Quantum ratchet effects induced by terahertz radiation in GaN-based two-dimensional structures

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(Rceived 30 March 2008; revised manuscript received 6 May 2008; published 4 June 2008)

Photogalvanic effects are observed and investigated in wurzite (0001)-oriented GaN/AlGaN low-dimensional structures excited by terahertz radiation. The structures are shown to represent linear quantum ratchets. Experimental and theoretical analysis exhibits that the observed photocurrents are related to the lack of an inversion center in the GaN-based heterojunctions.

DOI: 10.1103/PhysRevB.77.245304 PACS number(s): 73.21.Fg, 78.67.De, 73.63.Hs

I. INTRODUCTION

In recent years, physics of quantum ratchets draw a growing attention. In mechanics, a ratchet is a device that is used to restrict motion in one direction while permitting it in another. In general, one means by a ratchet any sort of asymmetric potential or a potential lacking a center of the spatial inversion. At the turn of 1980s and 1990s, it was understood that unbiased nonequilibrium noncentrosymmetric systems can generate transport of particles, and this conception has roots in different fields of physics, chemistry, and biology. In mechanical, electronic, optical, and biological systems, a particle, classical, or quantum, charged or neutral, propagating in a periodic potential with broken centrosymmetry and subjected to an ac force exhibits a net dc macroscopic flow. Examples are electrons in solids, Abrikosov vortices in superconductors, and biological motor proteins. One of implementations of the ratchet phenomenon is a linear photogalvanic effect (LPGE). It represents a generation of a dc electric current under absorption of linearly polarized light in unbiased crystals of piezoelectric classes. Glass et al. were the first to attribute a photoinduced current observed in ferroelectric LiNbO3 to a novel photogalvanic effect and proposed the first correct model for its microscopic qualitative interpretation. A consistent quantitative theory of LPGE was developed by Belinicher and Sturman followed by other theorists (see Refs. 3 and 4).

Noncentrosymmetric bulk semiconductors and heterostructures are natural quantum ratchets and the further studies of LPGE in these systems allow one to elucidate the whole problem of the ratchet effect. In particular, a current of the LPGE consists of two contributions, ballistic and shift, which as a rule are comparable in the order of magnitude. It is important to note that similar two contributions to the electric current, called the skew-scattering and side-jump currents, do exist in the anomalous Hall effect (see the recent review by Sinitsyn). Another important point is that one should include into the light absorption process contributing to the ballistic current an additional simultaneous scattering from a static defect or a phonon compared to the light-induced optical transition, leading to the shift current. In GaN-based structures first observation of LPGE has been reported quite recently. Here, we present results of detailed experimental and theoretical investigation of LPGE in heterostructures based on GaN and its alloys with AlN. The commercial fabrication of blue and green light-emitting diodes have led to well established technological procedures of epitaxial preparation of these heterostructures and initiated a great activity on investigations of their properties. The photogalvanics serves as a solid bridge between transport and optics and, therefore, reveals both transport and optical properties of the systems under study.

II. SAMPLES AND EXPERIMENTAL METHODS

The experiments are carried out on (0001)-oriented wurzite n-GaN/Al0.3Ga0.7N heterojunctions grown by metal-organic chemical vapor deposition on C-plane sapphire substrates (for details of growth, see Ref. 7). The thickness of the AlGaN layers was varied between 30 and 100 nm. An undoped 33 nm thick GaN buffer layer grown under a pressure of 40 Pa at a temperature of 550 °C is followed by an undoped GaN layer (~2.5 μm) grown under 40 Pa at 1025 °C; the undoped Al0.3Ga0.7N barrier was grown under 6.7 Pa at 1035 °C. The mobility and density in the two-dimensional (2D) electron gas measured at room temperature are μ ≈ 1200 cm2/Vs and N_e ≈ 10^{13} cm^{-2}, respectively. To measure the photocurrent two pairs of contacts are centered at opposite sample edges with the connecting lines along the axes x||[1\bar{1}00] and y||[1\bar{1}20] (see inset in Fig. 1). The current generated by the light in the unbiased samples is measured via the voltage drop across a 50 Ω load resistor in a closed-circuit configuration. The voltage is recorded with a storage oscilloscope.

The photocurrents were induced by indirect intrasubband (Drude-type) optical transitions in the lowest size-quantized subband. The emission from a terahertz molecular laser optically pumped by a transversely excited atmospheric pressure (TEA) CO2 laser is used for the optical excitation.
orthogonal component in the 180° covering all possible orientations of the electric field
incidence geometries was applied with the angle of incidence which enabled us to vary the azimuth angle in the active media.14
tum selection rules for the pump and the terahertz transitions

\( J_{\text{incidence}} \) in the Fig. 1

Optically pumped molecular lasers emit linearly polarized radiation with the polarization plane determined by that of the pump light: the electric field vector of the terahertz radiation \( E \), generated by the molecular laser can be either parallel (like for the lines \( \lambda = 90.5, 148, \) and \( 280 \mu m \)) or orthogonal (lines \( \lambda = 77, 385, \) and \( 496 \mu m \)) to the polarization vector of the pump beam depending on the angular momentum selection rules for the pump and the terahertz transitions in the active media.14

In the experiments, the plane of polarization of the radiation incident on the sample was rotated applying \( \lambda / 2 \) plates, which enabled us to vary the azimuth angle \( \alpha \) from 0° to 180° covering all possible orientations of the electric field component in the \( (xy) \) plane. Hereafter, the angle \( \alpha = 0 \) is chosen in such a way that the incident light polarization is directed along the \( y \) direction [see inset in Fig. 1(b)].

To investigate the photogalvanic effects, we also use elliptically polarized light. In this case, the polarization of the laser beam is modified from linear to elliptical by means of crystal quartz \( \lambda / 4 \) plates. The counterclockwise rotation (viewing from the laser side) of the optical axis of the quarter-wave plate by the angle \( \varphi_p \) results in the variation of

the radiation helicity as \( P_{\text{circ}} = - \sin 2\varphi_p \). Here, the angle \( \varphi_p = 0 \) is chosen for the position of the quarter-wave plate optical axis coinciding with the incoming laser polarization, in which case, the linear polarization degree is given by fourth harmonics of \( \varphi_p \).

A series of measurements is carried out by making use of the frequency tunability and short pulse duration of the free electron laser “FELIX” at FOM-Rijnhuizen in the Netherlands operated in the spectral range between 70 and 120 \( \mu m \).15 The output pulses of light from the FELIX were chosen to be \( \approx 6 \) ps long, separated by 40 ns in a train (or “macropulse”) of 7 \( \mu s \) duration. The macropulses had a repetition rate of 5 Hz.

III. EXPERIMENTAL RESULTS

Irradiating the (0001)-grown GaN/AlGaN heterojunction by polarized light at oblique incidence, as sketched in the inset to Fig. 1(a), causes a photocurrent signal measured across a contact pair. The width of the photocurrent pulses is about 100 ns, which corresponds to the terahertz laser pulse duration. The signal depends on the light polarization, and all characteristic polarization properties persist from 4.2 to 300 K. The experimental data presented below are obtained at room temperature. The effect is observed for all the wavelengths applied (between 77 and 496 \( \mu m \)). We use two geometries: the longitudinal geometry \( J_x \) in the Fig. 1, in which the photocurrent is measured in the direction along in-plane component \( \hat{E}_x \) and the transverse geometry \( J_y \) in the Fig. 1, where the signal is detected in the direction normal to the light propagation unit vector \( \hat{E} \) [see the inset in Fig. 1(a)].

