**In situ** strain measurements on GaN/AlGaN Schottky diodes with variable bias

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**In situ** high resolution x-ray diffraction measurements were performed on AlGaNGaN Schottky diodes under variable bias conditions. The results show a linear variation in strain for the GaN channel with bias. For forward bias conditions, an in-plane tensile strain was observed, whereas for reverse bias a compressive strain was present. A discontinuity in the strain for the reverse bias measurements was also present because the width of the depletion region exceeds the ~2 μm GaN layer. The linear variation in the strain caused by variable bias may be due to a change in the piezoelectric charge at the AlGaN/GaN interface. © 2008 American Institute of Physics.

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Aluminum gallium nitride/gallium nitride (AlGaN/GaN) based high electron mobility transistor (HEMT) devices have superior characteristics, which are useful in making electronic, optoelectronic, high-temperature, and high-power devices.₁,² AlGaNGaN HEMTs have the ability to achieve very high power densities with minimal cooling due to the very high breakdown field of GaN, which is estimated to be 3 MV/cm.³ Significant progress has been made in the fabrication and electrical characterization of the AlGaN/GaN HEMT devices.₄⁻⁷ The AlGaN/GaN HEMT structures have shown high electron mobility (>1500 cm²/V s), resulting in low channel resistivity values. However, it has been shown both for zinc-blende semiconductors with a (111) orientation⁵ as well as for III nitrides with a (0001) orientation⁶ that piezoelectric effects can vary the charge density and electric field distributions within these materials. It has been shown that piezoelectric polarization in hexagonal AlGaN/GaN heterostructures leads to an increase in the carrier concentration at the interface.₆⁻¹₀ In addition, pseudomorphically grown AlGaN/GaN layers have strain, which contributes to a piezoelectric field at the interface. It has also been reported that due to this polarization, the electron and hole wave functions are spatially separated in the AlGaN/GaN quantum well, thereby affecting the two-dimensional electron gas (2DEG).¹⁵

Furthermore the polarization effects due to piezoelectric fields and other surface states in AlGaN/GaN HEMT devices have been reported and correlated with the density of the 2DEG.¹⁶⁻¹⁷ They show a significant increase in the carrier concentration as a result of an increase in the strain induced piezoelectric charge at the AlGaN/GaN interface. It has been found in these studies that both when the Al concentration is increased or when the AlGaN layer thickness is increased the piezoelectric charge increases due to the strain at the AlGaN/GaN interface.

Although the correlation of strain induced piezoelectric charges and carrier concentration at the AlGaN/GaN interface has been studied, it is important to know the variation in the strain with applied bias in these devices. This would provide further insight into the 2DEG density in the GaN channel and the transport properties of the AlGaN/GaN devices. In this work, we attempt to observe the variation in strain due to the change in bias applied to the AlGaN/GaN Schottky diodes. Using **in situ** high resolution x-ray microdiffraction techniques, we obtained the localized strain and the respective rocking curves of the GaN channel. This non-destructive technique is very useful because it provides the bias dependent variation in the material parameters, within the active device region. Additionally, the extrapolated piezoelectric charges from the strain measurements can also be correlated with the bias applied to the device.

The AlGaN/GaN samples were grown epitaxially on sapphire substrate using metalorganic chemical vapor deposition. An unintentionally doped 2 µm thick GaN channel layer was grown, followed by an undoped 250 Å Al₀.₇₅Ga₀.₂₅N layer. The Schottky diodes were fabricated by lift-off lithography using Ni/Au metallization. The diode structure consists of 115 µm diameter Schottky dots separated from the field metal by exposed (lift-off metal) ring areas. The separation between a dot and the field metal area is 70 µm. The field metal surrounding the exposed ring regions is considered as the body metal contact for the semiconductor. This structure inherently has a high series resistance due to the field metal being on the AlGaN layer, which results in a large forward voltage drop. We measured the series resistance from the inverse slope of the linear segment of the forward I-V characteristics and found it to be ~2.7 kΩ.

High resolution x-ray rocking curve measurements were made using a triple axis four-circle Rigaku ATX-E diffractometer. Two channel-cut Ge (220) crystals were used to monochromatize the incident beam and to obtain pure Cu Kα₁ radiation. In this configuration, the horizontal divergence component θ₀ is minimized and the rocking curve widths represent the intrinsic value of the sample. The diffractometer also has an open Eulerian cradle with independent χ (tilt) and φ (rotation) movements and an x, y, z moving stage. This enables us to align the sample perfectly. In order to obtain the rocking curves from the region of the device under bias, the incident beam slits were used to collimate the incident x-ray beam. X-ray rocking curves were measured by varying bias conditions. Thus, the measured
rocking curves provide structural information on strain located in the device area under variable bias conditions.

A Tektronix Type 576 Curve tracer was used to apply/measure the bias during the high resolution x-ray measurements. Wire bonding was performed in order to make contacts to the Schottky diode dots and the GaN body contact. Forward bias was applied in the range of 0–10 V and reverse bias was applied in the range from 0 to −100 V. Large forward bias is the result of large series resistance between the electrodes of the diode. The device under bias was allowed to settle for 10 s before making the x-ray measurements.

