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2007 Semicond. Sci. Technol. 22 870

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Demonstration of Rashba spin splitting in an $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ heterostructure by microwave-modulated Shubnikov–de Haas oscillations

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Received 30 November 2006, in final form 28 May 2007

Published 29 June 2007

Online at stacks.iop.org/SST/22/870

Abstract

We report zero-field spin splitting using both conventional and microwave-modulated Shubnikov–de Haas (SdH) oscillations in an $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ heterostructure. By studying the apparent beating pattern in SdH oscillations, we are able to measure the spin splitting parameter α . In addition, the persistent photoconductivity effect allows us to increase the carrier concentration in our AlGaIn/GaN two-dimensional electron system and vary α . With our microwave-modulation technique, we suggest that a sizeable Rashba type of spin splitting is present in AlGaIn/GaN heterostructures.

1. Introduction

AlGaIn/GaN heterostructures have been widely studied for their applications in high-voltage and high-temperature microwave devices [1, 2]. Since the performance of these devices is based on the transport properties of two-dimensional electron gas (2DEG), the electronic properties of 2DEG at AlGaIn/GaN interface have been extensively investigated [3–5]. Recently, there has been growing interest in spin splitting because the control of spin dynamics in electronic materials can lead to conceptually novel devices. Nowadays, several popular methods have been developed to probe the Rashba spin splitting in GaN-based heterostructures. One is the circular photogalvanic effect (CPGE) [6, 7]. In CPGE theory, the direction and magnitude of the photocurrent depend on the incident circular polarization light and the degree of inversion asymmetry. Experimentally, the spin orientation induced current, which can prove the Rashba spin splitting in AlGaIn/GaN heterostructures has been demonstrated in inter-subband [6] and inter-band [8, 9] absorption. The second method used to study spin splitting is the low magnetic field magneto-conductivity measurement [10]. The weak anti-localization experiment usually detects spin–orbit coupling for the 2DEG with a low carrier density

[10]. The other method suitable for high carrier density is based on the beating pattern of the Shubnikov–de Haas (SdH) oscillations [11, 12]. However, according to early experimental work, the SdH technique is not suitable for the measurement at high temperature or in samples with low mobility because of the large Landau level broadening in SdH oscillations. In addition, due to the poor crystalline quality of nitride semiconductors compared with GaAs materials at the present stage, it is not easy to obtain a pronounced beating pattern as those shown in the $\text{InGaAs}/\text{InAlAs}$ system [13]. Therefore, in order to reveal a unified picture of spin splitting in AlGaIn/GaN heterostructures, we employ a *microwave-modulated* technique for obtaining pronounced beating patterns in the SdH oscillations.

In this paper, we show that the microwave-modulated technique can be used to observe clear beating patterns in AlGaIn/GaN heterostructures without changing the carrier concentration. Using this method, one is able to study the spin splitting effect in AlGaIn/GaN heterostructures. A similar technique has been used to investigate the two-subband populated AlGaIn/GaN heterostructures recently [14]. Moreover, we also demonstrate that the beating pattern is sensitive to the blue light radiation. Our results suggest that the photo-excited electrons and ion vacancies are spatially

separated after the blue light illumination, which causes a persistent current. With this persistent photoconductivity effect, the internal electric field changes and leads to a different zero-field spin splitting parameter α . According to the pronounced beating patterns based on the microwave technique, the zero-field spin splitting in AlGaN/GaN can be observed.

2. Experiments

The sample used in this study is a modulation-doped $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ heterostructure, which is grown by metalorganic chemical vapour deposition on a c -plane (0001) Al_2O_3 substrate. The structure consists of a 1 μm thick undoped GaN layer and a 10 nm undoped AlGaN spacer with a thin 20 nm Si-doping $n\text{-Al}_{0.25}\text{Ga}_{0.75}\text{N}$ barrier. The Si-doping concentration is $8 \times 10^{17} \text{ cm}^{-3}$. The dimensions of the sample are about 5 mm $\times$ 5 mm. Ohmic contacts are made by In deposition and the annealing temperature is at 600 K. The experiments were performed in a liquid helium cryostat equipped with a superconducting magnet of a maximum field of 6 T. The microwave was generated by a Gigatronics GT 9000S microwave sweeper which is modulated by a function generator. No special cavity or waveguide system is demanded; only a microwave coaxial cable is needed for transmitting the radiation. The sample is placed near the transmitter head of the microwave coaxial cable and the oscillatory magnetoresistance is measured by a lock-in amplifier with the reference frequency provided by the function generator modulating the microwave sweeper. Figure 1 shows the simple geometry of the microwave-modulated experiment. The electric signal we measured is in phase with the function generator and the modulated wave shape is also shown in the inset of figure 1.