Figure 1 shows the dependence of the photocurrent on the azimuth angle \( \alpha \) for both experimental geometries obtained
FIG. 3. Spectral dependence of the transverse photocurrent $J_y$ measured at room temperature at oblique incidence ($\theta_0=15^\circ$) for azimuth angle $\alpha=135^\circ$. The data are obtained with the free electron laser FELIX (dots) and with molecular optically pumped laser (triangles). The full line shows fit to Eq. (1). The fit is obtained using $\tau_0$ as an adjustable parameter and a scaling the whole dependence by the ordinate. The dashed line shows $J_y \propto \omega^{-2}$ for comparison.

at the positive incidence angle $\theta_0=15^\circ$ and $\hat{e}_y\parallel \hat{x}$. The polarization dependence of the current in the longitudinal geometry is well fitted by $J_\parallel = J_\parallel(1-\cos 2\alpha) + J_{\text{offset}}$, while for the transverse geometry, we have $J_\perp = -J_\perp \sin 2\alpha$. Note that the offset contribution $J_{\text{offset}}$ is observed in the longitudinal geometry only. Below, in Sec. IV B, we will demonstrate that exactly these dependences follow from the theory. As a function of the incidence angle, the photocurrent changes sign at $\theta_0=0$. This is demonstrated in Fig. 2, which shows the dependence $J_y(\theta_0)$ for the fixed azimuth angle $\alpha=45^\circ$. A similar dependence is also detected for the longitudinal current $J_\parallel$. We note that, like the polarization dependent contribution to the photocurrent, the detected offset current in the longitudinal geometry $J_{\text{offset}}$ inverts its direction when the incidence angle changes its sign.

The wavelength dependence of the photocurrent obtained in transverse geometry at azimuth angle $\alpha=135^\circ$ and angle of incidence $\theta_0=15^\circ$ is shown in Fig. 3. The data are measured both on FELIX (dots) and on molecular laser (triangles). Fitting the data to the well known spectral behavior of the Drude absorption,

$$J_y(\omega) \propto \eta(\omega) \propto \frac{1}{1 + (\omega\tau_p)^2}, \quad (1)$$

we obtain that the spectral behavior of the photocurrent can reasonably be described by this equation (see full line in Fig. 3). For the fit we used $\tau_p$ as an adjustable parameter and scaled the whole dependence by the ordinate. Analyzing this dependence, we obtained that the momentum relaxation time controlling absorption is about 0.05 ps. This value is twice shorter than the transport time ($\tau_0=0.1$ ps) extracted from the mobility measurements at room temperature. We attribute the shortening of the momentum relaxation time by electron gas heating due to absorption of the intense terahertz radiation. The reduction in the mobility due to heating stems from enhancement of scattering by phonons under increase of temperature. Using short 6 ps pulses of FELIX, we observed that the response time is determined by the time resolution of our setup but it is at most 100 ps or shorter (see the inset in the left upper corner of Fig. 3). This fast response is typical for photogalvanics where the signal decay time is expected to be of the order of the momentum relaxation time, being in our samples at room temperature of the order of 0.1 ps.

In addition to the signal excited by the radiation at oblique incidence, we also detected a small photocurrent at normal incidence. The polarization behavior of this signal is shown in Fig. 4. In this setup, photocurrent dependences can be well fitted by $J_y = J_\parallel \sin 2\alpha$ and $J_\perp = J_\perp \cos 2\alpha$ (see also Sec. IV A). Rotating the sample around $z$ axis, we proved that the current direction is solely determined by the orientation of radiation electric field relative to the in-plane crystallographic axes. We note that this contribution is about 1 order of magnitude smaller than that at oblique incidence even at small angles $\theta_0=15^\circ$.

Besides investigations of photocurrent in response to linearly polarized radiation, we also performed measurements under excitation with elliptically polarized light. Such experiments are of particular interest because such radiation, in partially circularly polarized light, has previously been used for investigation of the circular photogalvanic effect (CPGE), which coexist with the LPGE yielding beatings in $\phi_{\psi}$ dependence. The CPGE is characterized by a photocurrent whose direction is changed upon reversal of the radiation helicity. It has been observed in GaN-based structures demonstrating a substantial structural inversion asymmetry (SIA) in this wide band gap material. We have shown...
FIG. 5. Photocurrent as a function of angle \( \varphi_p \) measured at oblique incidence (\( \theta = 15^\circ \)) in the longitudinal [J1] in (a) and (c)] and transverse [J1 in (b) and (d)] geometries at wavelength \( \lambda = 148 \mu m \) and power \( P = 5 \) kW. The ellipticity of the radiation is varied by passing linearly polarized laser radiation (\( E_p \)) through a quarter-wave plate (see insets in the left and right panels). The left panels show transverse and longitudinal photocurrents measured in experimental setup with \( E_p \) perpendicular to the incidence plane (s polarization at \( \varphi_p = 0 \), see inset in the left panel). Photocurrents obtained for \( E_p \) parallel to the incidence plane (p polarization at \( \varphi_p = 0 \), see inset in the right panel) are shown in the right panel. The full lines are fits of the photocurrent to Eqs. (9) and (10) obtained correspondingly in the experimental setup sketched in the inset in the left and right panels. The fits are obtained using the same values of \( J_0 \) and \( J_{\text{offset}} \), as in the experiments with linearly polarized radiation. The inset in the left panels shows the experimental geometry. On top the polarization, ellipses corresponding to various phase angles \( \varphi_p \) are plotted viewing from the source of radiation.

![Figure 5](image_url)

helicity of the beam at the sample. In order to check how this transformation influence results, we provided an additional experiment using laser beam with again \( \lambda = 148 \mu m \) and \( \theta = 15^\circ \) but for \( E_p \) parallel to the incidence plane (p polarization at \( \varphi_p = 0 \)). Figures 5(c) and 5(d) show the data obtained in this geometry. In contrast to the results presented in Figs. 5(a) and 5(b), the photocurrent now shows another type of polarization dependences: \( J_x = J_0 (3 + \cos 4 \varphi_p)/2 + J_{\text{offset}} \) and for transverse geometry \( J_y = J_0 \sin 4 \varphi_p/2 + J_2 \sin 2 \varphi_p \). The fact that contribution given by \( J_2 \) did not change is not surprising because this term is due to radiation helicity which does not change: \( P_{\text{circ}} = -\sin 2 \varphi_p \). The changes in contribution induced by the degree of linear polarization are caused by the fact that the orientation of corresponding ellipses at the sample at a given \( \varphi_p \) is different.

The photocurrent polarization properties revealed experimentally both under normal and oblique incidences are explained in Sec. IV, where we propose a simple illustrative model to interpret the nature of the photocurrent under study and derive general phenomenological equations. The measured wavelength and temperature dependences of the LPGE current are described in Sec. V where a microscopic theory is developed.

