Rashba Spin-Splitting and Spin Currents in GaN Heterojunctions

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ABSTRACT

The circular photogalvanic effect, spin-galvanic effect and magneto-gyrotropic effect have been observed in hexagonal (0001)-oriented GaN low-dimensional structures excited by infrared and terahertz radiation. Experimental and theoretical analysis exhibits that the observed photocurrents are related to the gyrotropy of the GaN based heterojunctions and give evidence for a substantial structural inversion asymmetry caused by the built-in electric fields at the AlGaN/GaN interface.

INTRODUCTION

Gallium nitride is a potentially interesting material system for spintronics since long spin relaxation times are detected in this material [1] and it is expected to become ferromagnetic with a Curie-temperature above room temperature if doped with manganese [2]. Recently we observed that in GaN heterojunctions also a substantial Rashba spin-splitting in the electron band structure is present, allowing spin manipulation by an electric field [3]. The Rashba spin-splitting due to structural inversion asymmetry, which is not expected in wide-band semiconductors, is caused in GaN heterostructures by a large piezoelectric effect which yields a strong electric field at the AlGaN/GaN interface and a strong polarization induced doping effect. In [4,5] it was shown by magneto-transport measurements that this splitting is comparable to that of GaAs heterostructures being of the order of 0.3 meV at the Fermi energy. Here we report on an investigation of the circular photogalvanic effect (CPGE) caused by the Rashba spin-splitting [6] and on the observation of the spin-galvanic effect (SGE) [6] and magneto-gyrotropic photogalvanic effect (MGPGE) [7-9] in this material. All these effects have been detected in (0001)-oriented GaN heterostructures in a wide range of temperatures from technologically important room temperature to 4.2 K. The CPGE results in a spin polarized electric current and is caused by selective photoexcitation of carriers in *k*-space with circularly polarized light due to optical selection rules. The microscopic origin of the spin-galvanic effect is the inherent asymmetry of spin-flip scattering of electrons in systems with removed *k*-space spin degeneracy of the band structure. The magneto-gyrotropic photogalvanic effect so far was demonstrated in GaAs, InAs, and SiGe QWs where its microscopic origin is a zero-bias spin separation [8,9]. Zero-bias spin separation is caused by spin-dependent scattering of electrons due to a term in the scattering matrix elements linear in wavevector k and generates a pure spin current which can be converted in an electric current by the application of a magnetic field.

SAMPLES AND EXPERIMENTAL METHODS

The experiments are carried out on $Al_{0.3}Ga_{0.7}N/GaN$ heterojunctions grown by MOCVD on a C(0001)-plane sapphire substrate. The thickness of the AlGaN layers was varied between 30 nm and 100 nm. An undoped 33 nm thick GaN buffer layer, which was grown under a pressure of 40 Pa at 550°C, is followed by an undoped GaN layer (~ 2.5 µm), grown under a pressure of 40 Pa at 1025°C. The undoped $Al_{0.3}Ga_{0.7}N$ barrier was grown at 6.7 Pa and a temperature of 1035°C. The electron mobility in the 2DEG was typically about 1200 cm^2/Vs at electron density $n_s = (1\text{-}1.4)\cdot 10^{13}$ cm^{-2} at room temperature. To measure the photocurrent two pairs of ohmic contacts have been centred along opposite sample edges (see insets in Fig. 1).

The experiments were carried out in two different spectral ranges: the mid-infrared (MIR) regime with wavelength between 9.2 µm and 10.8 µm and the terahertz (THz) regime at 77 µm, 90.5 µm, 148 µm, 280 µm and 496 µm. The latter wavelengths were achieved by an optically pumped molecular NH_3 laser [6] while a pulsed TEA CO_2 laser and a commercial Q-switched CO_2 laser with a peak power of about 1 kW were employed in the MIR-regime. While the THz radiation causes indirect Drude-like optical transitions in the lowest subband of the 2DEG, the MIR radiation can additionally induce direct optical transitions between the subbands. To obtain circularly polarized radiation needed for CPGE the laser light was passed through a Fresnel rhombus or quartz $\lambda/4$ plates for MIR and THz radiation, respectively. The helicity $P_{circ} = \sin 2\varphi$ of the incident light was varied from $P_{circ} = -1$ (left handed circular, σ_-) to $P_{circ} = +1$ (right handed circular, σ_+). Here φ is the angle between the initial polarization plane and the optical axis of the $\lambda/4$ plate or the Fresnel rhombus. The current j generated by the circularly polarized light in the unbiased samples was measured at room and liquid nitrogen temperatures via the voltage drop across a 50 Ω load resistor in a closed circuit configuration. The voltage was recorded with a storage oscilloscope. In experiments on SGE and MGPE an external magnetic field with a maximum strength of $B = 0.6$ T is applied parallel to the heterojunction interface. In these experiments the samples are irradiated under normal incidence. Magnetic field induced photocurrents are investigated applying both circular polarized and linear polarized radiation. In the latter case the angle α between the polarization plane of the light and the x axis is varied (see inset in the upper panel of Fig. 2).