3. Results and discussions

Let us now turn our attention to our main results. Figure 2(a) shows the conventional four-terminal magnetoresistance measurements R_{xx} as a function of the perpendicular magnetic field at $T = 3.3 \text{ K}$. In these measurements, the beating patterns cannot be seen clearly. Even after subtracting the background as shown in figure 2(b), the beating pattern can only be barely resolved. Note that only one node appears at about $B = 5.5 \text{ T}$ and the noise level in the low field regime does not allow us to see any other nodes ($B < 3.3 \text{ T}$). Therefore, we cannot determine reliably the spin-up and spin-down carrier concentrations in the Fourier transformation (FFT) spectrum because at least two nodes are needed in the FFT analysis. This is ascribed to the fact that the nonoscillatory background remains large in the detected signal, and the mobility of the AlGaN/GaN heterostructure is much smaller than that of the GaAs-based systems with a similar structure. In contrast, the microwave-modulated SdH measurement at the same temperature $T = 3.3 \text{ K}$ is shown in figure 3(a). Better resolved beating patterns can be seen in figure 3(b) and this allows one to obtain two closed oscillating frequencies by the FFT analysis. Since the nonoscillatory background is suppressed, these SdH signals can be obtained more obviously. In order to have a clear physical picture here,

Figure 1. A schematic diagram showing the simple geometry of the microwave-modulated experiment. The inset below is the shape of the modulated microwave.

we provide a brief description for the microwave-modulation technique. We emphasize that the intensity of the chopped microwave is a function of time and the measured signal can be separated into the background and oscillatory part. The background part is not sensitive to the temperature, and remains approximately the same during illumination. However, during the microwave pulse, the free carriers near the Fermi level absorb the incident radiation and become hot carriers. After the end of the pulse, the carriers and the lattice have equal temperature. In the microwave-modulation process, the background signal will be subtracted by the lock-in amplifier when the signal is modulated by the chopped microwave. After subtracting the temperature-independent background signal, the experimental technique can directly detect the oscillatory part. Thus, the observed oscillatory SdH pattern is enhanced and the pronounced beating pattern is observed. Moreover, both conventional and microwave-modulated SdH oscillations give the same carrier concentration indicating that there are no excess carriers generated by microwave radiation. It is not surprising because the photon energy of microwave ($\sim 0.01 \text{ meV}$) is much smaller than the band gap of GaN (3.4 eV). In addition, because the carrier concentration determined from the period of the SdH oscillations is consistent with the measurement from the Hall effect, we conclude that the behaviour of the two frequencies in the SdH oscillations is due to the spin splitting of one subband. With the cautious FFT analysis, no other oscillation mode occurred in our FFT diagram; the magneto-intersubband scattering due to the occupation of two subbands [15] does not need to be taken into account in our work.

As pointed out by Bychkov and Rashba [16], the spin-orbit Hamiltonian due to inversion asymmetry of a gyrotropic

Figure 2. (a) Conventional Shubnikov–de Hass oscillations on the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ heterostructure at $T = 3.3$ K. (b) The curve obtained by subtracting the background at $T = 3.3$ K.

material in the first order has the form $\mathbf{H} = \alpha_{\text{so}}(\boldsymbol{\sigma} \times \mathbf{k}) \cdot \mathbf{z}$, where α_{so} is a spin–orbit coupling parameter, $\boldsymbol{\sigma}$ is the vector of Pauli matrices, $\mathbf{k}$ is the in-plane wave vector and $\mathbf{z}$ is the unit vector along the growth direction. One can transform the Hamiltonian into $\mathbf{H} = \alpha_{\text{so}}(\mathbf{k} \times \mathbf{z}) \cdot \boldsymbol{\sigma}$ and interpret that the effective magnetic field B_{so} proportional to α_{so} exists in the inversion asymmetric materials. Consequently, this Hamiltonian gives the underlying physics for the beating pattern of the SdH oscillations at a low magnetic field in the studied AlGaIn/GaN heterostructure. In order to investigate the zero-field spin splitting in our AlGaIn/GaN system, we calculate the parameter α which governs spin precession. By calculating the total value n and the difference Δn ($n_+ - n_-$) of the carrier concentration, we can determine the value of α using the following equation [11]:

$$n_{\pm} = \frac{n}{2} \left[1 + \frac{2m^*\alpha}{\hbar^2 k_F} \right], \quad (1)$$

where k_F and m^* are the Fermi wave number and the effective mass of the electron confined in the triangular well, respectively. A value of $0.215m_0$ for m^* is used in our calculation. With our results of n and Δn , the spin–orbit interaction parameter $\alpha = 2.57 \times 10^{-12}$ eV m is obtained. The α value has the same order of magnitude as other III–V semiconductors, such as 3.0×10^{-12} eV m and 6.3×10^{-12} eV m for InGaAs/InAlAs heterostructures [13]. Theoretically, the large spin–orbit parameter α resulting from a strong spin splitting effect is expected to occur only in narrow-gap materials [17]. However, in the AlGaIn/GaN system, a large piezoelectric effect and strong polarization may