Figure 1 shows a rocking curve measured for the (004) reflection of the GaN channel under no bias condition. The full width at half maximum (FWHM) value is ∼300 arc sec, suggesting a dislocation density of ∼2×10^8 lines/cm^2, and this high dislocation density is attributed to the relaxation of strain due to lattice mismatch of GaN with the sapphire substrate. The depletion width for 50 V reverse bias is calculated using the relation

\[ W = \left[ \frac{2e(V_0 - V)}{q N_d} \right]^{1/2}, \]

where \( e = 8.41 \times 10^{-13} \) F/cm is the permittivity of GaN, \( q \) is the electric charge, and \( N_d \) (∼10^{16}/cm^3) is the doping concentration. The depletion width for 50 V reverse bias is calculated to be 2.2 μm, which is roughly the thickness of the GaN layer for this device structure.

Using least squares fitting the following equations were obtained for the in-plane strain:

For forward bias:

\[ \varepsilon_1 = 1.3652 \times 10^{-5} + 1.9715 \times 10^{-6}X, \] (4)

For reverse bias < 50 V:

\[ \varepsilon_1 = 3.1899 \times 10^{-5} - 4.3545 \times 10^{-6}X. \] (5)

The piezoelectric polarization in a strained material can be computed using the relation

\[ P_{\text{PE}} = \varepsilon_{33} \varepsilon_1 + 2\varepsilon_{31} \varepsilon_3. \] (6)

where \( \varepsilon_{33} = 1 \) C/m^2 (Ref. 23) and \( \varepsilon_{31} = -0.49 \) C/m^2 (Ref. 24) are piezoelectric coefficients of GaN. The AlGaN/GaN interface has a much higher piezoelectric polarization variation in the in-plane strain with forward and reverse biases, respectively. We can see from Fig. 3(a) that the strain is positive, which reflects increasing tensile strain in the GaN channel, whereas in Fig. 3(b) the strain is negative and decreasing, which means that a compressive strain is developed in the GaN channel. Also in Fig. 3(b) we see a discontinuity in the strain after −50 V, which is due to the depletion of the entire GaN layer causing considerably high strain in the material. The depletion width with applied bias for a Schottky diode is calculated using the relation

\[ W = \left[ \frac{2e(V_0 - V)}{q N_d} \right]^{1/2}, \] (3)

where \( e = 8.41 \times 10^{-13} \) F/cm is the permittivity of GaN, \( q \) is the electric charge, and \( N_d \) (∼10^{16}/cm^3) is the doping concentration. The depletion width for 50 V reverse bias is calculated to be 2.2 μm, which is roughly the thickness of the GaN layer for this device structure.

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where \( \varepsilon_{33} = 1 \) C/m^2 (Ref. 23) and \( \varepsilon_{31} = -0.49 \) C/m^2 (Ref. 24) are piezoelectric coefficients of GaN. The AlGaN/GaN interface has a much higher piezoelectric polarization
compared to other III-nitride semiconductor heterostructures even at zero bias due to strain at the interface. In this study we report the strain relative to the strain at zero bias for the calculation of the piezoelectric polarization. Also, we assume that all the bias induced strain may contribute to the piezoelectricity and find the upper limit of the polarization field, which is in the ranges from \(-1.1 \times 10^{-4}\) to \(-2.1 \times 10^{-4}\) C/m² for forward bias and from \(5 \times 10^{-4}\) to \(12 \times 10^{-4}\) C/m² for reverse bias before the possible depletion of the entire GaN layer. We can also compute the maximum change in the sheet carrier concentration using the relation

\[
\Delta n_s = \frac{P_{PE}}{e}. \tag{7}
\]

The change in the sheet carrier concentration with applied bias is found to be in the range of \(10^{10} - 10^{12}\) cm⁻². This change in the sheet concentration is significant for reliable device operation since the 2DEG density depends on the bias. This effect needs to be considered for accurate device modeling.

In conclusion, the high resolution x-ray rocking curve measurements were performed in situ on AlGaN/GaN Schottky diodes as a function of applied bias. The in-plane strain for the GaN channel region of the AlGaN/GaN Schottky diodes as a function of applied forward and reverse bias was in the ranges of \((1.7 - 3.36) \times 10^{-5}\) for 0–10 V forward bias and \(-7.7 \times 10^{-5}\) to \(-111.4 \times 10^{-5}\) for the reverse bias from 0 to \(-100\) V. The strain was found to vary linearly with increasing bias, but there was a discontinuity in the strain measurements for reverse bias greater than 50 V due to possible depletion of the entire GaN layer. The piezoelectric polarization due to the bias induced strain is calculated and found to be in the range from \(-1.1 \times 10^{-4}\) to \(-2.1 \times 10^{-4}\) C/m² for forward bias. For reverse bias we calculated \((5 - 12) \times 10^{-4}\) C/m² before the carrier depletion width exceeds the \(2.2\) μm thick GaN layer. This polarization causes a change in the sheet carrier concentration in the range of \(10^{10} - 10^{12}\) cm⁻², which may cause a variation in the 2DEG density in the GaN channel of the AlGaN/GaN devices. The variation in the 2DEG density due to the bias induced strain may result in unpredictable operation of the device and needs to be considered for the correct modeling of the device transport characteristics.

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