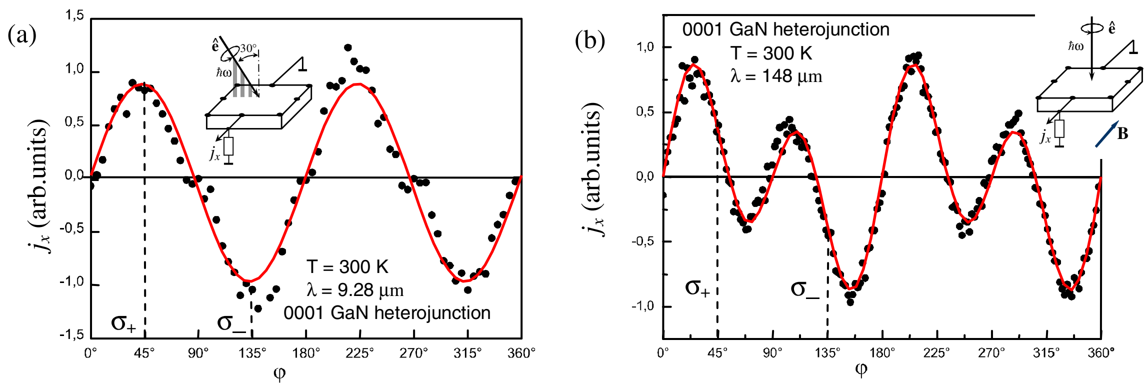

Fig. 1. Photocurrent as a function of the phase angle φ defining helicity measured in GaN heterojunction at: (a) oblique incidence and zero magnetic field and (b) in the presence of the external magnetic field at normal incidence in the direction parallel to magnetic field. Full lines are fitted using one ordinate scaling parameter according to Eq. (1) (Fig. 1a) and Eq. (4) (Fig. 1b). The insets show the experimental geometry.

RESULTS AND DISCUSSION

Irradiating the (0001) AlGaN/GaN heterojunction by circularly polarized light without magnetic field and at oblique incidence, as sketched in the inset of Fig. 1a, causes a photocurrent signal measured across a contact pair. The measured current follows the temporal structure of the applied 40 ns laser pulses and reverses its direction by switching the sign of the radiation helicity (see Fig. 1a). The fact that the current is proportional to the radiation helicity proves the circular photogalvanic effect as origin of the photocurrent. The signal proportional to the helicity is only observed under oblique incidence. The current vanishes for normal incidence and changes its polarity upon variation of the angle of incidence. The photocurrent in the layer flows always perpendicularly to the direction of the incident light propagation and its magnitude does not change by rotating the sample around the growth axis. All characteristic features persist from 77 to 300 K. The observed photocurrents have the same order of magnitude as those measured in GaAs, InAs, and SiGe QWs [6]. The effect is observed for all wavelengths used between 9 μm and 496 μm. Data in Fig. 1a shows the effect for a wavelength of 10.6 μm using a Q-switched CO_2 laser. While the overall signature is the same the strength of the photocurrent depends on the wavelength. The spectral dependence of the CPGE in the THz range (λ ≥ 77 μm) agrees with the expected behaviour of the CPGE for indirect (Drude-like) transitions. The resonance-like increase of the signal at short wavelengths is obtained with the CO_2 laser (9.2-10.8 μm) and attributed to resonant direct intersubband optical transitions. In addition to the CPGE current detected in the direction normal to the in-plane wave vector of radiation a signal is also observed along the in-plane propagation direction. This signal has equal magnitude and the same sign for right- and left-handed circularly polarized radiation and is ascribed to the linear photogalvanic effect and the photon drag effect [6].