IV. MODELS, PHENOMENOLOGY, AND POLARIZATION DEPENDENCES OF THE PHOTOCURRENTS

The appearance of the LPGE can be visualized by a simple one-dimensional model of randomly distributed but identically oriented wedges acting as asymmetric scattering centers. This model showing the generation of a galvanic current is relevant for 2D GaN/AlGaN structures excited by the radiation at normal incidence. In Fig. 6 a wedge with a base oriented along x direction is depicted which obviously does not possess a center of inversion. In equilibrium the velocities of electrons are isotropically distributed. Application of an external in-plane alternating field \( E(t) = E \sin \omega t \) adds an oscillatory motion along the electric field to the random thermal motion of the electrons. If the field points along the height of the wedges (\( E \parallel y \) or \( \alpha = 0 \)), then the scattering results in a carrier flow in the (\( -y \)) direction, yielding an electric current \( j_x > 0 \) shown by the up arrow in Fig. 6(a). By that electron fluxes along the x direction compensate each other and \( j_x \) is absent. A variation of the
relative direction between the electric field and the orientation of the wedges changes the direction of the carrier flow resulting in a characteristic polarization dependence. It may, e.g., reverse its direction, as it is shown in Fig. 6(b) for the field oriented along the base of the wedges, or rotate by 90° in the case of $\mathbf{E}$ directed at 45° to $y$ axis.

In order to describe the observed polarization and angle of incidence dependences, we derive here phenomenological equations for the photocurrents in 2D GaN-based structures and give a model for LPGE. The linear photogalvanic current density $j$ is phenomenologically described by the following expression:

$$j_{\lambda}^{\text{LPGE}} = \sum_{\mu \nu} \chi_{\lambda \mu \nu} (E_\mu E'_\nu + E'_\mu E_\nu),$$

where $E$ is the electric field amplitude of the light wave and $\chi$ is the third-rank tensor symmetric in the last two indices. The index $\lambda$ enumerates two in-plane coordinates $x$ and $y$, while $\mu$ and $\nu$ run over all three Cartesian coordinates.

The LPGE is allowed only in piezoelectric crystal classes of noncentrosymmetric media where nonzero components of the tensor $\chi$ do exist. The point symmetry of wurtzite 2D electron systems confined in the [001] direction is $C_{3v}$, which differs from the $C_{6v}$ symmetry of the bulk GaN due to the absence of translation along the growth axis $z$, i.e., because of the presence of interfaces. The coordinate frame $x,y,z$ chosen in the experimental setup means that the plane $(yz)\parallel(1\bar{1}00)$ coincides with the mirror-reflection planes $\sigma_v$ contained in the $C_{3v}$ point group. In this point group, the tensor $\chi$ has two linearly independent components for $\lambda \neq z$,

$$\chi = \chi_{xxz} = \chi_{yyz}, \quad \chi' = \chi_{xzy} = \chi_{yzy} = -\chi_{xyy}.$$  

This means that the phenomenological equation (2) reduces to

$$j_{\lambda}^{\text{LPGE}} = \chi'(E_x E'_y + E'_x E_y),$$

$$j_{\lambda}^{\text{LPGE}} = \chi'(E_x E'_y + E'_x E_y),$$

(4)

where $\{E_\mu E'_\nu\} = E_\mu E'_\nu + E'_\mu E_\nu$.

**A. Normal incidence**

In our experiments, a linear photogalvanic current is observed at normal incidence (see Fig. 4). It follows from Eqs. (4) that while at normal incidence the photocurrent proportional to the constant $\chi$ vanishes because $E_x=0$, the contribution determined by the constant $\chi'$ is nonzero. The observation of this photocurrent is an important result demonstrating substantial difference in symmetry between wurtzite 2D GaN(0001)-based structures with $C_{3v}$ symmetry and zinc-blende GaAs- and InAs-based heterostructures having $C_{2v}$ or $D_{2h}$ symmetry, where the LPGE is forbidden at normal light incidence.

The polarization dependences for normal incidence follow from Eqs. (4) and are given by

$$j_\lambda = \chi'(t_0 E_0)^2 \sin 2\alpha,$$

(5)

where $t_0 = 2/(n_0 + 1)$ is the amplitude transmission coefficient for normal incidence and $n_0$ is the refractive index of the medium (for GaN, $n_0 = 2.3$). Both polarization dependences well describe our experimental data with one fitting parameter $\chi'$ (see the solid lines in Fig. 4). This agreement clearly demonstrates the generation of LPGE current at normal incidence. We emphasize that the current direction depends on the orientation of the polarization plane with respect to the crystallographic axes $x$ and $y$. In the case that contacts are arbitrary oriented relative to the crystallographic directions, Eq. (5) holds but the phase shift appears. This is considered in Appendix A.

**B. Oblique incidence**

**1. Linear polarization**

Linear photogalvanic effect is also observed at oblique incidence. Moreover, comparison of Figs. 1 and 4 shows that even at a small incidence angle $\theta_b$, the photocurrent is substantially (by the order of magnitude) larger than that at normal incidence. While at normal incidence the photogalvanic current is solely described by the constant $\chi'$ at oblique incidence, another term in Eq. (4) shows up. This term is determined by the second linearly independent constant $\chi$. The polarization dependence of this contribution in the geometry relevant to the experiment depicted in Fig. 1, where the incidence plane is chosen to be the plane $(xz)$ and the angle $\alpha$ is counted from $y$, is given by

$$j_\lambda(\alpha) = \chi' \epsilon_0^2 t_\rho \sin \theta \sin(1 - \cos 2\alpha),$$

$$j_\lambda(\alpha) = -\chi' \epsilon_0^2 t_\rho \sin \theta \sin 2\alpha,$$

(6)

Here, $\theta$ is the refraction angle related to the incidence angle $\theta_b$ by $\sin \theta = \sin \theta_b / n_\rho$ and $t_\rho$ and $t_0$ are the Fresnel amplitude transmission coefficients from vacuum to the structure for the $s$- and $p$-polarized lights, respectively. These functions are shown in Fig. 1 by the solid lines. To get agreement with experiments, we used the above equations with one fitting parameter $\chi$ and introduced an offset for the current $j_\lambda$ detected in the direction of the light propagation. Registration of these characteristic polarization dependences proves observation of LPGE at oblique incidence.

Comparing the results presented in Figs. 1 and 4, we can estimate of the ratio of different components of the tensor $\chi$ for the studied structures. At $\theta = 0.1$ rad, $t_\rho = t_0$, therefore from the ratio of the amplitudes in Figs. 1 and 4 equal to $|\chi'|/\chi \theta$, we get $|\chi'|/\chi \approx 10^{-2}$. This hierarchy of components of the third rank tensor $\chi_{x \mu \nu}$ in the systems of $C_{3v}$ symmetry is expectable, however, we demonstrate that the $\chi'$-related effect is observable. While the effect described by the constant $\chi$ also exists in the bulk GaN as well as in the $C_{3v}$ group, the photocurrent proportional to $\chi'$ arises only due to the reduced symmetry $C_{3v}$ of the system, i.e., due to size quantization. Therefore, the latter contribution should increase at narrowing of the 2D layer.

Equations (6) show that the photogalvanic current should follow the dependence $t_\rho \epsilon_0 \sin \theta$, in particular, reverse its di-
rection upon inversion the angle of incidence. This behavior is indeed observed. Figure 2 shows the LPGE current dependence on the incidence angle \( \theta_0 \) obtained for \( J_j \) at a fixed linear polarization of radiation (\( \alpha=45^{\circ} \)). We note that the offset photocurrent observed in the longitudinal direction only is always directed antiparallel to \( \hat{e}_z \). We ascribe the offset to the photon drag current which is linearly coupled to the photon momentum. This effect is out of scope of the present paper.

