs and InAs/i-GaAs were obtained by molecular beam epitaxy (MBE) at the NRNU MEPHI Nanocenter and MOCVD method at the Material Research
Science and Engineering Centre of Wisconsin University. The electrophysical parameters of the InSb/i-GaAs heterostructures under study are shown in table 1, those for the InAs/i-GaAs heterostructure – in table 2.

The thickness of the InAs active layer in MOCVD method was 100 nm, and for the InSb active layer in the MBE method was about 1 μm. The thin semiconductor layers in heterostructures feature much higher defects content against almost defect free single crystal whiskers. These defects are caused by the misfit dislocations due to the mismatch of lattice parameters of the thin film and the substrate. The metamorphic buffer layers are created to minimize the defects concentration in heterostructures. In the MBE method a 60 nm In$_{1-x}$Al$_x$As metamorphic buffer layer was grown, while in the MOCVD method a low-temperature 30 nm InAs layer of was grown.

The studies on single-crystal whiskers and heterostructures were carried out at the International Laboratory of High Magnetic Fields and Low Temperatures (ILHMF&LT) in Wroclaw (Poland), using the MN-1 superconducting solenoid (Oxford Instrument), which provides the range of magnetic field induction of $B = (0.14 \div 14)$ T. The field dependences of Hall voltage $V_{H}$ were recorded at the following fixed temperatures: 1.5 K, 4.2 K, 77 K and 280 K. The B increment during $V_{H}(B)$ recording was 0.01 T. A Keithley 220 current source was used to sensors power supply, while a Keithley 2000 digital multimeter was used to measure the Hall voltage.

3. Results and discussion

Shubnikov – de Haas effect has been studied quite well both theoretically and experimentally in bulk materials. It is based on the quantization of the electron energy spectrum under the effect of magnetic field. This quantization leads to the appearance of periodic changes in the density of states with the increase in the magnetic field, and correspondingly, the oscillations are observed in both resistance and the Hall voltage field dependences.

The various scattering processes could affect the nature of these oscillations; one should note first the lattice defects, temperature and degree of material doping by impurities.

The present study considers the influence of these scattering factors on the oscillations in Hall voltage in the indium antimonide and indium arsenide samples with different degree of structural perfectness: in whiskers 22, 19, 18, 17 and heterostructures 14, 15, 27 samples (see tables 1 and 2).

Figures 1-4 show the field dependences of Hall voltage for whiskers and heterostructures with different doping content.

A comparison of field dependences for two InSb samples with different degree of crystalline structure perfectness, but with similar concentrations of carriers is shown in figure 1: an InSb whisker (sample 22, $n = 2.8 \cdot 10^{17}$ cm$^{-3}$) is compared with a heterostructure of InSb/i-GaAs (sample 14, $n = 1.7 \cdot 10^{17}$ cm$^{-3}$). At the same temperature of $T = 4.2$ K the quantum oscillations are observed in the field dependence for the whisker, but they do not appear for the heterostructure.

| Sample No. | Structure       | Concentration, $n$ (cm$^{-3}$) | Mobility, $\mu$ (cm$^2$/V·s) | Resistivity, $\rho$ (Ohm·cm) |
|------------|-----------------|-------------------------------|-------------------------------|------------------------------|
| 19         | whisker         | 5.0 $\cdot 10^{16}$           | 18000                         | 68$\cdot 10^{-4}$            |
| 18         | whisker         | 2.3 $\cdot 10^{17}$           | 17000                         | 15$\cdot 10^{-4}$            |
| 17         | whisker         | 1.7 $\cdot 10^{18}$           | 900                           | 4$\cdot 10^{-4}$             |
| 15         | MBE heterostructure | 1.4 $\cdot 10^{18}$     | 8846                          | 4.8$\cdot 10^{-4}$           |
| 27         | MOCVD heterostructure | 3.3 $\cdot 10^{18}$ | 2970                          | 15.6$\cdot 10^{-4}$          |
Field dependences for three InAs whiskers (samples 19, 18, 17) are given in figures 2 (a, b) and 3 (a). These samples have equal degrees of the structure perfection but differ in the doping level. A weakly doped sample 19 ($n = 5.0 \cdot 10^{16}$ cm$^{-3}$) shows quantum oscillations. However, with the doping level increasing up to $n = 2.3 \cdot 10^{17}$ cm$^{-3}$ (sample 18) the oscillations amplitude drops from 22% to 8%.

