

In-plane polarization anisotropy and polarization rotation for *M*-plane GaN films on LiAlO₂

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We investigate the dependence of the transmittance spectra of strained *M*-plane GaN films on the angle of the linear in-plane polarization, with the *c* axis of the underlying wurtzite crystal structure in the film plane. Because of the reduced in-plane symmetry and the large in-plane anisotropic strain, the transmission spectra for an arbitrary in-plane polarization angle can be directly derived from two transitions with polarizations parallel and perpendicular to the *c* axis. Since the energy gap for these two polarizations is shifted by more than 50 meV, the *M*-plane GaN film becomes dichroic, resulting in a polarization rotation after transmission for energies between the two gaps for an initial angle of 45° by as much as 40° towards the *c* axis. © 2003 American Institute of Physics.

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Optically anisotropic materials are used to fabricate devices such as polarization-sensitive photodetectors (PSPDs), in which the state of polarization is of critical importance for optical information processing. The advantage of intrinsically anisotropic materials for the fabrication of PSPDs is that it allows for the miniaturization of the detection system, leading to large-scale integration and easier alignment. Isotropic materials such as GaAs can exhibit a polarization anisotropy in the in-plane dielectric function, when anisotropic strain reduces the underlying symmetry of the valence bands (VBs), resulting in a mixing of heavy- and light-hole states.¹ Modulators based on the rotation of the polarization vector have been demonstrated in uniaxially strained, [001]-oriented GaAs/(Al,Ga)As multiple quantum wells (MQWs)^{2,3} and biaxially strained [110]-oriented MQWs.⁴ The anisotropic crystal properties of CuPt_B-type ordered materials such as In_{0.5}Ga_{0.5}P alloys have been increasingly utilized for devices such as tunable polarization converters⁵ and polarized light-emitting diodes⁶ as well as a device feature such as polarization stabilization of vertical-cavity surface-emitting lasers.^{7,8} Polarization threshold switches⁹ and reset flip flops¹⁰ have also been realized using ordered In_{0.5}Ga_{0.5}P alloys, which exhibit different absorption coefficients along the [011] and [0 $\bar{1}1$] directions.

Recently, it has been shown that strained *M*-plane GaN films are a potential candidate for the fabrication of PSPDs,^{11,12} since the *c* axis of the wurtzite crystal structure lies in the film plane. Theoretical calculations of the strain dependence of the interband transition energies as well as the oscillator strengths reveal that for anisotropically strained *M*-plane GaN with sufficiently large strain values the VB structure (VBS) is modified in such a way that the corresponding transitions with electrons in the conduction band *T*₁, *T*₂, and *T*₃ can be fully *x*-, *z*-, and *y*-polarized, respectively.¹³

In this letter, we study the in-plane polarization anisotropy and polarization rotation for an anisotropically strained *M*-plane GaN film with the *c* axis of the wurtzite crystal structure lying in the film plane. The transmission spectrum

for an arbitrary in-plane polarization angle is a linear combination of the transmission spectra originating from two transitions with polarizations parallel and perpendicular to the *c* axis. An incident linearly polarized light beam with an energy between these two transitions is rotated after transmission through the film. For an initial polarization angle of 45°, the measured angle of polarization rotation can be as large as 40°, which corresponds to about 90% of its maximum value.

LiAlO₂ has a tetragonal unit cell with lattice constants $a=b=5.1687$ Å, which is almost equal to c_{GaN} , and $c=6.2679$ Å, which is about $2a_{\text{GaN}}$. Therefore, the *M* plane of GaN exhibits a rather good lattice matching with the (100) face of LiAlO₂. The *M*-plane GaN film was grown by rf plasma-assisted molecular-beam epitaxy on a γ -LiAlO₂(100) substrate.^{14,15} The film thickness of 0.7 μm was determined by scanning electron microscopy. The *M*-plane orientation of the film and its single phase nature were verified by high-resolution triple-axis x-ray diffraction (XRD). The XRD measurement performed at 295 K revealed that the film is under biaxial compressive strain of $\epsilon_{yy}=0.57\%$ (the *y* direction is perpendicular to the *M* plane) giving rise to an anisotropic in-plane strain with $|\epsilon_{xx}|$ and $|\epsilon_{zz}|$ (the *z* direction is parallel to the *c* axis in the *M* plane) being both larger than 0.2%. The anisotropic compressive strain is due to the anisotropic mismatch of the lattice constants between GaN(1 $\bar{1}$ 00) and γ -LiAlO₂(100), which at room temperature is -0.3% and -1.7% in the *z* and *x* direction, respectively. At low temperatures, the lattice mismatch increases due to the difference in the thermal expansion coefficients of the two materials.