In our experiments, we also probe LPGE for the light directed along other crystallographic directions. Investigating transverse and longitudinal currents being perpendicular and parallel to the incidence plane, respectively, we observed that all polarization dependences are described by the same constant \( \chi \) independently of the in-plane direction of the light propagation. The reason of this fact is that the current contribution proportional to \( \chi \) is due to cone asymmetry being axially isotropic in the plane of our structures. Thus, this photocurrent is totally determined by the light polarization state and propagation direction, and it is independent of the incidence plane orientation relative to the in-plane crystallographic axes. For linearly polarized light, the photocurrent can be presented in the invariant form as 

\[
j_{j_2}^\parallel = \chi \text{E}_{0j_2}^2 \text{E}_2 \sin 2 \beta \hat{e}_1 \times \hat{z},
\]

\[
j_{j_1}^\parallel = \chi \text{E}_{0j_2}^2 \cos \theta (1 - \cos 2 \beta) \hat{e}_1,
\]

where \( \hat{z} \) is the unit vector along the normal.

2. Elliptical polarization

Illumination of the structure by elliptically polarized radiation also results in generation of the LPGE current, which is determined by the linear polarization degree of the light. However, elliptically polarized radiation is also characterized by the nonzero helicity. This results in the additional effect solely determined by the degree of circular polarization, the circular photogalvanic effect.\(^{3,4,14}\) This effect is phenomenologically described by

\[
j_{j_1}^{\text{CPGE}} = \sum_{\mu} \chi_{j_1}^\mu (E \times E')_\mu = E_{0j_2}^2 t_0 P_{\text{circ}}(\gamma \hat{e})_\lambda,
\]

where \( \hat{e} \) is the light propagation unit vector and \( \gamma \) is the second-rank pseudotensor. In the systems of \( C_{3v} \) symmetry, the tensor \( \gamma \) has one linearly independent component, namely, \( \gamma_{xy} = -\gamma_{yx} = \gamma \). Thus, the CPGE current flows always perpendicularly to the incidence plane.

In our experimental setup, a quarter-wave plate is rotated by the angle \( \varphi_p \) between the laser light polarization vector \( E_l \) and the principal axis of the polarizer (see inset to Fig. 5). The total photogalvanic current is given by both second and fourth harmonics of this angle. While radiation handedness is solely determined by the angle \( \varphi_p \), and does not depend on the relative orientation between \( E_l \) and the plane of incidence, the orientation of the ellipse is substantially different. In particular, for \( E_l \) perpendicular to the incidence plane at \( \varphi_p=0 \) (s polarization) and for \( E_l \) parallel to the incidence plane at \( \varphi_p=0 \) (p polarization), the orientation of the corresponding ellipses on the sample differs by 90°. Therefore, in the former case, light is never \( p \) polarized, and in the latter case, \( s \) polarization cannot be achieved, which is quite different from the geometry of half-wave plate where all states of linear polarization can be obtained. Thus, we derive two sets of equations describing experimental setup of Figs. 5(a)–5(d).

In the first geometry (s polarization at \( \varphi_p=0 \)) from Eqs. (4) and (8), we get

\[
j_{j_2}^{\varphi_p=0} = \frac{X}{2} E_{0j_2}^2 \cos \theta \sin \theta (1 - \cos 4 \varphi_p),
\]

\[
j_{j_1}^{\varphi_p=0} = E_{0j_2}^2 t_0 \sin \theta \left( -\frac{X}{2} \sin 4 \varphi_p + \gamma \sin 2 \varphi_p \right),
\]

and for the latter geometry (p polarization at \( \varphi_p=0 \)),

\[
j_{j_2}^{\varphi_p=0} = \frac{X}{2} E_{0j_2}^2 \cos \theta \sin \theta (3 + \cos 4 \varphi_p),
\]

\[
j_{j_1}^{\varphi_p=0} = E_{0j_2}^2 t_0 \sin \theta \left( \frac{X}{2} \sin 4 \varphi_p + \gamma \sin 2 \varphi_p \right).
\]

Here, we again took into account that in our samples \( |\chi'| \ll |\chi| \). Fits of experiment with the constant \( \chi \) independently obtained from experiments with half-wave plates and \( \gamma \) as a single adjustable parameter being the same for all curves yields a good agreement with the experiment. Here, again for the longitudinal photocurrent, the offset due to photon drag effect shows up and has the same value as that in the experiments with half-wave plates.

V. MICROSCOPIC THEORY

In order to describe the measured dependences of the photocurrent on wavelength and temperature, we have developed a microscopic theory of LPGE. First we consider the contribution proportional to the coefficient \( \chi \) in Eq. (4). This contribution does exist not only in systems of the \( C_{3v} \) or \( C_{6v} \) symmetry but is also allowed by the uniaxial point group \( C_{4v} \). Therefore, we can calculate the \( \chi \) contribution to \( j_{j_1}^{\text{LPGE}} \) in the uniaxial approximation. Then we turn to calculation of the contribution proportional to \( \chi' \) in Eq. (4) and surviving under normal incidence due to the reduced \( C_{3v} \) symmetry of the system. We note that so far the LPGE in 2D systems has been treated theoretically for direct intersubband transitions only.\(^{25,26}\) The mechanism of the LPGE under Drude absorption differs strongly because scattering is unavoidably present in the intrasubband absorption process.
the electron in-plane effective mass, \( V \) comes from two-quantum processes where the factor "two" accounts for spin degeneracy. The only.

A. Microscopic model for oblique incidence

Microscopically the LPGE current consists of the shift and ballistic contributions, which in general can be comparable in order of magnitude. We start from the analysis of the shift contribution and then turn to the ballistic contribution.

1. Shift contribution

The shift contribution arises due to coordinate shifts of the free-carrier wave-packet center-of-mass by microscopic lengths in quantum transitions. The corresponding current is a product of the elementary charge \( e \), the transition probability rate \( W_{k'k} \), and the shift vector \( \mathbf{R}_{k'k} \) or, explicitly,

\[
J_{\text{LPGE}}^{\text{(shift)}} = 2e \sum_{k'k} ^{\text{f}} W_{k'k} \mathbf{R}_{k'k},
\]

where the factor "two" accounts for spin degeneracy. The elementary shift is related to the transition matrix element \( M_{k'k} \) by

\[
\mathbf{R}_{k'k} = - \frac{\text{Im}[M_{k'k}(\nabla_k + \nabla_{k'})M_{k'k}^*]}{|M_{k'k}|^2} = - (\nabla_k + \nabla_{k'}) \text{arg}(M_{k'k}),
\]

where \text{arg}(u) is the phase of the complex number \( u \). The above two equations are general and valid for the shift photocurrent calculation in any frequency range. Here, for the first time, we apply them to consider the LPGE under the Drude absorption. Note that Eq. (12) was applied in the theory of anomalous Hall effect where the coordinate shift at scattering is called a side jump.

The main contribution to the matrix element for indirect intrasubband optical transitions,

\[
M_{1k',1k} = U_{1k',1k} \left( \frac{V_{k'}}{E_{k'} - E_k - \hbar \omega} \right),
\]

comes from two-quantum processes \( a_1 \) and \( a_2 \) with intermediate virtual states in the same \( e1 \) subband (see Fig. 7).

