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Very narrow-band ultraviolet photodetection based on strained *M*-plane GaN films

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The authors demonstrate a photodetection configuration where the responsivity in the ultraviolet spectral region is limited to a few nanometers, representing high-quality-factor, narrow-band detection together with polarization sensitivity. Both features are obtained by utilizing a polarization-sensitive photodectector in combination with a polarization filter made from two identical *M*-plane GaN films on γ-LiAlO$_2$ (100) substrate. The optical band gap of these films depends on the direction of the in-plane polarization vector of the incident light beam with respect to the *c* axis. Electronic-band-structure calculations show that the naturally present anisotropic in-plane strain in these films is the crucial parameter to achieve both a high responsivity and a high polarization contrast. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2710769]

Group-III nitride semiconductors of the wurtzite crystal structure are increasingly used as ultraviolet (UV) photodetectors for applications[1–6] such as solar blind detection, UV radiation dosimetry, combustion control, flame sensors, atmospheric ozone and pollution detection, data storage, and very recently, polarization-sensitive detection.[7,8] In the area of biophotonics, the suitability of group-III nitride-based devices is being studied for real-time, laser-induced fluorescence detection of hazardous airborne biological and chemical agents.[9] For a rapid identification of a range of such chemical species, it is necessary to be able to simultaneously detect radiation emitted at specific wavelengths. This requires a set of photodetectors with very narrow-band spectral responsivity. The use of bandpass interference filters exhibiting a high quality factor in combination with a broadband detector is not ideal because of the usually poor UV transmission of typical dielectric coatings. The most common way to fabricate semiconductor UV photodetectors that operate only within a limited wavelength range is to integrate a passive filter layer into the device structure during growth. The filter layer has a larger band gap than the active region and absorbs the short-wavelength radiation, thereby limiting the short-wavelength responsivity, while the long-wavelength limit is determined by the band gap of the active region. For example, combinations consisting of Al$_{x_1}$Ga$_{1-x_1}$N as the active region and Al$_{x_2}$Ga$_{1-x_2}$N as the filter ($x_2 > x_1$) have been demonstrated with bandwidths ranging from 55 nm (Ref. 10) to 30 nm.[11] To achieve a bandwidth of 6 nm in the vicinity of 360 nm, this procedure would require very precisely controlled growth of layers with $x_1=0.00$ and $x_2=0.03$.

Here, we propose and demonstrate a different approach to achieve very narrow-band detection, which is based on GaN films of nonpolar orientation such as *M*-plane or *A*-plane films [see inset in Fig. 1(a)]. In such films, the effective optical band gap depends on the state of linear polarization of the incident light relative to the *c* axis, which lies in the film plane. Unlike the bandwidth-limited photodetectors described above, which are fabricated using *C*-plane films, our approach results in a detection system which is also sensitive to the state of polarization of the incident light. This added functionality may be helpful for a further reduction in spurious background signals and can yield more information in suitably designed applications.[12] Finally, we discuss how the in-plane strain in these films affects the performance of our narrow-band detection configuration (NBDC).

The 0.4 μm thick, $[1\bar{1}00]$ oriented *M*-plane GaN film was grown on a γ-LiAlO$_2$ (100) substrate using rf plasma-assisted molecular-beam epitaxy.[13] Its orientation and single-phase nature were verified using high-resolution x-ray diffraction (HRXRD) measurements, which also demonstrated that the film is under an overall compressive in-plane strain with an out-of-plane dilation $\epsilon_{yy}=0.39\%$. The in-plane strain is anisotropic, i.e., $\epsilon_{xx} \neq \epsilon_{zz}$. It is mainly determined by the lattice mismatch between the film and substrate but also depends on the difference in their thermal expansion coefficients along directions parallel and perpendicular to the *c* axis. By changing the film thickness, the in-plane strain can be varied within a certain range. Planar Schottky barrier photodetectors of circular geometry were fabricated from one piece of the wafer, while a polarization filter was taken from another piece of the same wafer. The active region of the photodetector with a radius of 200 μm has a semitransparent, rectifying Au (12 nm thick) contact with a surrounding Ohmic contact of Ti (50 nm)/Al (200 nm).[8] The optical measurements were performed using a 75 W Xe lamp and a reflection-grating-based monochromator. The light was po-