The polarized transmittance was measured using a monochromatic beam from a Xe arc lamp filtered by a 0.64 m monochromator (energy bandpass of about 4 meV). The incident beam was linearly polarized with a Glan–Taylor prism. The measurement of the polarization rotation after transmission through the film was carried out using a photoelastic modulator and an analyzer as described by Oakberg.¹⁶ In order to remove any rotation by the substrate, we attached a second LiAlO₂ crystal on the substrate with the crystal orientation rotated by 90°. The light was detected with an

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UV-enhanced photodetector connected to a lock-in amplifier.

The $k \cdot p$ approach to calculate the band structure reveals that for M -plane GaN under biaxial anisotropic compressive strain the VBS is modified in such a way that only two transitions T_1 and T_2 have to be considered for light polarized in the M plane.¹³ These two transitions occur for light linearly polarized parallel to the z axis ($E \parallel c$) and parallel to the x axis ($E \perp c$). Therefore, we expect that for light polarized at an arbitrary angle with respect to the c axis the transmittance becomes a linear combination of the transmittance for the two orthogonally polarized transitions T_1 and T_2 .

The calculation of the transmittance and reflectance of multilayered system is usually performed using the transfer matrix method (TMM) because of its power to deal with multiple reflections at the various interfaces. In the case of an isotropic layered system, the TMM involves only the manipulation of 2×2 matrices, since the electromagnetic wave can be expressed by two independent modes. However, the M -plane GaN film is clearly an anisotropic medium, since the interband-transition oscillator strength depends on the in-plane polarization angle.^{12,13} In such anisotropic media, the electromagnetic wave is expressed by four modes, two for $E \parallel c$ and two for $E \perp c$, resulting in a 4×4 matrix.¹⁷ We will apply this formalism to our particular system, which consists of a thin M -plane GaN film on a thick LiAlO_2 substrate. Both the film and the substrate are anisotropic media with different dielectric constants for the two orthogonal directions.

Following Yeh,¹⁷ we obtain

$$\begin{pmatrix} A_z \\ B_z \\ A_x \\ B_x \end{pmatrix} = \begin{pmatrix} M_{11}M_{12}M_{13}M_{14} \\ M_{21}M_{22}M_{23}M_{24} \\ M_{31}M_{32}M_{33}M_{34} \\ M_{41}M_{42}M_{43}M_{44} \end{pmatrix} \begin{pmatrix} C_z \\ D_z \\ C_x \\ D_x \end{pmatrix}, \quad (1)$$

where A_z and A_x (C_z and C_x) denote the amplitudes of the waves traveling before the system (after the system) in air to the right with a polarization parallel to the z and x axis, respectively, while B_z and B_x (D_z and D_x) denote the corresponding amplitudes for waves traveling before the system (after the system) in air to the left. Since we consider the transmission under normal incidence, the axes in the laboratory frame overlap with the optical axes of the uniaxial medium. Therefore, the matrix elements M_{13} , M_{14} , M_{23} , and M_{24} as well as M_{31} , M_{32} , M_{41} , and M_{42} are all equal to zero so that the 4×4 matrix is reduced to a block diagonal form with two 2×2 matrices, corresponding to the two primary directions, i.e., z and x . Since the final medium (air) is considered to be semi-infinite, there are no traveling waves to the left so that D_z and D_x are equal to zero. After multiplication, we therefore obtain

$$\begin{pmatrix} A_z \\ B_z \\ A_x \\ B_x \end{pmatrix} = \begin{pmatrix} M_{11}C_z \\ M_{21}C_z \\ M_{33}C_x \\ M_{43}C_x \end{pmatrix}. \quad (2)$$