Here, the 2D electron kinetic energy \( E_k = \hbar^2 k^2 / 2m \), \( m \) is the electron in-plane effective mass, \( V_k \) is the matrix element of electron-light interaction,

\[
V_k = \frac{e \hbar A}{mc} \mathbf{e} \cdot \mathbf{k},
\]

\( \omega, A, \) and \( \mathbf{e} \) are the frequency, amplitude, and unit polarization vector of the light wave, \( U_{1k',1k} \) is the matrix element of intrasubband elastic scattering \( e1 \rightarrow e1', k \rightarrow k' \), and the superscript \( \perp \) indicates that the process is allowed for the polarization \( e \) containing an in-plane component \( e_z \). In the following, for simplicity, we ignore the wave vector dependence of \( U_{1k',1k} \) and replace it by a constant \( U_{11} \). The probability rate \( W_{k'k} \) is given by Fermi golden rule and expressed via the squared modulus of the transition matrix element and \( \delta \) function describing the energy conservation,

\[
E_{k'} - E_k = \hbar \omega.
\]

The processes \( a_1 \) and \( a_2 \) in isolation from other processes make no contribution to \( J_{\text{LPGE}}^{\text{(shift)}} \) because \( M_{1k',1k} \) is independent of \( e_z \), while the \( \chi \)-related photocurrent in the phenomenological Eq. (4) is proportional to \( e_z \) or because the microscopic expression in the square brackets in Eq. (12) is real and hence the elementary shift is absent. The shift contribution becomes nonzero if two other indirect processes, \( b_1 \) and \( b_2 \) in Fig. 7, are taken into account. The virtual states in these processes lie in the second size-quantized subband \( e2 \). The corresponding current element reads as

\[
M_{1k',1k} = \frac{-i e A}{\hbar c} z_{21} \Delta_{21} \left( \frac{U_{12}}{\Delta_{21} - \hbar \omega} - \frac{U_{21}}{\Delta_{21} + E_{k'} - E_k} \right).
\]

Here, \( U_{21} = U_{12} \) is the intersubband scattering matrix element, \( \Delta_{21} \) is the energy spacing between the \( e2 \) and \( e1 \) subbands, and \( z_{21} \) is the intersubband matrix element of the coordinate \( z \). The superscript \( \perp \) indicates that transitions (15) are allowed in the polarization perpendicular to the interface plane.

Substituting \( M_{k'k} = M_{1k',1k} + M_{2k'k} \) into Eq. (12), taking then into account the energy conservation equation (14) and assuming \( \hbar \omega \ll \Delta_{21} \), we obtain for the elementary shift,

\[
|M_{k'k}|^2 R_{k'k} = M_{2k'k} = - z_{21} \left( \frac{e A}{\hbar c} \right)^2 U_{11} U_{21} \Delta_{21} \hbar \omega, \frac{e A \mathbf{e} \cdot (3k' - k)}{|3k' - k|}, \frac{(3k' - k)}{|3k' - k|}.
\]

Note that the shift is different from zero only due to the wave vector dependence of denominators \( E_{k'} - E_k \) and \( E_{k'} + E_{k'} - E_k \) in the matrix elements (13) and (15).

The result for the shift photocurrent can be presented in the form

\[
J_{\text{LPGE}}^{\text{(shift)}} = - e x z_{21} e \cdot \frac{e}{2 \Delta_{21} \hbar \omega} F[2E + \hbar \omega].
\]

Here, the factor \( x \) is given by

\[
\xi = \frac{\langle U_{12}^2 \rangle}{\langle U_{11}^2 \rangle},
\]

where the angular brackets mean averaging over the distribution of static scatterers along \( z \), the functional \( F[\phi(E)] \)
turns any function \( \phi(E) \) into a real number as follows:

\[
F[\phi(E)] = \int_0^\infty \left[ f(E) - f(E + \hbar \omega) \right] \phi(E) dE \int_0^\infty f(E) dE,
\]

\( f(E) \) is the Fermi–Dirac distribution function. \( \eta \) is the absorbance under normal incidence \((\theta = 0)\) given by \(29\)

\[
\eta = \frac{e^2}{\hbar c n_d m \omega} F[2E + \hbar \omega],
\]

(18)

the momentum relaxation time \( \tau_p = \hbar^3 / (m N_d U_{1j}^2) \), and \( N_e \) and \( N_d \) are the 2D concentrations of electrons and scatterers, respectively.

Note that allowance for nonzero value of \( \xi \) and, hence, of the LPGE current, presupposes the uniaxial asymmetry of the structure. \(28\) This corresponds to the phenomenology of the LPGE, which requires the absence of an inversion center in the system. A value of \( \xi \) is nonzero due to an asymmetrical shape of the electron envelope functions in the one and two substrands caused by the build-in electric field. An inhomogeneous asymmetrical distribution of scatterers along the \( z \) axis can also contribute to \( \xi \).

2. Ballistic contribution

In order to obtain a nonzero ballistic photocurrent, it is necessary to go beyond the approximation of single-impurity scattering and take into account simultaneous scattering by two impurities in one process. Such optical-absorption processes are schematically shown in Fig. 8. Let us introduce the antisymmetrical part \( W'_{k'k} \) of the \( k \rightarrow k' \) transition rate \( W_{k'k} \), which changes sign under simultaneous inversion of the wave vectors \( k \) and \( k' \). It can be expressed in terms of Fermi golden rule,

\[
W'_{k'k} = \frac{2 \pi}{\hbar} |M_{k'k_0}|^2 \{ f(E_k) - f(E_{k'_0}) \} \delta(E_{k'_0} - E_k - \hbar \omega),
\]

(19)

where \( |M_{k'k_0}|^2 \) is the antisymmetric part of the squared modulus of the optical two-impurity-mediated matrix element \( M_{k'k} \). Then the ballistic contribution to the LPGE current is given by

\[
J_{\text{LPGE}}^{\text{ball}} = 2e \sum_{k,k'} W'_{k'k} \tau_p (\mathbf{v}_{k'} - \mathbf{v}_k).
\]

(20)

where \( \mathbf{v}_k = \hbar k / m \) is the electron velocity.

Here is worth discussing the dependence of the ballistic and shift contributions on the concentration of elastic scatterers \( N_d \). For two-impurity scattering the probability rate \( W_{k'k}^b \approx N_d^{-1} \). In contrast, the single-impurity scattering rate \( W_{k'k} \) in Eq. (11) linearly depends on \( N_d \). However, the ballistic current is controlled by the momentum relaxation time \( \tau_p \) in the right-hand side of Eq. (20). Since \( \tau_p \approx N_d^{-1} \), the ballistic and shift currents are both proportional to \( N_d \). In this sense, there is an analogy between a pair of the two contributions to the photocurrent and a pair of the side-jump and skew-scattering currents in the anomalous Hall effect. \(5\)

In order to get the photocurrent proportional to both \( e_\perp \) and \( e_z \), we extract from \( |M_{k'k_0}|^2 \) the interference term proportional to \( \text{Re}(M'M^{-1}) \), where \( M' \) and \( M^{-1} \) are the contributions to the matrix element of the indirect optical transition proportional to \( e_\perp \) and \( e_z \), respectively. To the lowest order in \( \hbar \omega / \Delta_{21} \ll 1 \), one should include into consideration six two-impurity scattering processes \( a_5 \cdots a_8 \) contributing to \( M' \) and two processes \( b_3 \) and \( b_4 \) for \( M^{-1} \) depicted in Fig. 8.

