Article ID: 1000-7032(2018)05-0687-05

Highly-sensitive Sb-based Quantum-well 2DEG-Hall Device

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Abstract: The highly sensitive Hall device made of InAs/AlSb quantum-well structures pseudomorphically grown on the GaAs substrate by molecular beam epitaxy has been developed. The advanced InAs/AlSb Hall device includes double δ-doped layers, which significantly elevate the sheet electron density. Moreover, electron mobility is increased from 15 000 $cm^2 \cdot V^{-1} \cdot s^{-1}$ to 16 000 $cm^2 \cdot V^{-1} \cdot s^{-1}$ at room temperature, compared with that of an unintentionally doped AlSb/InAs Hall device. AFM measurement results show a smooth surface morphology and high crystalline quality of the samples. The quantum Hall device can be operated in the temperature ranging from 77 K to 300 K. Hall measurements show different scattering mechanism on electron mobility at temperature range. The advanced highly-sensitive InAs/AlSb heterostructure two-dimensional electron gases (2DEG) Hall device including double δ-doped layers is promising in near future.

Key words: Hall device; quantum well; double δ-doping; molecular beam epitaxy

CLC number: TN305; TN382 **Document code**: A **DOI**: 10.3788/fgxb20183905.0687

高灵敏度 Sb 基量子阱 2DEG 的霍尔器件

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摘要: 用分子束外延技术将高灵敏度的 InAs/AlSb 量子阱结构的 Hall 器件赝配生长在 GaAs 衬底上。设计了由双 δ 掺杂构成的 Hall 器件的新结构,有效地提高了器件的面电子浓度。与传统的没有掺杂的 InAs/AlSb 量子阱结构的 Hall 器件相比,室温下器件电子迁移率从 15 000 $cm^2 \cdot V^{-1} \cdot s^{-1}$ 提高到 16 000 $cm^2 \cdot V^{-1} \cdot s^{-1}$。AFM 测试表明材料有好的表面形态和结晶质量。从 77 K 到 300 K 对 Hall 器件进行霍尔测试,结果显示器件不同温度范围有不同散射机构。双 δ 掺杂结构形成高灵敏度、高二维电子气(2DEG)浓度的 InAs/AlSb 异质结 Hall 器件具有广阔的应用前景。

关 键 词: 霍尔器件; 量子阱; 双 δ 掺杂; 分子束外延

1 Introduction

The 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

收稿日期: 2017-11-05; **修订日期**: 2018-01-13

基金项目: 国家自然科学基金青年基金项目(51302215); 陕西省教育厅科研计划(17JK0698); 陕西省科技厅专项基金(2016KRM029)资助项目

Supported by National Natural Science Foundation of China(51302215); Scientific Research Program Funded by Shaanxi Provincial Education Department(17JK0698); The Science and Technology Project of Shaanxi Province(2016KRM029)

temperature stability. The use of two-dimensional electron gases (2DEG) already demonstrated to give the best compromise between high mobility and high carrier concentration while maintaining a reasonably high sheet resistance[1].

The criterion for a good material Hall magnetic sensors is a low carrier concentration and a high carrier mobility which is difficult to meet[2]. As a small band gap means a high intrinsic carrier density, InSb(E_g = 0.18 eV) and InAs(E_g = 0.36 eV) bulk crystals do not meet the criterion, especially above room temperature, although they have high carrier mobility. The majority of Hall magnetic sensors are made of Si and GaAs during the past decades. Their stability at high temperature and the possibility of using mature technology outweigh the drawback of small carrier mobility. As the epitaxy technology developed, InSb and InAs thin films were considered to produce Hall elements and the researchers made great progress[3-5]. The electrical and magnetic field characteristics of InSb thin films show a great difference from the bulk crystal. InAs films are a kind of promising material for magnetic sensors because of their larger band gap than InSb and higher electron mobility than GaAs[6-9].

In this paper, we report on a comparative study on the sensing performance and temperature stability of undoped and double δ-doped InAs/AlSb quantum well structures for the application in Hall sensors by MBE technology. Moreover, the influence of the measurement temperature on the sheet electron density and electron mobility is investigated.

2 Experiments

The Hall devices were grown on semi-insulating GaAs substrates by molecular beam epitaxy MBE. Nucleation layers of GaAs were firstly grown to ensure good starting conditions for the subsequent deposition of buffer layers of approximately 700 nm thickness. The standard buffer layer stack consists of AlGaSb that was followed by 50 nm AlSb. The buffer section was finished by growing a short-period smoothing superlattice. Finally, the InAs/AlSb quantum well structure was grown. The wafer was capped with dual layers of InAlAs and InAs, which placed the top of the InAs quantum well channel. The heterointerface was forced to be InSb like by using an appropriate shutter switching sequence. Hall mobilities and carrier concentrations were determined using van der Pauw method.