The transmittance for $E \parallel c$ ($E \perp c$) is then given by T_{\parallel} ($T_{\perp} = 1/|M_{33}|^2$). The transmittance $T(\phi_i)$ for an arbitrary initial polarization angle ϕ_i can be expressed as

$$T(\phi_i) = T_{\parallel} \cos^2(\phi_i) + T_{\perp} \sin^2(\phi_i), \quad (3)$$

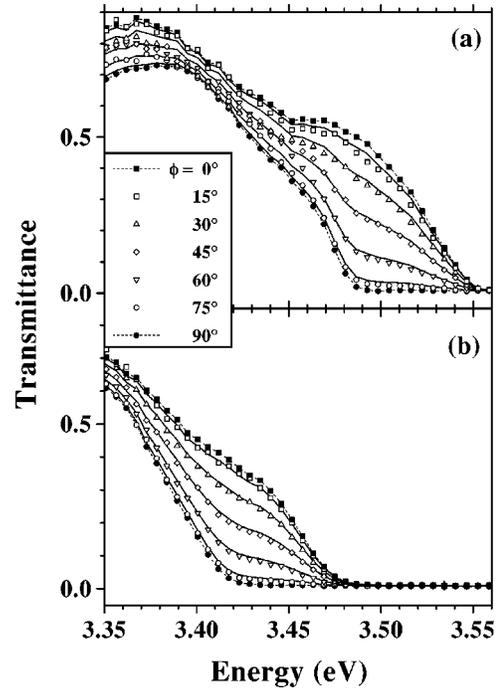


FIG. 1. Measured transmission spectra (symbols) for several polarization angles ϕ_i between 0° and 90° in steps of 15° at (a) 6 and (b) 295 K for the M -plane GaN film. The solid lines for $\phi_i = 15^\circ - 75^\circ$ indicate the result of the calculation according to Eq. (3).

where T_{\parallel} and T_{\perp} denote the transmittance for $\phi_i = 0^\circ$ and $\phi_i = 90^\circ$, respectively. Note that the transmittance should be exactly the same for ϕ_i and $180^\circ - \phi_i$. A similar expression exists for the transmittance T as a function of the polarization angle after transmission ϕ_f through the film

$$\frac{1}{T(\phi_f)} = \frac{1}{T_{\parallel}} \cos^2(\phi_f) + \frac{1}{T_{\perp}} \sin^2(\phi_f). \quad (4)$$

The polarization angle after transmission ϕ_f is related to ϕ_i by

$$\phi_f = \arctan \left[\tan(\phi_i) \sqrt{\frac{T_{\perp}}{T_{\parallel}}} \right], \quad (5)$$

For any initial polarization angle $0 < \phi_i < 90^\circ$, this equation implies that in the energy region, where T_{\perp} is zero, but T_{\parallel} is finite, $\phi_f = 0^\circ$, i.e., the initial polarization will be completely rotated back to be parallel to the c axis after transmission.

The measured transmittance under normal incidence of the M -plane GaN film is shown in Figs. 1(a) and 1(b) by the full symbols for polarization parallel ($\phi_i = 0^\circ$) and perpendicular to the c axis ($\phi_i = 90^\circ$) for 6 and 295 K, respectively. At both temperatures, we observe a significant shift of the effective energy gap towards higher energies for $\phi_i = 0^\circ$, i.e., $E \parallel c$, in comparison to $\phi_i = 90^\circ$, i.e., $E \perp c$. The band gap increases by 49 meV (60 meV) at 295 K (6 K). The larger separation at low temperatures may be due to a higher in-plane strain because of the larger thermal expansion coefficient mismatch compared to room temperature. A different inhomogeneous broadening of the two transitions at the two temperatures could also contribute to the difference in the separation. Note that the energy scales in Figs. 1(a) and 1(b) are identical in order to clearly demonstrate the redshift of the energy gap from low to room temperature. The different energy gaps for the two polarizations occur, because the

three uppermost VBs have changed their symmetry and energy separation due to the anisotropic in-plane strain as discussed in Ref. 13.