For example, below we present the contributions to \( M' \) from the processes \( a_5 \) and \( a_6 \).

\[
M'_{a_5} = \sum_{k,k_2} N_d \frac{U_{11}' V_{k_2} U_{11} U_{11}' \delta_{k+k_2,k'-k_1}}{(E_{k_2} - E_k - \hbar \omega - i\theta)(E_{k_2} - E_k - i\theta)(E_{k_1} - E_k - i\theta)},
\]

\[
M'_{a_6} = \sum_{k,k_4} N_d \frac{V_{k'} U_{11}' U_{11} \delta_{k+k_4,k'-k_1}}{(E_{k'} - E_k - i\theta)(E_{k'} - E_k - i\theta)(E_{k_1} - E_k - i\theta)},
\]

(21)
where the prime means the scattering (shown by dotted lines in Fig. 8) by a defect different from that which is related to the matrix element $U_{11}$ in these equations and to $U_{21}$ in Eq. (15) (shown by the dashed lines). The Kronecker symbols are obtained after averaging the matrix element over the in-plane distribution of the second scatterer. Note that averaging over its distribution in the $z$ direction results in replacement of the square $(U'_{11})^2$ by $(U_{11}^2)$. The energy denominators are rewritten by using the identity

$$ \frac{1}{x - i0} = PV \frac{1}{x} + i \pi \delta(x), $$

and, among such three terms in each contribution $M_{aj}^k (j = 3...8)$, we retain the $\delta$ function in one of them and take the Cauchy principal values for two others. This additional $\delta$ function, together with the energy conservation law (14) and the relation $k + k_2 = k' + k_1$, fixes absolute values of the wave vectors $k, k', k_1, k_2$. The integration over the azimuthal angle of the vector $k_1$ or $k_2$ is performed by using the principal value integral,

$$ PV \int_0^{2\pi} \frac{d\varphi}{2\pi a - b \cos \varphi} = \Theta(a^2 - b^2) \text{sign} a \sqrt{a^2 - b^2}, $$

where $\Theta(x)$ is the Heaviside step function. The calculation shows that, among the eight processes presented in Fig. 8, only two, namely, the processes $a_4$ and $a_6$, lead to nonzero ballistic current. The final result for this current reads

$$ J_{\text{LPEG}} = \varepsilon_2 \varepsilon'_z \eta \xi_{21} F[L(h\omega/E)] F[E(h\omega + 1/2)], $$

where

$$ L(x) = \frac{x}{2\pi} \int_{\varphi_0(x)}^{2\pi} \frac{d\varphi}{\sqrt{(x - 2)\sqrt{1 + x \cos \varphi} - 4}}, $$

$$ \varphi_0(x) = \Theta(8 - x) \arccos \left( \frac{x - 2}{2\sqrt{1 + x}} \right). $$

The function $L(x)$ goes to zero as $x \rightarrow 0$ and tends to 1 at $x \rightarrow \infty$. A sum of the shift and ballistic contributions given by Eqs. (17) and (22) represents the photocurrent phenomenologically described by the coefficient $\chi$ in Eq. (4).

**B. Microscopic model for normal incidence**

An ideal GaN/AlN interface has the point-group symmetry $C_{3v}$, which is a subgroup of the $C_{6v}$ space group of a bulk wurtzite crystal. The group $C_{6v}$ is nonsymmetric and contains, in addition to $C_3$ and $\sigma_g$, the elements $C_{6d}, \sigma_d^\tau$, where $\tau$ is the fractional lattice translation $(0, 0, c/2)$ and $c$ is the lattice constant along the principal axis $z$. In the 2D structures, the screw- and glide-plane operations shift the interfaces along $z$ not bringing the system into coincidence with itself and, as a result, the point-group symmetry reduces to $C_{3v}$.

For the $C_{6v}$ symmetry of bulk wurtzite structure, characteristic of III-nitrides, the nonvanishing third order tensor components $\chi_{\mu\nu}$ symmetrical in $\mu$ and $\nu$ are $\chi_{xx} = \chi_{xy}, \chi_{yy} = \chi_{yx}, \chi_{zz} = \chi_{zx}, \chi_{zy} = \chi_{yz} = \chi$. Therefore, forbidden are such bulk effects as the second-harmonic generation for excitation along $z$, a piezoelectric field induced in the $(x, y)$ plane under the deformation in this plane and the photocurrent in the $(x, y)$ plane for the light propagating along $z$. The reduction from $C_{6v}$ to $C_{3v}$ removes these restrictions and four new nonzero components appear, $\chi_{xx} = \chi_{xy}, \chi_{yy} = \chi_{yx}, \chi_{zz} = \chi_{zx}, \chi_{zy} = \chi_{yz} = \chi$ [see Eqs. (4)]. Note that it is the interface that is exclusively responsible for the appearance of new components.

Here we propose a microscopic model of the LPGE under normal incidence. In this geometry virtual transitions via other size-quantized electronic subbands are forbidden; therefore, we should consider the light absorption with intermediate states either in the same $e_1$ electronic subband or in the valence band. In the first case, see Fig. 7, the reduced $C_{3v}$ symmetry manifests itself in the scattering matrix element $U_{1k', 1k}$, and, instead of Eq. (16), one should replace the elementary shift in the product $|M_{k'k}|^2 R_{k'k}$ by the scattering induced shift,

$$ R_{k'k}^{(i)} = \frac{\text{Im}[U_{1k', 1k}] (\nabla_k + \nabla_{k'}) U_{1k', 1k}^*}{|U_{1k', 1k}|^2}. $$

Note that the main contribution to $U_{1k', 1k}$ dependent only on the difference $(k' - k)$ does not result in the shift because the operator $(\nabla_k + \nabla_{k'})$ nullifies such a term. Similar contribution to the LPGE current has been calculated for Drude absorption in the heavy-hole subband of a bulk $p$-GaAs, where the shift appeared due to interference of polar and deformation scattering mechanisms on optical phonons.

For optical transitions going via $\Gamma_6$ valence-band states, the elementary shift can be related to asymmetry of the interband optical matrix elements, in which case the asymmetry of the interband scattering matrix element is neglected. We consider this mechanism in more detail. Taking into account the symmetry considerations, we can present the interband matrix elements of the operator $e_1 \cdot p$ (where $p$ is the momentum operator) between the conduction-band state $\Gamma_1$ and the valence-band states $\Gamma_6$ as

$$ e_1 \cdot p \Gamma_1 \rightarrow \Gamma_6 (k) = i \mathcal{P} e_1 + Q(e_x k_y + e_y k_x), $$

where $\mathcal{P}$ and $Q$ are real constants. Multiband derivation of these contributions for GaN-based 2D structures is given in Appendix B. The matrix element $Q$ is nonzero due to the presence of the interface in the heterostructure. This approach is similar to description of interface inversion symmetry induced spin splitting in the envelope-function method, where the $\delta$-functional terms are introduced into the interband Hamiltonian (see Refs. 31 and 32). As a result, we expect a strong dependence of $Q$ on the confinement size because $Q$ is proportional to a product of the electron and hole envelope functions at the interface [see Eq. (B3)]. We expand $M_{k'k}$ and $R_{k'k}$ in powers of small parameters $h\omega/E_{\Gamma_6}$, $\tilde{E}/E_{\Gamma_6} \ll 1$. In the same nonvanishing order, we should take into account $k$ dependence of the matrix element $\mathcal{P}$. This
could be done by replacing in Eq. (23) the constant $P$ by the function

$$P(k) = P_0 \left( \frac{1 - E_k}{2E_g} \right).$$

The interband scatterings $e\Gamma_i k \rightarrow e\Gamma_i' k'$ and $e\Gamma_j k \rightarrow \Gamma_j' k'$, $\Gamma_j' k'$ are described by the constant matrix elements $U_{e\Gamma_j}^2$ and $U_{e\Gamma_j'}^2$, assumed to be independent of $k$ and $k'$, with $(U_{e\Gamma_j}^2) = (U_{e\Gamma_j'}^2)$.

