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In-plane electric field induced by polarization and lateral photovoltaic effect in *a*-plane GaN

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A lateral photovoltaic effect was observed in *a*-plane GaN films grown on *r*-plane sapphire at room temperature. Under various light sources illuminations, contacts along the *c*-axis exhibited about ten times the photovoltage than those along the *m*-axis, which kept linear relationship with the illumination intensity. It was attributed to anisotropic in-plane electrical field induced by the intrinsic spontaneous/piezoelectric polarization, which spatially separated photogenerated carriers to produce the photovoltage. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3144270]

Due to the asymmetric of wurtzite structures, the piezoelectric/spontaneous polarization is III-nitrides inherent property. Conventional nitrides-based opt-/electronic devices are grown along the *c*-axis. The piezoelectric/spontaneous polarization is proved to greatly affect *c*-plane materials and devices performances. For AlGaN/GaN heterojunction, the built-in electrical field induced by the polarization causes the free electrons to congregate preferentially to form the two-dimensional electron gas.[1] However, for light-emitting diode (LED) or laser diode (LD), this built-in electrical field spatially separates electron-holes pairs, the so-called quantum-confined Stark effect (QCSE), which redshifts the emission peak and reduces the combination efficiency.[2]

To overcome QCSE, many groups turned to develop nitrides grown along the nonpolar directions: *a*- or *m*-plane GaN,[3–5] and nonpolar InGaN/GaN LEDs (Ref. 6) and LDs (Ref. 7). Nonpolar does not mean no polarization, which just changes the polarization direction from the out-of-plane direction to the in-plane direction. Unfortunately, this in-plane polarization is commonly neglected. By now, only Metcalfe *et al.*[8] observed enhanced terahertz emission in nonpolar GaN and they attributed it to the in-plane electric field induced by intrinsic spontaneous/piezoelectric polarization. Based on the well-known mechanism of photovoltaic (PV) effects,[9–11] we predict that this in-plane electric field can separate photogenerated carriers to create photovoltage. Further, lateral PV effect is demonstrated in *a*-plane GaN and *a*-plane $In_{0.2}Ga_{0.8}N/GaN$ multiquantum wells (MQWs).

All samples were grown on *r*-plane sapphire substrates by MOVPE. Trimethylgallium, trimethylindium, and ammonia (NH_3) were used as the source of Ga, In, and N, respectively. In our experiments, the optimum growth temperature was 1060 °C. Under this temperature, we got the best sample, which was labeled as sample A. For comparison, another sample grown under 1080 °C was chose as sample B. In addition, *a*-plane $In_{0.2}Ga_{0.8}N/GaN$ by five MQWs was also grown on sample A, which was labeled as sample C. The thicknesses of $In_{0.2}Ga_{0.8}N$ and GaN were 4.5 and 7.0 nm, respectively. The crystal quality and stress were characterized by high-resolution x-ray diffraction (XRD). Atomic force microscopy (AFM) and Hall measurements were performed to characterize morphology and electrical properties, respectively. PV effects were measured under 325 and 213 nm UV laser illumination. The intensity and spot size of 325 nm UV laser were 14.6 kW/m^2 and 0.78 mm^2, respectively, and the intensity and spot size of 213 nm UV laser were 5.3 kW/m^2 and 0.95 mm^2, respectively. A series of neutral density filters were inserted into optical route to change relative illumination intensity from 100% to 0.1%. The samples were cut into 5×5 mm^2 squares. Common Ohmic contact metallization, Ti/Al (20nm/100nm),[12] were deposited by e-beam evaporation along *c*-axis and *m*-axis, and the size was about 1×1 mm^2. The PV measurements and contact pattern were illustrated in Fig. 1.