In order to experimentally prove the independence of the two transitions for $\phi_i=0^\circ$ and 90° , we have measured the angular dependence of the transmittance for ϕ_i between 0° and 180° . First, we confirmed that the transmittances for ϕ_i and $180^\circ - \phi_i$, e.g., for 60° and 120° , are the same. Second, we measured $T(\phi_i)$ for $\phi_i=15^\circ$ to 75° in steps of 15° , the results of which are shown by the open symbols in Fig. 1. Using Eq. (3), we calculated the transmittance for different values of ϕ_i from the measured transmittances $T_{\parallel}(\phi_i=0^\circ)$ and $T_{\perp}(90^\circ)$. The solid lines in Fig. 1 show the calculated transmittances, which agree very well with the measured data, proving the independence of the two transitions for $\phi_i=0^\circ$ and 90° .

A consequence of the large in-plane anisotropy is the rotation of the polarization vector in the energy range, where the transmittances (absorption coefficients) for the two orthogonal polarizations are very different. In this energy range, the film is dichroic. An incoming beam linearly polarized at an angle ϕ_i with respect to the c axis will be rotated to ϕ_f according to Eq. (5) by

$$\Phi = \phi_i - \phi_f = \phi_i - \arctan \left[\tan(\phi_i) \sqrt{\frac{T_{\perp}}{T_{\parallel}}} \right]. \quad (6)$$

Since in the energy range of interest $T_{\perp} < T_{\parallel}$ (cf. Fig. 1), the polarization rotation angle Φ will be positive so that the rotation will occur towards the c axis. In the ideal case, when T_{\perp} becomes orders of magnitude smaller than T_{\parallel} , the rotation angle Φ will become almost equal to ϕ_i . Experimentally, however, the ratio T_{\perp}/T_{\parallel} is considerably larger than in the ideal case due to a finite signal-to-noise ratio. Furthermore, the incident linearly polarized light will become elliptically polarized during transmission, since also the indices of refraction are different for both polarizations in this energy range, i.e., both the film and the substrate are birefringent. Figures 2(a) and 2(b) show the measured (full symbols) and calculated (open symbols) polarization rotation angles for linearly polarized light with $\phi_i=45^\circ$ at 6 and 295 K, respectively, as a function of energy. The agreement between the measured and calculated curves is very good. Note that in comparison to ZnO, for which the largest measured rotation angle is 10° ,¹⁸ the maximum measured rotation angle for M -plane GaN at 6 K is almost equal to 40° , which corresponds to about 90% of the expected rotation angle of 45° . According to Eq. (6), the smaller the value of the ratio T_{\perp}/T_{\parallel} , the larger the experimentally achievable rotation angle. Since the shift of the energy gap between the two polarization directions is much larger for our M -plane GaN film than for the ZnO film in Ref. 18, the minimum value of the ratio T_{\perp}/T_{\parallel} becomes much smaller for the GaN film in comparison to the ZnO film. This difference demonstrates the advantage of M -plane GaN over ZnO for devices based on polarization rotation.

In summary, we have demonstrated that for anisotropically strained M -plane GaN films with large values of the in-plane strain the transmittance for an arbitrary in-plane polarization angle can be described by a linear combination of the transmittances originating from two transitions being po-