The dependence of the CPGE photocurrent on helicity and angle of incidence can be described by phenomenological theory [6,7] adapted to wurtzite-type low-dimensional systems of C_{3v} symmetry yielding

$$\mathbf{j} = P_{circ}\hat{\boldsymbol{\gamma}}\hat{\mathbf{e}}_{\parallel}\,. \qquad (1)$$

Here $\mathbf{j}$ is the net current density, P_{circ}, I and $\hat{\mathbf{e}}_{\|}$ are the degree of circular polarization, radiation intensity and the projection onto the QW plane of the unit-vector $\hat{\mathbf{e}}$ pointing in the direction of light propagation, respectively. The second-rank pseudotensor $\hat{\gamma}$ is proportional to the spin-orbit splitting α. It has two nonzero components and is described by one linearly-independent constant:

$$\gamma_{xy} = -\gamma_{yx}, \quad \gamma_{ii} = 0 \tag{2}$$

Equations (1), (2) fully describe the experimental observations of CPGE. Corresponding calculations are shown as solid line in Fig. 1a. In contrast to zinc-blende structure based systems like GaAs QWs the CPGE in wurtzite based systems (with the hexagonal *c*-axis normal to the QW) should be independent of the in-plane propagation direction $\hat{\mathbf{e}}_{\|}$. This prediction of the phenomenological theory is observed in experiment as discussed above.

At normal incidence of elliptically polarized radiation the CPGE vanishes and irradiation of the samples at $\mathbf{B} = 0$ does not lead to any current. A photocurrent response is obtained, however, when $\mathbf{B}$ is applied. The polarity of this current changes upon reversal of the magnetic field direction as well as upon changing the helicity from right- to left-handed, like it was observed for CPGE. The overall magnetic field and polarization dependences of the photocurrent remain the same, independent of temperature and wavelength. Typical helicity dependence of this current measured in the direction parallel to the magnetic field is shown in Fig. 1b demonstrating more complicated behaviour of the photocurrent compared to that of CPGE. The current j as a function of radiation helicity can be well fitted by $j_x = AB_x \sin 4\varphi + CB_x \sin 2\varphi$ (see Fig. 1b). This behaviour of the magnetic field induced photocurrent follows from the phenomenological theory which yields

$$j_\alpha = I \sum_{\beta\gamma\delta} \phi_{\alpha\beta\delta\gamma} B_\beta \left(e_\gamma e_\delta^* + e_\delta e_\gamma^* \right) + I \sum_{\beta\gamma} \mu_{\alpha\beta\gamma} B_\beta \hat{e}_\gamma P_{circ} \, . \tag{3}$$

Here ϕ is the fourth-rank tensor symmetric in the last two indices, μ is the third-rank tensor and $\mathbf{e}$ is the light polarization vector. The effect described by the tensor ϕ is independent of the sign of circular polarization and may be nonzero even for unpolarized radiation. It is usually measured under linearly polarized photoexcitation.

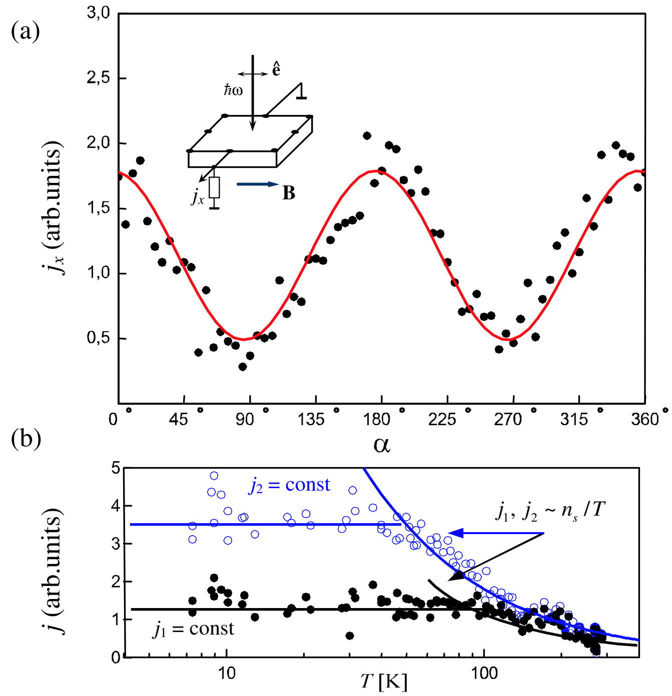

Fig. 2. (a) Magnetic field induced photocurrent as a function of the azimuth angle α measured at room temperature in transversal geometry. Full line is fitted according to Eq. (4) using one ordinate scaling parameter. (b) Temperature dependence of the polarization dependent (j_1) and polarization independent (j_2) contributions to the total current, respectively. Full lines show fits at low temperatures to a constant and at high temperatures to n_s/T. The inset sketches the experimental geometry.