Figure 3. The microwave-modulated longitudinal magnetoresistivity as a function of the magnetic field is shown in (a). The pronounced beating curve is obtained by subtracting the background at $T = 3.3$ K. The frequency of the microwave is 2 GHz.

introduce a strong electric field [18]. With the internal electric field perpendicular to the heterojunction, sizable spin–orbit interaction can be obtained [19, 20]. Indeed, we obtain the built-in internal electric field taking place in the AlGaIn/GaN triangular quantum well. The typical value in our result is 1.0 MV cm^{-1} which is in excellent agreement with theoretical and experimental reports [21].

In order to get further insight into the spin splitting mechanism, we perform microwave-modulated SdH oscillations after brief light illumination. In our case, a blue light was shined upon the surface of our sample through the optical window of our cryostat. After illumination, the optical window was blocked. We note that the photon energy of our blue light is ~ 2.9 eV which is lower than the bandgap of GaN (3.42 eV). Therefore, we believe the optical-excited carriers are probably from the defects in our sample. After illumination, the photo-excited electrons from nitrogen vacancies or other defects [22] have enough energy to overcome the binding, and the vacancies would still stay in both GaN and AlGaIn layers. With this effect, the electrons will be confined in the triangular well and the carrier concentration is expected to be increased. As shown in figure 4, the beating nodes shift after illumination and the different FFT values indicate different carrier concentrations. In our results, the carrier concentration *only* increases 1.6%. It is not surprising because the increase results from defects and impurities rather than the band-to-band transition. After separating the excess electrons and vacancies

Figure 4. Inverse magnetic field ($1/B$) dependence of magnetoresistivity R_{xx} at the temperature $T = 3.3$ K before and after illumination. The arrows indicate the position of beating nodes and the insets show the corresponding FFT spectra of our data.

spatially, the internal electric field changes. Because the induced field could be parallel or antiparallel to the intrinsic field formed by piezoelectric polarization effects at the heterojunction originally, the internal electric field could be expected to increase or decrease. In our results, after illumination, the carrier concentration increases from $8.81 \times 10^{12} \text{ cm}^{-2}$ to $8.95 \times 10^{12} \text{ cm}^{-2}$ but the spin–orbit interaction parameter α decreases from $2.57 \times 10^{-12} \text{ eV m}$ to $2.02 \times 10^{-12} \text{ eV m}$. This phenomenon could be explained by the reason that the thickness of the GaN layer is $1 \mu\text{m}$ which is much thicker than that of the AlGa N layer (20 nm); the major contribution is from the GaN side. Since the GaN layer is the primary contributor, the field induced by illumination is opposite to the field formed by piezoelectric polarization effects. Besides, the underlying crystalline structure cannot be changed with illumination; we thus conclude that the beating nodes which shift in our data are most likely due to the variation of built-in electric field.

In addition, the spin splitting energy can be calculated by the following equation: $E_{\uparrow} - E_{\downarrow} = \frac{2\pi\hbar^2\Delta n}{m^*}$. The obtained spin splitting energies are 3.82 meV before illumination and 3.03 meV after illumination. With the increasing carrier concentration, the spin splitting energy decreases. If we attribute the spin splitting to the bulk inversion asymmetry called the Dresselhaus term, we have the relation $\Delta_{\text{spin}} \propto \gamma k^3$, where γ is the bulk material coefficient. With the increasing Fermi wave vector k , the spin splitting energy should become larger which is not observed in our results. Thus, the Dresselhaus term may not be the predominant mechanism. The reason for the reduction spin splitting could be the suppression of α resulting from the reduction built-in electric field. We therefore conclude that the suitable model for spin splitting in the AlGa N/GaN heterostructures is the structure inversion asymmetry called Rashba term.

4. Summary

In summary, we have investigated zero-field spin splitting in an $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ heterostructure using the microwave-modulation technique to enhance the beating patterns in SdH

oscillations. With pronounced beating patterns, we are able to determine the spin–orbit parameter α . In addition, we can vary the internal electric field after brief blue light radiation which results in a different α value. We suggest that the zero-field spin splitting effect is due to a sizeable Rashba type of spin splitting. In view of a wide range of applications in nitride semiconductors such as spintronics, our microwave technique shown here should be very useful.

Acknowledgment

This work was supported by the National Science Council and the Ministry of Education, Republic of China. One of the authors (CTL) thanks Dr Chun Feng Huang at NML, ITRI, Taiwan, for helpful discussions.

