2006

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(Received 29 December 2005; accepted 2 March 2006; published online 9 June 2006)

The current-voltage characteristics of *n*-GaN/*u*-AlGaN/*n*-GaN heterostructure devices are investigated for potential pressure sensor applications. Model calculations suggest that the current decreases with pressure as a result of the piezoelectric effect, and this effect becomes more significant with thicker AlGaN layers and increasing AlN composition. The change in current with pressure is shown to be highly sensitive to the change in interfacial polarization charge densities. The concept is verified by measuring the current versus voltage characteristics of an *n*-GaN/*u*-$Al_{0.2}Ga_{0.8}N$/*n*-GaN device under hydrostatic pressure over the range of 0–5 kbars. The measured current is found to decrease approximately linearly with applied pressure in agreement with the model results. A gauge factor, which is defined as the relative change in current divided by the in-plane strain, approaching 500 is extracted from the data, demonstrating the considerable potential of these devices for pressure sensing applications. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2200742]

I. INTRODUCTION

Group III-nitride based devices have demonstrated excellent potential for high power, high frequency, and high temperature electronics.[1,2] The III-nitrides are particularly attractive materials for sensor applications due to their ability to operate in harsh environments. Distinguishing features of wurtzite structure III-nitrides are their spontaneous polarization and large piezoelectric constants, which may be useful for stress sensing applications. Examples of suitable effects include the piezoresistivity of AlGaN layers and AlGaN/GaN heterostructures,[3,4] the piezoresistivity of *p*-GaN,[5] the stress dependence of the Schottky barrier heights on *n*-GaN and *n*-AlGaN,[6,7] and the effect of pressure on the dc characteristics of AlGaN/GaN heterostructure field effect transistors (HFETs).[8]

Wurtzite structure III-nitride compounds possess a so-called spontaneous polarization parallel to their hexagonal crystal axes. In addition, there are usually piezoelectric polarizations in epitaxial AlGaN and GaN layers because of built-in strain due to their inherent lattice mismatch and due to the mismatch between their lattice constants and that of the foreign substrates on which the structures are grown. Hence, differences in the polarizations of the AlGaN and GaN layers of [0001]-oriented GaN/AlGaN/GaN heterostructures produce polarization charge densities of equal magnitude but opposite sign, $\pm\sigma$, at the two interfaces. If the structure is doped and mobile carriers are available, the interfacial polarization charges induce accumulation and depletion layers on the two sides of the AlGaN layer, as shown in Fig. 1. Applying a voltage between the two GaN layers causes a current to flow across the AlGaN layer. Even though the structure is symmetric in its composition (and may even be made symmetric in its doping profile) the resulting current-voltage (*I-V*) characteristics can be highly asymmetric due to the nonsymmetric space charge profile. Data for the *I-V* characteristics of these devices at atmospheric pressure have been reported.[9,10]

Applied stress changes the polarization charges at the AlGaN/GaN interfaces due to the piezoelectric effect. This phenomenon may be exploited to measure stress by measuring the resulting change in current parallel to the interface in

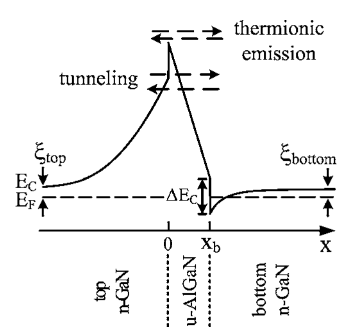

FIG. 1. Schematic diagram of the band profiles for an *n*-GaN/*u*-AlGaN/*n*-GaN heterostructure in equilibrium.

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AlGaN/GaN HFETs (Ref. 8) or by measuring the current across the AlGaN layer in the n-GaN/u-AlGaN/n-GaN heterostructures explored in this work. The mechanism by which the interfacial polarization charges control the current is quite different in the two kinds of devices. In AlGaN/GaN HFETs, the polarization charge determines the threshold voltage and consequently the charge carrier density in the channel. The change in drain current, ΔJ, is proportional to the change in the interfacial polarization charge density, $\Delta\sigma$.[8] For the GaN/AlGaN/GaN devices, the current across the interfaces (normal to the device surface) depends exponentially on the effective potential barrier height, which itself to first order is linearly dependent on $\Delta\sigma$. Based on this qualitative difference greater control over the sensitivity to stress may be expected for the GaN/AlGaN/GaN heterostructure devices. In this paper, we present a theoretical and experimental study of the effect of hydrostatic pressure on the I-V characteristics of GaN/AlGaN/GaN heterostructures.

