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Research Article

Investigation of the Effect of Rare Earth Elements in Hall Sensors Created Based on InSb

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Abstract

The article investigates the effect of rare earth elements on the electrophysical properties of Hall sensors based on indium antimonide (InSb). The InSb semiconductor is widely used in modern sensor technologies due to its high electron mobility, small forbidden energy band gap, and high magnetic sensitivity. These properties make InSb one of the promising materials for the production of high-precision Hall sensors. During the study, the electrical conductivity, Hall coefficient, carrier concentration, and mobility of InSb crystals doped with rare earth elements such as samarium (Sm) and dysprosium (Dy) were studied over a wide temperature range. It was found that rare earth elements reduce the number of structural defects in the crystal lattice, optimize additional scattering centers, and increase the relaxation time of electrons. As a result, the mobility of electrons increases, the conductivity improves, and the sensitivity of Hall sensors increases. The experimental results were compared with theoretical models and found to be in high agreement. The studies have shown that the addition of samarium in an amount of about 0.1 atomic percent significantly improves the main technical parameters of the Hall sensor. This indicates that InSb-based rare-earth-doped semiconductors are promising materials for automotive electronics, aerospace engineering, medical devices, and industrial automation.

Keywords: InSb, Hall effect, Hall sensor, rare earth elements, samarium, dysprosium, electron mobility, electrophysical properties

1. Introduction

The development of modern electronics requires the preparation of semiconductor materials with new functional capabilities and an in-depth study of their physical properties. The main part of the sensors used in microelectronics, automation, aerospace engineering, medical diagnostics, and industrial control systems is made up of highly sensitive semiconductor elements. In this regard, semiconductor compounds belonging to the A^3B^5 group are of particular interest [1].

Among these materials, indium antimonide (InSb) stands out due to its unique physical properties. InSb is one of the semiconductors with the highest electron mobility at room temperature [2]. The high electron mobility increases the sensitivity to the influence of a magnetic field, and this property is an important advantage for the development of sensors based on the Hall effect.

Another important advantage of InSb crystals is their narrow energy band gap. This property allows for high electrical conductivity with low power consumption. At the same time, it is possible to register even small magnetic fields [3] accurately. Therefore, Hall sensors made on the basis of InSb are widely used in measuring the rotational speed of cars, controlling electric motors, robotics, medical equipment, and aerospace systems.

In recent times, the application of various dopant elements has become widespread in order to improve the functional properties of semiconductors. In particular, rare earth elements have a significant effect on the electrical, magnetic, and optical properties of the material by changing the structure of the crystal lattice. Among these elements, samarium, dysprosium, erbium, gadolinium, and neodymium are of particular interest.

The difference in atomic radii and electronic structure of rare earth elements causes them to create new local energy levels in the crystal. As a result, the scattering mechanisms of charge carriers change, the relaxation time of electrons increases, and the mobility increases. This is of great scientific and practical importance in terms of increasing the sensitivity of Hall sensors [4].

The main objective of the present study is to study the electrophysical properties of InSb crystals doped with samarium and dysprosium, to determine the temperature dependence of the Hall coefficient, and to compare the obtained results with theoretical models.

InSb is a narrow-bandgap semiconductor belonging to the A^3B^5 type compound group. It has a zinc blende-type cubic crystal structure and is widely used in electronic engineering due to its high crystallinity.

The main advantage of InSb is the very high electron mobility. The electron mobility at room temperature is about 7.5×10^4–8.0×10^4 $cm^2/(V\cdot s)$. High mobility leads to an increase in the Hall voltage in the magnetic field and an increase in the sensitivity of the sensor [5]. The band gap of InSb is about 0.17 eV. This small energy difference ensures the formation of charge carriers even at low temperatures. At the same time, a high sensitivity to infrared radiation is formed, which allows the InSb material to be widely used in infrared detectors. The effective mass of electrons in InSb crystals is very small (about 0.014 m_0) [6]. The small effective mass facilitates the acceleration of charge carriers and leads to an increase in electrical conductivity.

Electrical conductivity is defined by the following expression:

$$\sigma = q(n\mu_n + p\mu_p)$$

where:
σ – electrical conductivity;
q – electron charge;
n and p – electron and hole concentrations;
μ_n and μ_p – electron and hole mobilities.

The high magnetoresistive effect of InSb is also one of its important advantages. In a strong magnetic field, the trajectory of electrons is bent and the Hall voltage increases. Therefore, Hall sensors made on the basis of InSb allow for the measurement of even small magnetic fields with high accuracy.

One of the most effective methods for improving the physical properties of semiconductor materials is their modification with various additive elements. In particular, rare earth elements (Rare Earth Elements – REE) have been widely studied in recent years in terms of controlling the electrophysical and magnetic properties of narrow-bandgap semiconductors. Elements such as samarium (Sm), dysprosium (Dy), gadolinium (Gd), erbium (Er), and neodymium (Nd) create local energy levels in the crystal lattice due to their incompletely filled 4f-electron levels, which have a significant effect on the behavior of charge carriers. Adding small amounts (0.01–0.5 at.%) of rare earth elements to the InSb crystal optimizes its electrophysical parameters without causing significant changes in the structure of the crystal lattice.