Two different layer samples were grown and processed. The schematic structures of two samples are shown in Fig. 1. Sample Ⅰ is a conventionally undoped quantum well structure with an InAs quantum well thickness of 15 nm. Sample Ⅱ consists of double δ doping. The first Si δ-doped layer is in-between undoped AlSb barrier and supply layers, which was grown after a lattice matched undoped 700 nm AlGaSb buffer layer. 15 nm InAs channel was grown as same as that of Sample Ⅰ, then highly tensile and undoped AlSb spacer with thickness of 5 nm was grown, followed by the second Si δ-doped layer. Wet chemical etching techniques were used for mesa isolation[10-11]. Afterwards, Ohmic contacts were made using Ti/Pt/Au metal. Fig. 1 shows the cross sections of the sample Ⅰ and sample Ⅱ.

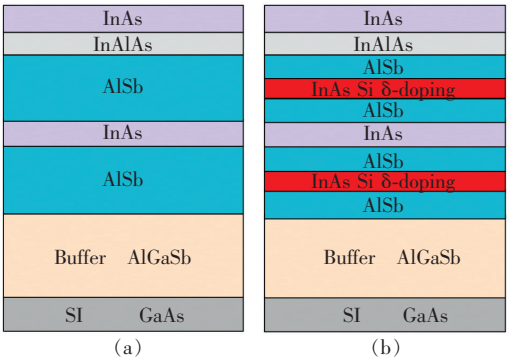

Fig. 1 Schematic structure of Hall devices epitaxial layers. (a) Sample Ⅰ, unintentionally doped. (b) Sample Ⅱ, double δ-doped.

3 Results and Discussion

Two types of Hall devices were tested, shown in Tab. 1. Sample Ⅰ represents a conventional Sb-based Hall device, and it is being used as reference in this study. Sample Ⅱ with the double δ-doped AlSb/InAs quantum well exhibits higher electron mobility and higher electron density. As the table shows, the room-temperature sensitivity of 96 mV · mA^{-1} · kG^{-1} · kΩ^{-1} was achieved for the Hall devices based on the

double Si-δ doped AlSb/InAs quantum well structure sample. The high mobility of the double δ-doped AlSb/InAs quantum well structure is advantageous to the high sensitivity for Hall devices. The higher sheet carrier concentration can improve the operation sensitivity. Thus, the double δ-doped AlSb/InAs quantum well structure for a Hall device is designed with the goal of improving its sensitivity.

To check the dominant scattering mechanism in determining the electron mobility in 2DEG layer, Hall measurements were performed from 77 K to 300 K on two samples. Electron mobility with high electron sheet density of 15 000 $cm^2 \cdot V^{-1} \cdot s^{-1}$ with $4.52 \times 10^{11}/cm^2$, and 16 000 $cm^2 \cdot V^{-1} \cdot s^{-1}$ with $7.71 \times 10^{12}/cm^2$ were achieved from epitaxial structure sample Ⅰ and Ⅱ at room temperature, respectively, employing van der Pauw Hall measurement. The measured results of samples Ⅰ and Ⅱ are listed in Tab. 1. Fig. 2 shows the measured electron mobilities from 77 K to 300 K as a function of different measurement temperatures. As can be seen from Fig. 2, two distinct temperature dependences of electron mobility can be observed. From 300 K to 175 K, the electron mobilities *vs.* temperature for sample Ⅰ and Ⅱ shows identical variation trend and the acoustic phonon scattering is the dominant scattering, which results in all of them in $T^{-3/2}$ temperature dependence[12]. This also agrees very well with earlier reports from other researchers. However, in the temperature lower than about 175 K, the variation trends split and show obvious difference. At low temperature, the phonon scattering is weakened because of the weak vibration of atoms, thus the dominant scattering mechanism is the ionized impurity scattering, which shows the electron mobility will be only related to N^{-1} doping concentration.