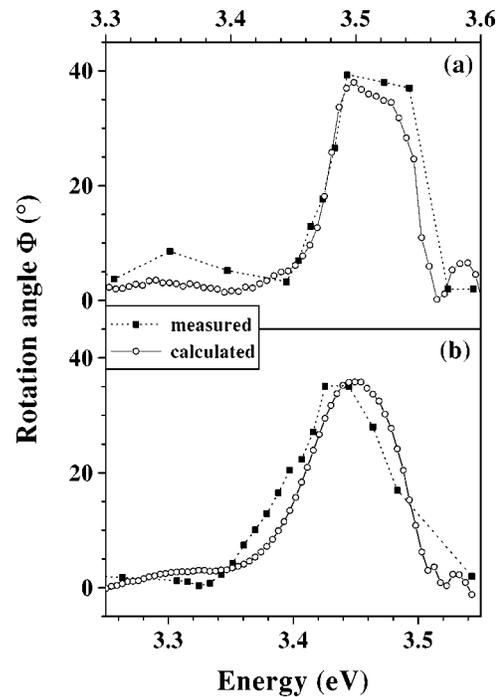


FIG. 2. Measured (full squares) and calculated (open circles) rotation angle Φ of the polarization vs energy for $\phi_i=45^\circ$ at (a) 6 and (b) 295 K for the M -plane GaN film.

larized parallel and perpendicular to the c axis. At the same time, M -plane GaN films can produce a very large rotation of the polarization vector, because within a certain energy range the transmittance for one polarization direction is orders of magnitude smaller than the transmittance for the orthogonal polarization direction.

- ¹H. Shen, M. Wraback, J. Pamulapati, P. G. Newman, M. Dutta, Y. Lu, and H. C. Kuo, Phys. Rev. B **47**, 13933 (1993).
- ²H. Shen, M. Wraback, J. Pamulapati, M. Dutta, P. G. Newman, A. Ballato, and Y. Lu, Appl. Phys. Lett. **62**, 2908 (1993).
- ³H. Shen, J. Pamulapati, M. Wraback, M. Taysing-Lara, M. Dutta, H. C. Kuo, and Y. Lu, IEEE Photonics Technol. Lett. **6**, 700 (1994).
- ⁴D. S. McCallum, X. R. Huang, A. L. Smirl, D. Sun, and E. Towe, Appl. Phys. Lett. **66**, 2885 (1995).
- ⁵R. Wirth, A. Moritz, C. Geng, F. Scholz, and A. Hangleiter, Appl. Phys. Lett. **69**, 2225 (1996).
- ⁶E. Greger, K. H. Gulden, P. Riel, H. P. Schweizer, M. Moser, G. Schmiedel, P. Kiesel, and G. H. Döhler, Appl. Phys. Lett. **68**, 2383 (1996).
- ⁷K. D. Choquette, R. P. Schneider, Jr., and J. A. Lott, Opt. Lett. **19**, 969 (1994).
- ⁸Y. H. Chen, C. I. Wilkinson, J. Woodhead, J. P. R. David, C. C. Button, and P. N. Robson, IEEE Photonics Technol. Lett. **9**, 143 (1997).
- ⁹E. Greger, P. Riel, M. Moser, T. Kippenberg, P. Kiesel, and G. H. Döhler, Appl. Phys. Lett. **71**, 3245 (1997).
- ¹⁰J. Krauss, T. Kippenberg, J. Spieler, P. Kiesel, G. H. Döhler, and M. Moser, Electron. Lett. **35**, 1878 (1999).
- ¹¹S. Ghosh, P. Waltereit, O. Brandt, H. T. Grahn, and K. H. Ploog, Appl. Phys. Lett. **80**, 413 (2002).
- ¹²S. Ghosh, O. Brandt, H. T. Grahn, and K. H. Ploog, Appl. Phys. Lett. **81**, 3380 (2002).
- ¹³S. Ghosh, P. Waltereit, O. Brandt, H. T. Grahn, and K. H. Ploog, Phys. Rev. B **65**, 075202 (2002).
- ¹⁴P. Waltereit, O. Brandt, M. Ramsteiner, R. Uecker, P. Reiche, and K. H. Ploog, J. Cryst. Growth **218**, 143 (2000).
- ¹⁵Y. J. Sun, O. Brandt, and K. H. Ploog, J. Vac. Sci. Technol. B **21**, 1350 (2003).
- ¹⁶T. C. Oakberg, *Linear Birefringence and Optical Rotation* (Hinds Instruments, Hillsboro, OR, 1992).
- ¹⁷P. Yeh, J. Opt. Soc. Am. **69**, 742 (1979).
- ¹⁸M. Wraback, H. Shen, S. Liang, C. R. Gorla, and Y. Lu, Appl. Phys. Lett. **74**, 507 (1999).