In order to carry out a reasonable estimation of the coefficient $\chi'$ in Eq. (4), we used a simple nonrelativistic $k$-$p$ model coupling the $e\Gamma_i$ and $\Gamma_j$ band states. In this model the valence band consists of two subbands, one with an infinite in-plane effective mass and the other with the hole in-plane effective mass coinciding with that for a conduction-band electron. Omitting the details of derivation, we present the final result,

$$\chi' = \frac{2\pi e^2}{m^*} \left( \frac{U_{e\Gamma_j}^2}{E_g} \right) \frac{Q}{N_s F_1},$$

(24)

where $F_1 = F[1]=\int_0^\infty [f(E) - f(E + \hbar\omega)]dE + \int_0^\infty f(E) dE$. Experiment shows a noticeable magnitude of the LPGE current under normal incidence (see Fig. 4).

VI. DISCUSSION

In this section, we discuss the role of the contributions to the total current and analyze the frequency and temperature dependences of LPGE. An analytical estimation for the shift and ballistic photocurrents at Drude absorption is readily available for the photon energies $\hbar\omega$ small compared to the electron typical energy $\tilde{E}$, which is relevant to our experiments performed at room temperature and applying terahertz radiation. In this case, Eqs. (17) and (22) reduce to

$$j_{\text{LPGE}}^{(\text{shift})} \sim 2\xi e z_{21} \frac{\eta I}{\Delta_{21}},$$

and

$$j_{\text{LPGE}}^{(\text{ball})} \sim \xi e z_{21} \left( \frac{\hbar\omega}{2\tilde{E}} \right)^2.$$

Since $\hbar\omega/\tilde{E} \ll 1$ the shift contribution dominates the LPGE. This estimation is confirmed by the study of the frequency dependence of LPGE. Indeed, while the shift photocurrent follows the frequency dependence of the absorbance which, for Drude processes, is given by Eq. (1), the ballistic contribution has another frequency dependence because in this case $j_{\text{LPGE}}^{(\text{ball})} \propto \eta \omega^2$. The observed good agreement of the current and absorption frequency behavior (see Fig. 3) unambiguously proves the dominating role of the shift contribution to the LPGE. We note that such a spectral behavior of the LPGE has been previously observed in bulk III-V semiconductors.33

We note that even for the opposite limit of $\hbar\omega/\tilde{E} \gg 1$ the LPGE due to Drude absorption is still dominated by the shift contribution. In this case, estimates yield

$$j_{\text{LPGE}}^{(\text{shift})} = -3/2 j_{\text{LPGE}}^{(\text{ball}).}$$

Now we analyze the temperature dependence. As follows from Eq. (17), the temperature dependence of the LPGE current is given by $j_{\text{LPGE}}^{(\text{shift})} \propto \xi g_h(T)$. Taking into account temperature behavior of the Drude absorption [see Eq. (18)], we get

$$j_{\text{LPGE}}^{(\text{shift})} \propto \xi \tau_p(T).$$

Here we again use the relation $\hbar\omega \ll \tilde{E} \sim k_BT$. Variation of the temperature results in the change of the dominant scattering mechanisms. Typically in the low-dimensional structures by raising temperature, we get a transition from the temperature-independent scattering rate by impurities $1/\tau_p$ to the fast-increasing rate due to scattering by phonons $1/\tau_p(T)$. As a result, we have for the LPGE current

$$j_{\text{LPGE}}^{(\text{shift})} \propto \xi \frac{\tau_p}{\tau_p} + \xi \frac{\tau_p}{\tau_p}(T).$$

This expression demonstrates that despite the inverse mobility $1/\mu(T) \propto 1/\tau_p + 1/\tau_p(T)$ is a monotonous function of temperature (see inset in Fig. 3) and the asymmetry factors $\xi$ are temperature independent, the LPGE current can have a minimum or even change the sign at temperature increase. This is due to the interplay between two contributions to the LPGE caused by different scattering mechanisms, characterized by substantially different values of $\xi\text{imp}$ and $\xi\text{ph}$ possibly being even opposite in signs. Due to the fact that only one time is temperature dependent, $1/\tau_p(T)$ variation of temperature may result in the dominance of one of the other contribution to the LPGE current.

VII. CONCLUSION

In conclusion, we have studied the linear photogalvanic effect in wurtzite GaN(0001)-based heterojunctions under excitation by linearly and elliptically polarized lights in the terahertz frequency range. Experimentally, the properties of LPGE have been revealed as a function of the incidence angle and the polarization state of radiation. A detailed point-group symmetry analysis of the polarization properties shows an agreement between the experimental data and the phenomenological theory of LPGE. Phenomenologically, the effect is described by the two linearly independent coefficients $\chi$ and $\chi'$, the former being allowed by the $C_{3v}$, $C_{3v}$, and even $C_{6v}$ symmetries and the latter being nonzero only for the $C_{3v}$ symmetry. An observation of the photocurrent under normal incidence determined by $\chi'$ unambiguously demonstrates a reduction in the heterojunction symmetry from hexagonal $C_{6v}$ to trigonal $C_{3v}$. However, beginning from very small oblique angles first contribution to the photocurrent prevails over the second one. The frequency dependence of the measured LPGE photocurrent exhibits a Drude-type behavior. A microscopic theory of LPGE under the intrasubband (Drude) absorption in the lowest $e\Gamma_1$ electron subband has been developed. While calculating the $\chi$-related photocurrent, we have included virtual indirect optical transitions via the higher subband $e2$, estimated both the shift and ballistic contributions and showed that the first one exceeds the other by a large factor $\sim (E/\hbar\omega)^2$. The dominating shift photocurrent repeats a Lorentzian frequency dependence of the Drude-absorption coefficient, in agreement with the experiment. The temperature dependence of the photocurrent is governed by a product of the absorption coefficient and the dimensionless parameter of asymmetry. Microscopically, the contribution vanishing under normal incidence
arises taking into account indirect optical transitions via virtual electronic states in the valence band.

ACKNOWLEDGMENTS

The financial support from the DFG and RFBR is gratefully acknowledged. E.L.I. thanks DFG for the Mercator professorship. Work of L.E.G. is also supported by “Dynasty” Foundation—ICFPM and President grant for young scientists. The high quality GaN samples were kindly provided by Hyun-Ick Cho and Jung-Hee Lee from Kyungpook National University, Korea. We gratefully acknowledge the support of the Stichting voor Fundamenteel Onderzoek der Materie (FOM) in providing beam time on FELIX.