The total polarization is the sum of the spontaneous/piezoelectric polarization: $P_{tol}=P_{pe}+P_{sp}$. In *a*-plane GaN, ideal spontaneous polarization[1] is $P_{sp}=-0.029$ C/m^2 and piezoelectric polarization[1] can be calculated by $P_{pe}=e_{33}\varepsilon_c+e_{31}\varepsilon_a+e_{31}\varepsilon_m$, where ε_i and e_{ij} are the strain and the piezoelectric coefficients, respectively. As the stress component

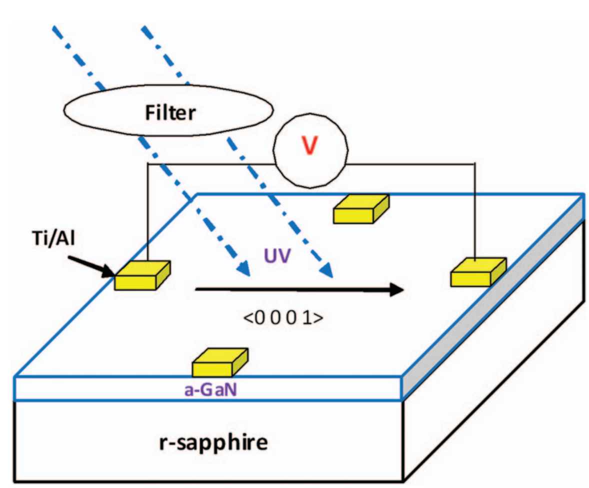

FIG. 1. (Color) Schematic illustration of the PV measurements.

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TABLE I. Polarization in ideal GaN, $In_{0.2}Ga_{0.8}N$, sample A, and sample B.

Sample	P_{pe} ($\times 10^{-2}$ C/m^2) c-axis	P_{pe} m-axis	P_{sp} ($\times 10^{-2}$ C/m^2) c-axis	P_{sp} m-axis	P_{tol} ($\times 10^{-2}$ C/m^2) c-axis	P_{tol} m-axis
a-plane $In_{0.2}Ga_{0.8}N$ without relaxation	1.801	0	−2.960	0	−1.158	0
a-plane GaN without relaxation	3.341	0	−2.900	0	0.441	0
Sample A	0.045	0	−2.900	0	−2.855	0
Sample B	0.006	0	−2.900	0	−2.894	0

along the growth direction vanishes because the surface is free to expand or contract, it can be shown that $\varepsilon_a = -C_{13}/C_{11} \times \varepsilon_c - C_{12}/C_{11} \times \varepsilon_m$,[13] where C_{ij} are the elastic constants of the GaN.[14] All parameters of InN and GaN can be founded in Refs. 1 and 14 and those of InGaN are deduced by Vegard interpolation.

Theoretically, *a*-plane GaN has large lattice mismatches with *r*-plane sapphire in the *m*- and *c*-axis of −16% and −1%, respectively. For sample A and sample B, XRD results revealed that most of stress was relaxed. No cracks were observed in sample A and sample B with optical microscopy and AFM. The main relaxation should be attributed to high density dislocations or stacking faults. Table I exhibited polarization deduced in ideal GaN, $In_{0.2}Ga_{0.8}N$, sample A, and sample B. From Table I, we found that stress relaxation greatly influenced total polarization: with neglecting stress relaxation, ideal total polarization was only 0.004 C/m^2. However, in sample A and sample B, this value was large to −0.028 C/m^2. In addition, we noticed that the piezoelectric polarization commonly opposite to the spontaneous polarization. It means that zero polarization can be achieved by controlling stress.

For *c*-plane III-nitrides, various measurements and theories proves that a large to MV/cm electric field is induced by the piezoelectric/spontaneous polarization. For *a*-plane GaN, Metcalfe *et al.*[8] proved an in-plane electric field with terahertz emission and deduced it to be 0.29 MV/cm with neglecting stress effect.[8] Most of stress was relaxed in our sample A and sample B, which is consistent with Metcalfe's[8] presumption. Thus, this MV/cm-order anisotropic in-plane electric field also appeared in our samples.