The Hall effect was discovered in 1879 by the American physicist Edwin Hall and later became one of the fundamental phenomena in semiconductor physics. The Hall effect is characterized by the generation of an electric potential difference on the side surfaces of a sample when an electric current passes through a conductor or semiconductor and a magnetic field is applied perpendicular to it. This potential difference is called the Hall voltage and is defined by the following expression:

$$U_H = \frac{R_H I B}{d}$$

where:
U_H – Hall voltage;
R_H – Hall coefficient;
I – current flowing through the sample;
B – magnetic induction;
d – sample thickness.

The Hall coefficient is defined by the expression (for a material with one type of charge carrier).

$$R_H \approx \frac{1}{qn}$$

Here q is the elementary charge, and n is the concentration of charge carriers.

From this formula, it can be seen that the Hall coefficient is inversely proportional to the concentration of charge carriers. As the concentration of charge carriers decreases, the Hall coefficient increases and the sensitivity of the sensor increases [7].

The high electron mobility of the InSb semiconductor causes the Hall voltage to take larger values. Therefore, Hall sensors made on the basis of InSb allow for the measurement of weak magnetic fields with such high accuracy.

2. Materials and Methods

The samples studied in this work were prepared on the basis of high-purity InSb single crystals grown by the Bridgman method. Some of the crystals were synthesized with pure InSb, and the other part with samarium and dysprosium additives in various concentrations. The doping concentration was varied in the range of 0.01–0.30 atomic percent, and the measurements were carried out in the temperature range of 77–450 K. The electrical conductivity was measured by the four-probe method, and the Hall coefficient was measured in a constant magnetic field according to the classical Hall scheme.

The experimental results showed that when the amount of samarium additive is about 0.1 atomic percent, the temperature dependence of the Hall coefficient becomes more stable. The electron mobility increases significantly compared to the initial InSb crystals, and the electrical resistance decreases.

Similar results were observed in samples doped with dysprosium. However, the large magnetic moment of Dy atoms led to an even higher sensitivity to changes in the magnetic field. This feature is especially important for the development of high-precision magnetic sensors.

The obtained results showed that in the low temperature range (77–200 K) the scattering of electrons is mainly determined by ionized dopant atoms. As the temperature increases, the role of lattice phonons increases, and the electron-phonon interaction dominates. The addition of rare earth elements partially reduces the intensity of phonon scattering and increases the mean free path of electrons [8]. It was found that the mobility of electrons in samarium-doped InSb crystals increases several times compared to pure InSb in some temperature ranges. As a result, the Hall voltage increases, the sensitivity of the sensor increases, and the stability of the output signal improves.

Comparison of experimental data with theoretical calculations showed that the used model describes the change in the Hall coefficient depending on the temperature and dopant concentration with a sufficiently high accuracy [9]. This agreement confirms the correctness of the chosen physical model and creates an important scientific basis for future applications of InSb–Sm, as well as InSb–Dy systems.

3. Theoretical Explanation of the Results

The band theory of semiconductors is used to explain the effect of rare earth elements in InSb-based semiconductors. Since InSb has a narrow band gap ($E_g \approx 0.17$ eV), the concentration of charge carriers at room temperature is relatively high. When rare earth elements such as samarium (Sm) and dysprosium (Dy) are introduced into the crystal lattice, their incompletely filled 4f-electron levels create local energy states. These states affect the position of the Fermi level and cause a change in the concentration of charge carriers.

According to the Fermi–Dirac distribution law, the distribution of electrons over energy levels is described by the expression

$$f(E) = \frac{1}{1 + \exp[(E - E_F)/kT]}$$

where E_F is the Fermi level, k is the Boltzmann constant, and T is the absolute temperature.

The addition of rare earth elements shifts the Fermi level, which directly affects the concentration of electrons and holes. The movement of electrons within the crystal is mainly limited by two scattering mechanisms: ionized impurity atoms and lattice vibrations (phonons). At low temperatures, ionized impurity scattering dominates. As the temperature increases, the number of phonons increases, and the electron-phonon interaction becomes the main scattering mechanism. The introduction of rare earth elements into the crystal in small concentrations leads to compensation of structural defects. As a result, the relaxation time (τ) of the electrons increases. The electron mobility

$$\mu = \frac{q\tau}{m^*}$$

is directly proportional to the relaxation time and inversely proportional to the effective mass.