Figure 3 (b) shows the field dependences for the same three single-crystal whisker samples (19, 18, 17) recorded at a higher temperature of $T = 77$ K. One can see that for all whiskers, including the weakly doped sample 19, the oscillations not observed.

**Figure 1.** Field dependences of the Hall voltage:
(a) – InSb whisker (sample 22, $n = 2.8 \cdot 10^{17}$ cm$^{-3}$);
(b) – InSb/i-GaAs heterostructure (sample 14, $n = 1.7 \cdot 10^{17}$ cm$^{-3}$) at $T = 4.2$ K.

**Figure 2.** Field dependences of the Hall voltage for InAs whiskers:
(a) – sample 19, $n = 5.0 \cdot 10^{16}$ cm$^{-3}$; (b) – sample 18, $n = 2.3 \cdot 10^{17}$ cm$^{-3}$ at $T = 4.2$ K.
Figure 3. Field dependences of the Hall voltage:
(a) – InAs whisker (sample 17, \(n = 1.7 \times 10^{17} \text{ cm}^{-3}\)) at \(T = 4.2\) K;
(b) – whisker samples 19, 18 and 17 at \(T = 77\) K.

Figure 4 shows the field dependences of the Hall voltage for two thin films InAs samples being parts of InAs/i-GaAs heterostructures manufactured by different technologies, sample 27 is obtained by MOCVD technique, while sampling 15 – by the MBE. One can see that the both field dependences are quite similar. Only the slope of the lines is slightly different due to small variation in carriers concentration and thickness of the active layer in these heterostructures. However, both are free of the quantum oscillations unlike the weakly doped and more structurally perfect single crystal whiskers.

Figure 4. Field dependences of the Hall voltage for InAs/i-GaAs, obtained by two technologies: sample 15, \(n = 3.3 \times 10^{18} \text{ cm}^{-3}\), MBE method and sample 27, \(n = 1.4 \times 10^{18} \text{ cm}^{-3}\), MOCVD method.

The results of these studies reveal the effect of scattering factors like lattice distortion, doping content as well as temperature, on the oscillations in Hall voltage field dependence in samples of heterostructures and single-crystal whiskers of indium-containing semiconductor materials III-V.

These results are of great practical importance. The presence of quantum oscillations in the output signal of Hall effect magnetic field sensors considerably limits the possibilities of increasing the measurement accuracy.
4. Conclusion
Quantum oscillations of the Hall voltage specific for materials with degenerate electron gas and high carriers mobility have been studied in InSb and InAs semiconductor compounds at strong magnetic fields and cryogenic temperatures. The Shubnikov – de Haas oscillations are observed in structurally perfect single crystal whiskers with a low concentration of carriers. Their amplitude decreases with increase in doping content and carriers concentration, as well as with temperature. These oscillations are absent in thin film heterostructures of InSb/i-GaAs and InAs/i-GaAs over the whole range of concentrations and temperatures at magnetic field ±14 T. This behavior is caused by such scattering factors as structural defects due to the mismatch lattice parameters between the semiconductor material and the substrate. Hence the heterostructures of indium-containing semiconductor materials can be recommended for manufacturing the high-accuracy sensors for measurements of high magnetic fields in the wide range of temperatures, down to cryogen ones.

References
[1] Bolshakova I et al 2015 Nucl. Fusion 55 8 083006
[2] Brandt N and Chudinov S 1982 Sov. Phys. Usp. 25 518–29
[3] Bolshakova I, Moskovets T, Krukovsky S and Zayachuk D 2000 Mater. Sci. & Engin. B 69-70 441–3
[4] Bolshakova I, Koptsev P, Melnyk I, Moskovets M, Krukovsky S and Zayachuk D 2001 Cryst. Res. and Tech. 36 989–96