PV devices such as solar cells work with below three physical processes: (1) absorb photons to generate excess carrier, (2) under the built-in field, the electrons and holes are spatially separated, and (3) electrodes collect the electrons and holes to produce voltage. For PV device fabrication, the built-in electric field is important, which commonly is achieved by adopting *p-n* junction, Schottky contacts, or polarizations. For nonpolar III-nitrides, this built-in electric field is spontaneously induced by polarization. Therefore, the lateral PV effect can be expected along the *c*-axis. In fact, surface photovoltage is obtained in *c*-plane III-nitrides,[15] which reveal that out-of-plane polarization separates electrons and holes. Additionally, the in-plane electrical field is proved to generate a lateral photovoltage, 7 V, in a ferroelectric film.[11]

The crystal qualities of the *a*-plane GaN were characterized in Fig. 2(a). The classic M-shape dependence on the azimuth angle is observed in sample A and sample B, which is commonly attributed to the anisotropic partial dislocation distribution, mosaic tilt, small lateral coherence lengths of the mosaic blocks, and anisotropic bending in the two perpendicular in-plane directions.[16,17] In sample A, full width at half maximum (FWHM) values of (11–20) omega scan are 430–870 arc sec. In sample B, these values are 740–1080 arc sec. AFM images are shown in Figs. 2(b) and 2(c). Sample A and sample B exhibit typical *a*-plane GaN morphologies. Primarily, crystallographic terraces perpendicular to the *c*-axis and submicron surface pits associate with threading dislocation terminations. The submicron surface pits density of sample A is smaller than that of sample B, which is basically consistent with FWHM values change. Electrical properties were revealed by Hall measurements. Carrier density values of sample A and sample B are 1.7×10^{16} and 3.3×10^{16} cm^{-3}, respectively, which keeps a same order with unintentional doping *c*-plane GaN. The mobility values of sample A and sample B are 10.6 and 9.2 cm^2/V s, respectively.

PV measurements results were exhibited in Fig. 3. In all of PV measurements, Ti/Al contacts along the *c*-axis exhib-

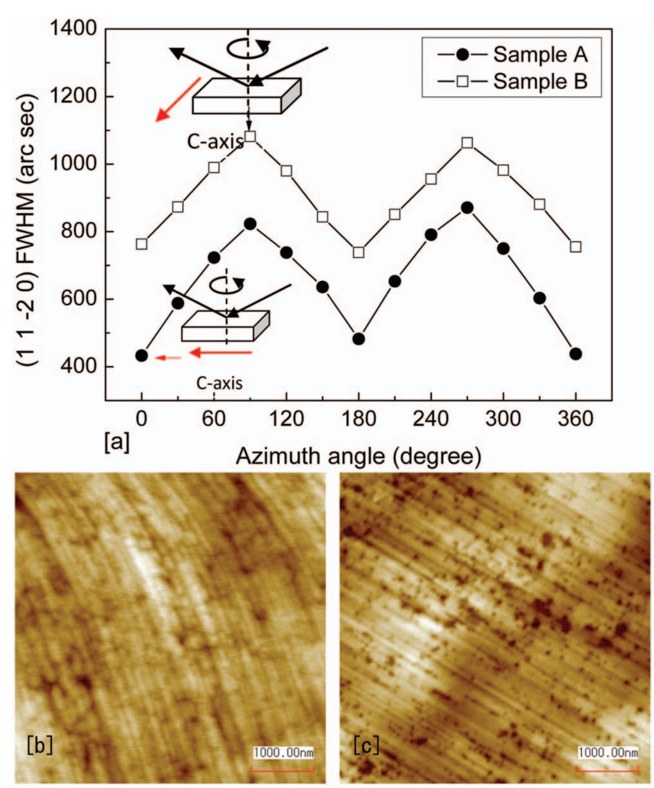

FIG. 2. (Color) (a) Azimuth angle dependence of the FWHM of the $(11\bar{2}0)$ rocking curves. (b) 5×5 μm^2 AFM images of sample A. (c) 5×5 μm AFM images of sample B.