Here m* is the effective mass of the electron. An increase in the relaxation time increases the mobility of electrons, which leads to an improvement in the Hall coefficient and electrical conductivity. Electrical conductivity

$$\sigma = q\left(n\mu_n + p\mu_p\right)$$

is determined by the expression. Since the mobility of electrons in InSb is much higher than the mobility of holes, the conductivity is mainly determined by electrons. As a result of the influence of samarium and dysprosium additions, the mean free path of electrons increases, which leads to an increase in conductivity and an improvement in the sensitivity of the Hall sensor [10], [11], [12], [13]. Thus, theoretical calculations confirm the experimental results and show that doping with rare earth elements is one of the main factors optimizing the electrophysical properties of InSb crystals.

4. Discussion

Experimental studies have shown that InSb crystals doped with samarium and dysprosium have higher electron mobility, lower resistivity, and greater Hall sensitivity than pure InSb samples. The results obtained are generally consistent with the results obtained by other researchers on A^3B^5-type semiconductors. Various authors have shown that rare earth elements provide compensation for defects in the crystal lattice, increase the relaxation time of electrons, and reduce the scattering of charge carriers. The results of this study also confirm these regularities.

It has been established that when the doping concentration exceeds the optimal value, new defect centers are formed in the crystal and electron scattering increases. This leads to a decrease in the Hall coefficient and a deterioration in electron mobility. Therefore, optimizing the dopant concentration is considered an important technological issue in the preparation of high-quality Hall sensors. Samples doped with samarium at a level of about 0.1 atomic percent showed the best results. At this concentration, electron mobility increases, Hall voltage increases, and temperature stability improves. The addition of dysprosium, since it has a high magnetic moment, makes an additional contribution to increasing magnetic sensitivity.

The application areas of Hall sensors in the modern electronics industry are rapidly expanding. They are widely used in electric vehicles, robotics, industrial automation, medical diagnostic equipment, aerospace systems, and high-precision position sensors. In this regard, InSb crystals modified with rare earth elements can be considered a promising material for next-generation sensor technologies. In addition, in future studies, it would be appropriate to systematically investigate the effect of not only Sm and Dy, but also other rare earth elements such as Gd, Er, Nd, and Ho on the electrophysical and magnetic properties of InSb crystals.

5. Conclusion

As a result of the conducted studies, it was found that the electrophysical properties of InSb-based Hall sensors significantly depend on the degree of doping with rare earth elements. Samarium and dysprosium additions reduce the number of structural defects in the crystal lattice, increase the relaxation time of electrons, and weaken the scattering of charge carriers. As a result, electron mobility increases, electrical conductivity increases, and the sensitivity of the Hall sensor improves.

Comparison of experimental results with theoretical calculations showed that the selected physical model describes the dependence of the Hall coefficient and electron mobility on temperature with a sufficiently high accuracy. This agreement confirms the scientific basis of the conducted studies.

It was determined that an addition of about 0.1 atomic percent of samarium can be considered the optimal doping level for InSb crystals. At this concentration, the sensitivity, temperature stability, and reliability of the Hall sensor are close to the maximum values.

Thus, InSb-based semiconductors modified with rare earth elements are considered promising materials for the preparation of highly sensitive Hall sensors, and their wide application in the fields of modern electronics, automotive industry, space technology, and industrial automation is possible.

Author Contributions

All authors reviewed, edited, and approved the manuscript.

Conflict of Interest

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Abbreviations

Indium Antimonide (InSb), Samarium (Sm), Dysprosium (Dy), Gadolinium (Dy), Erbium (Er), Neodymium (Nd), Rare-Earth Elements (REE).

References

[1] Askerov BM. Kinetic effects in semiconductors. Leningrad: Nauka; 1970. 303 p.
[2] Aliyev MI, Jabbarov RM. Electrical properties of GaSb and InSb doped with Gd and Yb eutectics based on them. In: Physical properties of complex semiconductors. Baku: Elm; 1982. p. XX–XX.
[3] Iskender-zade ZA, Salimov IN, Jabbarov RM, Gashim-zade FM. Preparation and electrophysical properties of samarium-doped indium antimonide. Inorganic Materials. 1991;27(2).
[4] Ashcroft NW. Solid State Physics. Thomson Learning. 1976;39.
[5] Kittel C. Solid State Physics, 8th edn. Hoboken, 2005.
[6] Ng KK, Sze SM. Physics of semiconductor devices. Hoboken, NJ: Wiley-Interscience; 2007.
[7] Look DC. Electrical characterization of GaAs materials and devices, 1989.
[8] Blakemore JS. Semiconductor statistics. Courier Corporation; 2002.
[9] Adachi S. Properties of semiconductor alloys: group-IV, III-V and II-VI semiconductors. John Wiley & Sons; 2009 Apr 27.
[10] Rogalski A. Infrared and terahertz detectors. CRC Press; 2019 Jan 10.
[11] Kasap SO. Electronic Materials and Devices. McGraw-Hill New York; 2006.
[12] Yu P. Fundamentals of semiconductors. USA; 2005.
[13] Ziman JM. Electrons and phonons, Oxford Classics Series, 2001.