For normal light incidence and C_{3v} point group relevant to our measurements Eq. (3) reduces to

$$j_x = IS_1 B_y - IS_2 B_x \left(e_x e_y^* + e_y e_x^*\right) + IS_2 B_y \left(\left|e_x\right|^2 - \left|e_y\right|^2\right) + I\mu B_x P_{circ},$$

$$j_y = -IS_1 B_x + IS_2 B_y \left(e_x e_y^* + e_y e_x^*\right) + IS_2 B_x \left(\left|e_x\right|^2 - \left|e_y\right|^2\right) + I\mu B_y P_{circ}. \quad (4)$$

Here three linearly independent constants are introduced $S_2 = \phi_{xxxy}$, $S_1 = S_2 + \phi_{xyyy}$, and $\mu = \mu_{xxz}$. For elliptically polarized light $\left|e_x\right|^2 - \left|e_y\right|^2 = (1 + \cos 4\varphi)$, $e_x e_y^* + e_y e_x^* = (\sin 4\varphi)/2$, and $P_{circ} = \sin 2\varphi$. From Eq. (4) it follows that in the geometry shown in Fig. 1b with **j** parallel **B** the photocurrent j_x is given by $j_x = IS_2 B_x \sin 4\varphi + I\mu B_x \sin 2\varphi$. Fig. 1b shows that this dependence fully describes experimental observations. It is seen that the photocurrent determined by the coefficient μ requires circularly polarized radiation which yields spin orientation of carriers. Microscopically this photocurrent contribution in quantum wells is caused by the spin-galvanic effect [11]. The effect is due to the optical orientation of carriers, subsequent Larmor precession of the oriented electronic spins and asymmetric spin relaxation processes (for details see [6,11]). The photocurrent described by the coefficient S_2, as well as by S_1, is caused by the magneto-gyrotropic photogalvanic effect [7-9]. Figure 1b shows that in GaN heterojunctions under investigation the MGPGE and spin-galvanic current contributions have comparable strengths.

As it follows from the Eq. (4) the MGPGE current can be generated also applying linearly polarized radiation. For linearly polarized light $|e_x|^2 - |e_y|^2 = \cos 2\alpha$, $e_x e_y^* + e_y e_x^* = \sin 2\alpha$, where α is the azimuth angle between the plane of linear polarization and *x* axis. Note, that the terms determined by the constant μ being proportional to the helicity P_{circ} vanish for linear polarization. This photocurrent can be present in direction parallel (longitudinal geometry) as well as perpendicular (transversal geometry) to magnetic field **B**. The dependence of the MGPGE photocurrent on the azimuth angle for transversal geometry is given in Fig. 2a demonstrating that the current follows to $j_x = j_1 \cos 2\alpha + j_2$. This Fig. 2a demonstrates a good agreement with theory and shows an essential contribution of the polarization independent first term on the right hand side of the Eq. (4) corresponding to the j_2.

The microscopic mechanism which describes the MGPGE in low dimensional structures has been suggested most recently to describe magneto-gyrotropic photogalvanic effect in GaAs, InAs and SiGe structures [8,9]. It has been shown that free carrier absorption of terahertz (THz) radiation results in a pure spin current and correspondent spin separation achieved by spin-dependent scattering of electrons in gyrotropic media. The pure spin current in this experiments was converted into an electric current by application of a magnetic field which polarizes spins due to Zeeman effect. The key experiment proving this microscopic mechanism is investigation of the temperature dependence of the photocurrent: the photocurrent due to zero-bias spin separation should be constant at low temperatures and behave as a n_s / T at high temperatures. Figure 2b shows the temperature dependence of j_1 and j_2 contributions can be well fitted by constant for low temperature range and n_s / T for high temperatures. This agreement demonstrates the applicability of the discussed model for MGPGE photocurrent observed in GaN heterojunctions. We note, however, that the influence of the magnetic field on electron scattering may also result in a photocurrent yielding an additional contribution to the MGPGE [12]. Since the microscopic origin of both contributions is different the relative role of them can be clarified by additional experiments, e.g. by the variation of *g*-factor.

CONCLUSIONS

In summary, we demonstrated that the presence of a substantial structural inversion asymmetry in GaN low dimensional structures give a root to a number of photocurrents like CPGE, spin-galvanic effect and magneto-gyrotropic photogalvanic effect. These effects have been proved in the past to be an effective tool for investigation of non-equilibrium processes, in-plane symmetry and inversion asymmetry of heterostructures, electron momentum and spin relaxation etc. and, therefore, may be used for investigation of this new and attractive for spintronics material.

ACKNOWLEDGMENTS

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