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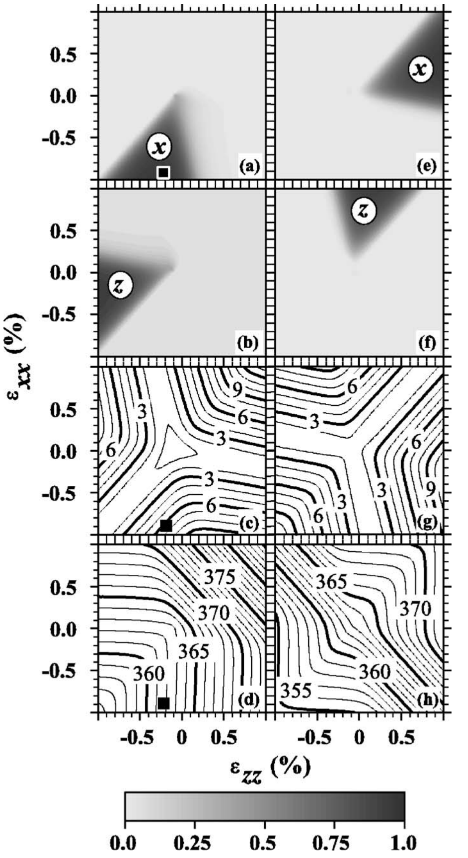

FIG. 3. (a) Positive values of $[f_{1x}-f_{1z}]f_{2z}$ and (b) $[f_{1z}-f_{1x}]f_{2x}$ as a function of in-plane strain in an M-plane GaN film. The dark regions indicate strain values favorable for NBDC involving the transitions T_1 and T_2. The label x (z) indicates that the polarization $\boldsymbol{E}\perp\boldsymbol{c}_{\mathrm{det}}$ ($\boldsymbol{E}\parallel\boldsymbol{c}_{\mathrm{det}}$) will be detected. (c) Detection bandwidth $\Delta\lambda$ and (d) central operating wavelength λ_c in nanometers for detection involving T_1 and T_2 [(a) and (b)]. Black squares mark the in-plane strain determined for the investigated M-plane GaN film. (e) Positive values of $f_{1y}[f_{2x}-f_{2z}]f_{3z}$ and (f) $f_{1y}[f_{2z}-f_{2x}]f_{3x}$ for detection involving T_2 and T_3. (g) $\Delta\lambda$ and (h) λ_c in nanometers for detection involving T_2 and T_3 [(e) and (f)].

for the operation of the NBDC, and a minimum bandwidth of $\Delta\lambda=3$ nm with high responsivity and polarization contrast can be achieved for compressive in-plane strain. We have ignored the combination T_1 and T_3, when T_2 is completely $\boldsymbol{y}$ polarized, since it results in a larger $\Delta\lambda$.

Comparing the HRXRD and optical spectroscopy data with the results of the EBS calculations, we can assign the transition edge in our film for $\boldsymbol{E}\perp\boldsymbol{c}$ ($\boldsymbol{E}\parallel\boldsymbol{c}$) to T_1 (T_2) and estimate the in-plane strain to be $\epsilon_{xx}\approx-0.9\%$ and $\epsilon_{zz}\approx-0.22\%$. These values fall in the dark region of Fig. 3(a) (marked by a square). The corresponding calculated values of $\Delta\lambda=6$ nm and $\lambda_c=361.5$ nm agree fairly well with the measured values for the NBDC. Note that a 1 μm thick M-plane film on γ-LiAlO$_2$ typically has in-plane strain[17] corresponding to the dark region of Fig. 3(a). The utilization of thicker films in the NBDC can further improve the rejection at $\lambda<\lambda_{\mathrm{short}}$ by a factor larger than 250. Due to the symmetry of the wurtzite crystal structure, these results are also valid for anisotropic strain in A-plane GaN films with x and y interchanged everywhere.[15] For a shorter (longer) λ_c, one can use suitable Al$_x$Ga$_{1-x}$N (In$_x$Ga$_{1-x}$N) alloy compositions, for which similar calculations are necessary to determine the strain required for optimal performance.

In conclusion, we have proposed and demonstrated very narrow-band photodetection in the UV spectral range using wurtzite group-III nitride films of nonpolar orientation, which in addition to its narrow-band spectral responsivity is also polarization sensitive. The anisotropic in-plane strain, which is naturally present in such films, is essential for the efficient operation of such a detection system. This configuration, when used specifically for polarization sensing, may perform better than the bare polarization-sensitive photodetector[8] because the limited spectral bandwidth ensures a lower spurious background signal.

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[20] The deformation potentials are $\alpha_{\mathrm{CB}}=-44.5$ eV, $D_1=-41.4$ eV, $D_2=-33.3$ eV, and $D_5=-3.6$ eV. The crystal-field and spin-orbit splitting energies are $\Delta_{\mathrm{cr}}=\Delta_1=9.2$ meV and $\Delta_{\mathrm{so}}=3\Delta_2=18.9$ meV. The other parameters are obtained under the quasicubic approximation. The exciton binding energies are taken to be 26 meV. The wavelength of the unstrained A-exciton transition is taken to be 363.6 nm at 297 K. The elastic constants are $C_{11}=390$ GPa, $C_{12}=145$ GPa, $C_{13}=106$ GPa, and $C_{33}=398$ GPa.