References

- [1] Yoshida S, Ishii H, Li J, Wang D and Ichikawa M 2003 A high-power AlGa N/GaN heterojunction field-effect transistor *Solid State Electron.* **47** 589–92
- [2] Chumbes E M, Smart J A, Prunty T and Shealy J R 2001 Microwave performance of AlGa N/GaN metal insulator semiconductor field effect transistors on sapphire substrates *IEEE Trans. Electron Devices* **48** 416–9
- [3] Kwack H S *et al* 2005 Optical properties and carrier dynamics of two-dimensional electrons in AlGa N/GaN single heterostructures *Appl. Phys. Lett.* **87** 041909
- [4] Lin D Y, Huang Y S, Chen Y F and Tiong K K 1998 Contactless electroreflectance and piezorefectance of a two-dimensional electron gas at a Ga N/AlGaN heterointerface *Solid State Commun.* **107** 533–6
- [5] Juang J R, Huang T Y, Chen T M, Lin M G, Kim G H, Lee Y, Liang C T, Hang D R, Chen Y F and Chyi J I 2003 Transport in a gated $\text{Al}_{0.18}\text{Ga}_{0.82}\text{N}/\text{GaN}$ electron system *J. Appl. Phys.* **94** 3181–4
- [6] Weber W, Ganichev S D, Danilov S N, Weiss D, Prettl W, Kvon Z D, Bel'kov V V, Golub L E, Cho H I and Lee J H 2005 Demonstration of Rashba spin splitting in Ga N -based heterostructures *Appl. Phys. Lett.* **87** 262106
- [7] Ganichev S D and Prettl W 2003 Spin photocurrents in quantum wells *J. Phys. Condens. Matter* **15** R935–83
- [8] Cho K S, Liang C-T, Chen Y F, Tang Y Q and Shen B 2007 Spin-dependent photocurrent induced by Rashba-type spin splitting in $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ heterostructures *Phys. Rev. B* **75** 085327
- [9] Cho K S, Chen Y F, Tang Y Q and Shen B 2007 Photogalvanic effects for interband absorption in AlGa N/GaN superlattices *Appl. Phys. Lett.* **90** 041909
- [10] Schmult S, Manfra M J, Punnoose A, Sergeant A M, Baldwin K W and Molnar R J 2006 Large Bychkov–Rashba spin-orbit coupling in high-mobility Ga $\text{N}/\text{Al}_x\text{Ga}_{1-x}\text{N}$ heterostructures *Phys. Rev. B* **74** 033302
- [11] Tsubaki K, Maeda N, Saitoh T and Kobayashi N 2002 Spin splitting in modulation-doped AlGa N/GaN two-dimensional electron gas *Appl. Phys. Lett.* **80** 3126–8
- [12] Lo I *et al* 2002 Spin splitting in modulation-doped $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ heterostructures *Phys. Rev. B* **65** 161306
- [13] Yang C L, He H T, Ding L, Cui L J, Zeng Y P, Wang J N and Ge W K 2006 Spectral dependence of spin photocurrent and current-induced spin polarization in an InGaAs/InAlAs two-dimensional electron gas *Phys. Rev. Lett.* **96** 186605
- [14] Hang D R, Huang C F and Chen Y F 2006 Two-subband-populated AlGa N/GaN heterostructures probed by electrically detected and microwave-modulated magnetotransport measurements *Appl. Phys. Lett.* **89** 092116

-
- [15] Tang N *et al* 2003 Magnetoresistance oscillations induced by intersubband scattering of two-dimensional electron gas in $\text{Al}_{0.22}\text{Ga}_{0.78}\text{N}/\text{GaN}$ heterostructures *J. Appl. Phys.* **94** 5420–2
- [16] Bychkov Y A and Rashba E I 1984 Oscillatory effects and the magnetic susceptibility of carriers in inversion layers *J. Phys.C: Solid State Phys.* **17** 6039–45
- [17] Das B, Miller D C, Datta S, Reifenberger R, Hong W P, Bhattacharya P K, Singh J and Jaffe M 1989 Evidence for spin splitting in $\text{In}_x\text{Ga}_{1-x}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ heterostructures as $B \rightarrow 0$ *Phys. Rev. B* **39** 1411–4
- [18] Ridley B K 2000 Polarization-induced electron populations *Appl. Phys. Lett.* **77** 990–2
- [19] Winkler R 2000 Rashba spin splitting in two-dimensional electron and hole systems *Phys. Rev. B* **62** 4245–8
- [20] de Andrada e Silva E A, La Rocca G C and Bassani F 1994 Spin-split subbands and magneto-oscillations in III–V asymmetric heterostructures *Phys. Rev. B* **50** 8523–33
- [21] Grandjean N, Massies J and Leroux M 1999 Self-limitation of AlGaIn/GaN quantumwell energy by built-in polarization field *Appl. Phys. Lett.* **74** 2361–3
- [22] Limpijumnong S and Van de Walle C G 2004 Diffusivity of native defects in GaN *Phys. Rev. B* **69** 035207