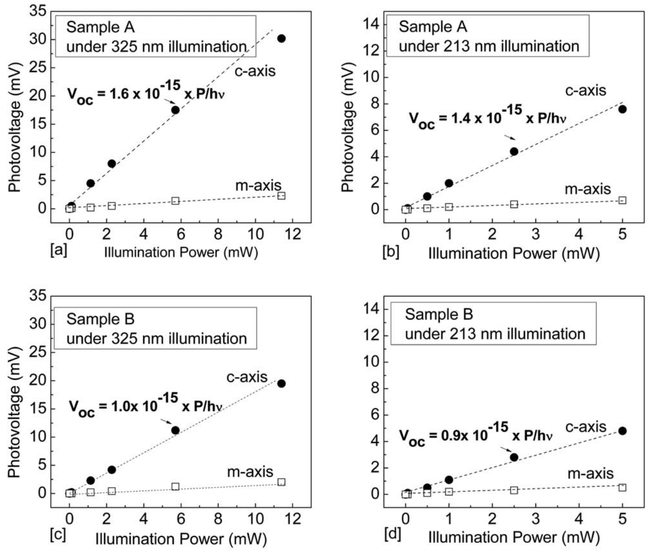

FIG. 3. PV measurement results. (a) Sample A under 325 nm illumination. (b) Sample A under 213 nm illumination. (c) Sample B under 325 nm illumination. (d) Sample B under 213 nm illumination.

ited about ten times large open-circle photovoltage than those along *m*-axis. Because all contacts were uniform and symmetric, the large difference of photovoltage between along *c*-axis and *m*-axis was attributed to the anisotropic polarization. Furthermore, by decreasing relative illumination intensity from 100% to 0.1%, we got a linear relationship between the photovoltage (V_{oc}) and photon number (N), $V_{oc}=C\times N=C\times P/h\nu$, where P is illumination power and $h\nu$ is photon energy. Similar linear relationship has been proved in various systems such as *c*-plane GaN (Ref. 15) and cubic GaN/GaAs,[18] and the coefficient C was theoretically deduced to depend on the geometry structure of sample and materials properties. Because the photon energy of 325 or 213 nm UV laser is far larger than the GaN band gap, photogenerated carriers contains all contributions such as band gap, defect, and exciton related absorption and so on. In this case, photogenerated carriers' density is approximately proportional to photon number (N). Thus, under 325 and 213 nm UV laser illuminations, same sample exhibits approximate coefficient C. Additionally, sample A exhibits a larger C value than sample B. It can be attributed to the worse crystal quality of sample B, which results in contradictory polarization to weak in-plane electrical field.

Based on this lateral PV effect, lateral PV devices such as solar cell, may get developed. The open-circle photovoltage were measured under out-of-door solar illumination as shown in Table II. Along the *c*-axis, the photovoltage of sample A and sample B are 58.1 and 38.8 mV, respectively. Along the *m*-axis, the photovoltage of sample A and sample B are 4.8 and 4.3 mV, respectively. Recently, InGaN becomes a powerful candidate for solar cell and theoretical convert efficiency is large to 40.3% at air mass (AM) 1.5.[19–21] Unfortunately, it is still difficult to achieve high-quality *a*-plane InGaN due to supercritical growth condition. Instead, an $In_{0.2}Ga_{0.8}N/GaN$ by five MQWs, were grown on the sample A. Anisotropic PV effect is proved in Sample C: photovoltage along the *c*-axis and *m*-axis are 75.6 and 5.2

TABLE II. PV measurement results under out-of-door illumination.

Sample	Thickness	Photovoltage under out-of-door illumination	
		c -axis (meV)	*m* -axis (meV)
Sample A	6.6 μm	58.1	4.8
Sample B	7.1 μm	38.8	4.3
Sample C	$In_{0.2}Ga_{0.8}N$:4.5 nm GaN: 7.0 nm	75.6	5.2

mV, respectively. By increasing In-content and thickness, the photovoltage is expected to get further enhanced.

In conclusion, we observed anisotropic lateral PV effect in *a*-plane GaN and *a*-plane $In_{0.2}Ga_{0.8}N/GaN$ MQWs. This phenomenon proved that the anisotropic in-plane electrical field was induced by the spontaneous/piezoelectric polarization. In addition, under out-of-door illumination $In_{0.2}Ga_{0.8}N/GaN$ by five MQWs exhibits 75.6 mV photovoltage along *c*-axis, which indicates a kind lateral PV device.

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