Tab. 1　Characteristics of two samples of Hall devices

Sample	Mobility/ ($cm^2 \cdot V^{-1} \cdot s^{-1}$)	Sheet density/ cm^{-2}	Input resistance/ Ω	Output resistance/ Ω	Sensitivity/ ($mV \cdot mA^{-1} \cdot kG^{-1} \cdot k\Omega^{-1}$)
Ⅰ	15 000	4.52×10^{11}	505	509	48
Ⅱ	16 000	7.71×10^{12}	215	217	96

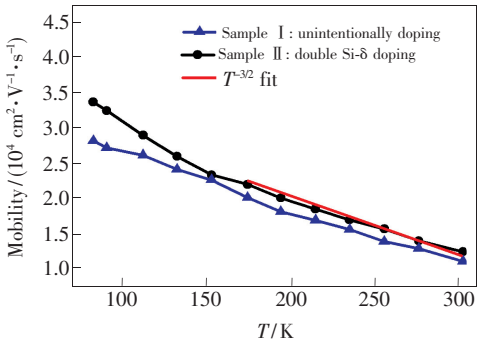

Fig. 2　Electron mobility *vs.* temperature for sample Ⅰ and sample Ⅱ

In Fig. 3, the sheet electron densities of these two samples are shown with measurement temperature from 300 K to 77 K. As can be seen from this figure, the sheet electron density keeps almost constant for the samples in different temperatures and becomes less temperature dependent, which indicates that high mobility two-dimensional electron gas does not consist of intrinsic electron generated in the channel by thermal-excitation. Otherwise, a sharp decrease of electron concentrations will be observed at 77 K as a result of the fact that most intrinsic electron is unionized at such low temperature range. Inserting double Si δ-doping on both sides of the quantum well, the sheet electron density up to $7.71 \times 10^{12}/cm^2$ has been obtained.

The 5 μm × 5 μm AFM micrographs of sample

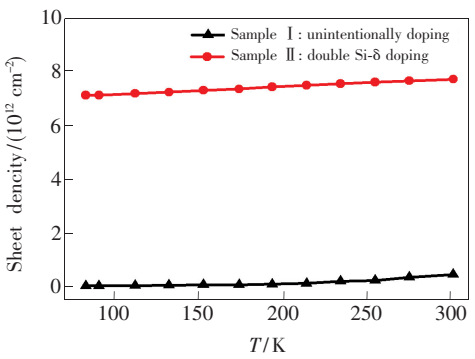

Fig. 3　Sheet electron density *vs.* temperature for sample Ⅰ and sample Ⅱ

Ⅱ are showed in Fig. 4. The surface root-mean-square roughness and peak-to-valley height are 0.73 nm and 10.2 nm respectively, indicating a smooth surface morphology. As can be seen from Fig. 4, mounds with spiral steps but without obvious anisotropy were found on the surface. Besides, surface cracks are one of the critical reasons of carrier mobility reduction.

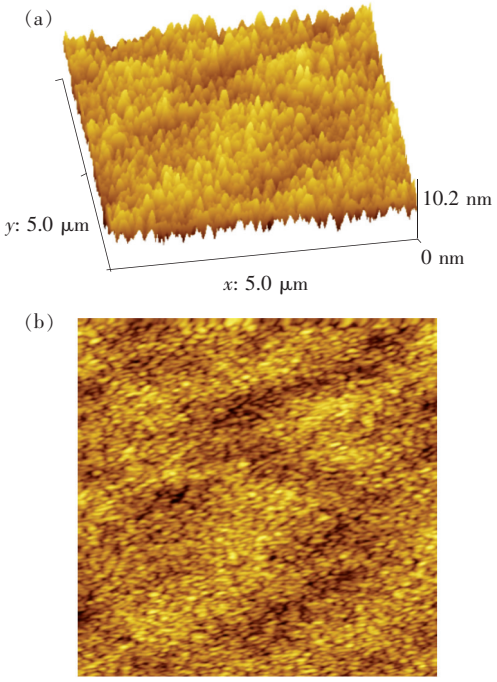

Fig. 4 5 μm × 5 μm AFM micrograph of sample Ⅱ. (a) Three-dimensional. (b) Two-dimensional.

4 Conclusion

In conclusion, two different InAs/AlSb heterostructure 2DEG-Hall devices with different doping concentrations were grown and characterized. Van der Pauw measurements show electron concentrations as high as $7.71 \times 10^{12}/cm^2$ at room temperature. AFM measurement results show a smooth surface morphology and high crystalline quality of all the samples. Hall measurement shows that the electron mobility is limited by phonon scattering from 175 K to 300 K but is determined by the ionized impurity scattering below 175 K. The sheet electron density is almost independent with temperature from 77 K to 300 K. Moreover, further optimization of the double δ-doped AlSb/InAs quantum well structures growth should lead to an even better micro-Hall devices performance.

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