APPENDIX A: PHOTOCURRENTS IN THE ROTATED COORDINATE FRAME

In Sec. IV A we get phenomenological equations for LPGE at normal incidence. We obtained that the photocurrent direction is determined by the orientation of the electric vector with respect to the crystallographic axes $x$ and $y$. Most convenient for this effect is to investigate the current in the directions along and perpendicular to one of the mirror-reflection planes of the $C_{3v}$ point group. However, in contrast to III-V semiconductor heterostructures where well determined in-plane crystallographic orientation is naturally obtained by cleaving in GaN/AlGaN heterojunctions grown on the sapphire substrate this may be not the case. Therefore, we obtain here the LPGE for the arbitrary orientation of contacts in respect to the crystallographic directions. To describe this situation, we introduce the angle $\Phi$ between the in-plane directions $x'$ and $y'$ along, which the contacts are made and the crystallographic axes $x$ and $y$ (see Fig. 9). The symmetry considerations yield the expression for the combination of $x'$ and $y'$ components of the photocurrent, which follows from Eqs. (4) for $E_x=0$,

$$j_{x'} + ij_{y'} = i\chi'(E_{x'} - iE_{y'}(E_{x'}^0 - iE_{y'}^0)\exp(3i\Phi)$$
or, equivalently,

$$j_{x'} = \chi'(t_xE_0)^2 \sin(2\alpha - 3\Phi),$$

$$j_{y'} = \chi'(t_yE_0)^2 \cos(2\alpha - 3\Phi),$$

(A1)

where $\alpha$ is counted from $y'$: $E(\alpha=0)\parallel y'$.

Equations (A1) demonstrate that the azimuth angular dependence for arbitrary orientation of contacts in respect to the crystallographic directions remains the same but differs by the phase shift $3\Phi$. Finally, we note that the photocurrent determined by the constant $\chi$ in Eq. (4) is independent of the angle $\Phi$ because it is totally defined by position of the incidence plane and polarization of light. Therefore, Eq. (7) holds for any angle $\Phi$.

APPENDIX B: DERIVATION OF INTERBAND MATRIX ELEMENTS

Equation (23) can be obtained from the two-band electron effective Hamiltonian

$$\mathcal{H}_{c,x':\Gamma_{6s}}(k) = \frac{\hbar}{m_0}(i\mathcal{P}_k + Q k_y k_y),$$

(B1)

$$\mathcal{H}_{c,x':\Gamma_{6s}}(k) = \frac{\hbar}{m_0}\left[ i\mathcal{P}_k + Q \frac{1}{2}(k_x^2 - k_y^2) \right]$$

by using the relation

$$e \cdot P_{c,x':\Gamma_{6}}(k) = \frac{m_0}{\hbar} (e \cdot \nabla k) \mathcal{H}_{c,x':\Gamma_{6}}(k).$$

We describe the symmetry reduction from $C_{6v}$ to $C_{3v}$ by introducing a $\delta$-functional perturbation $\hat{V}'\delta(z - z_d)$, where $z_d$ is the interface coordinate in the $z$ axis and the operator $\hat{V}'$ transforms according to the representation $B_1$ of the group $C_{6v}$ with the basic function $y^3 - 3x^2y$ (here as before we assume that one of the three mirror-reflection planes in the $C_{3v}$ group contains the axes $y, z$ and is perpendicular to $x$). The perturbation $\hat{V}'$ mixes the Bloch state $\Gamma_6$ with $\Gamma_5$ and the Bloch state $\Gamma_3$ with $\Gamma_1$.

In order to find the quadratic-in-$k$ correction in Eq. (B1), we calculate the third-order correction to the Hamiltonian using the perturbation theory,

$$\mathcal{H}_{c,x: \Gamma_{6s}}^{(3)} = \sum_{ss'} \mathcal{H}_{c,x: \Gamma_s} \mathcal{H}_{s,s'} \mathcal{H}_{s': \Gamma_s}(\Phi(\delta s')),$$

$$\Phi(\delta s') = \left[ \frac{1}{(E_0^s - E_0^t)(E_0^s - E_0^{s'})} + \frac{1}{(E_0^t - E_0^s)(E_0^t - E_0^{s'})} \right].$$

Here the indices $c, t, \delta s$, respectively, the lowest conduction and the highest valence bands of the symmetries $\Gamma_1$ and $\Gamma_{6s}$; $s, s'$ are other conduction or valence bands different from $c$ and $t$ (the electron spectrum throughout the Brillouin zone for bulk GaN can be found, e.g., in Refs. 35 and 36). $\mathcal{H}_{ss'}$ is the matrix of the first-order matrix elements of the $\mathbf{k} \cdot \mathbf{p}$ coupling or the interface mixing between the states in the bands $n$ and $n'$; $E_0^n$ is the electron energy in the band $n$ at the $\Gamma$ point. The dimension of the matrix $\mathcal{H}_{ss'}$ is $N \times N'$, where $N, N'$ are degeneracies of the bands $n$ and $n'$, respectively. Taking into account the bands $s\Gamma_6(s \neq t)$, $s\Gamma_5$, and $s\Gamma_3$, we can present the coefficient $Q$ in Eq. (B1) for a structure with a single interface in the following form:
\[ Q = \mathcal{V} \delta(z - z_d), \quad \text{(B2)} \]
\[
\mathcal{V} = \frac{\hbar}{m_0} \left[ P'(R'V_2 - V_1 R)\Phi(s's') - V_2 P''R\Phi(s''s') \right].
\]

The set of matrix elements is defined as follows:

\[
V_1 = \langle s, \Gamma_\alpha | \hat{V} | s', \Gamma_\beta \rangle, \quad V_2 = \langle v, \Gamma_\alpha | \hat{V} | s', \Gamma_\beta \rangle, \quad V_3 = \langle c, \Gamma_\alpha | \hat{V} | s', \Gamma_\beta \rangle,
\]

\[ P' = -i(c, \Gamma_\alpha | p_{\alpha} | v, \Gamma_\beta), \quad P'' = i(s'', \Gamma_\beta | p_{\beta} | s', \Gamma_\alpha). \]

For the band \( s', \Gamma_\beta \), we choose the basis \( |s, \Gamma_\alpha \rangle \) and \( |s', \Gamma_\beta \rangle \), which transforms under operations of the \( C_3 \) group as the coordinates \( x \) and \( y \), i.e., as functions \( |s', \Gamma_\alpha \rangle, |s', \Gamma_\beta \rangle \).

While deriving Eq. (B2) we took into account the relation between matrix elements imposed by the symmetry, e.g.,

\[ \langle c, \Gamma_\beta | p_{\beta} | s, \Gamma_\alpha \rangle = -\langle c, \Gamma_\beta | p_{\beta} | s, \Gamma_\beta \rangle, \quad \langle c, \Gamma_\beta | p_{\beta} | s, \Gamma_\alpha \rangle = -\langle c, \Gamma_\beta | p_{\beta} | s, \Gamma_\beta \rangle, \quad \text{etc.} \]

It follows then that, for a heterojunction, the interband optical matrix elements are indeed given by Eq. (23) where

\[ P = \mathcal{P} \int f_\alpha(z)f_\beta(z)dz, \quad Q = \mathcal{V} f_\alpha(z_0)f_\alpha(z), \quad \text{and} \quad P = -i(c, \Gamma_\beta | p_{\beta} | v, \Gamma_\alpha) = -i(c, \Gamma_\beta | p_{\beta} | v, \Gamma_\beta), \quad \text{and} \quad f_\alpha(z) \]

are the electron and hole envelope functions.