II. THEORETICAL MODEL

The GaN/AlGaN/GaN heterostructure devices discussed here are all assumed to be grown on 6H-SiC or 4H-SiC in the [0001] direction (Ga polarity), as shown in Fig. 1. The regional model constructed is based on the assumption that the current is limited by the AlGaN barrier layer and that the regions outside that barrier are in local thermal equilibrium. Hence, modeling begins by solving Poisson's equation with suitable boundary conditions:

$$\frac{d^2\phi(x)}{dx^2} = -\frac{\rho(x)}{\varepsilon\varepsilon_0}, \tag{1}$$

where $\phi(x)$ is the potential and $\rho(x)$ is comprised of the interfacial polarization charge densities, $-\sigma\delta(x)$ and $+\sigma\delta(x-x_b)$, and the charge densities of the electrons and the ionized donors. The nominally undoped u-AlGaN layer thickness is designated by x_b, and the GaN layers are assumed to be doped n type with donors that have an ionization energy of 30 meV.[11] The conduction band profile $E_C(x)$ is obtained from $\phi(x)$ by adding the flat band profile of the conduction band of the GaN and AlGaN layers, which have band offset ΔE_C:

$$E_C(x) = \Delta E_C[\theta(x) - \theta(x-x_b)] - e\phi(x), \tag{2}$$

where $\theta(x)$ is the unit step function.

The electric fields at the interfaces satisfy

$$\varepsilon_{\mathrm{AlGaN}}\varepsilon_0 F_{\mathrm{AlGaN}} + P_{\mathrm{AlGaN}} = \varepsilon_{\mathrm{GaN}}\varepsilon_0 F_{\mathrm{GaN}} + P_{\mathrm{GaN}}, \tag{3}$$

where F_{AlGaN} and F_{GaN} are the electric fields on the AlGaN and GaN sides of the interfaces, respectively, and P_{AlGaN} and P_{GaN} are the total polarizations of the AlGaN and GaN layers. Under applied bias V_a, the external boundary conditions are

$$E_C(-\infty) - \xi_{\mathrm{top}} - eV_a = E_C(\infty) - \xi_{\mathrm{bottom}}, \tag{4}$$

where ξ_{top} and ξ_{bottom} are the differences between the equilibrium conduction band edge and the Fermi level in the flat band regions of the top ($x<0$) and bottom ($x>x_b$) n-GaN layers, respectively.

TABLE I. ε_{zz} for $Al_xGa_{1-x}N$ on SiC under 10 kbar pressure, σ_0 (in C/m^2) for GaN/$Al_xGa_{1-x}N$/GaN heterostructure devices, and $\Delta\sigma$ (in C/m^2) and $\Delta\sigma/\sigma_0$ for these devices under 10 kbar pressure.

x	ε_{zz}	σ_0	$\Delta\sigma$	$\Delta\sigma/\sigma_0$ (%)
0.10	-2.210×10^{-3}	0.0065	1.02×10^{-4}	1.57
0.15	-2.192×10^{-3}	0.0101	1.51×10^{-4}	1.50
0.20	-2.174×10^{-3}	0.0139	1.98×10^{-4}	1.43

The current across the AlGaN barrier layer is assumed to be limited by a combination of tunneling through and thermionic emission over the potential barrier. The tunneling probability is calculated in Wentzel-Kramers-Brillouin (WKB) approximation.[12] (The small difference in the effective masses of AlGaN and GaN is neglected.) Defining a total transmission coefficient $\tau(E,V_a)$ the current density including tunneling and thermionic emission emanating from the top side of the barrier, J_{top}, is calculated as[12]

$$J_{\mathrm{top}} = \frac{A^*T}{k}\int_{E_{\min}}^{\infty} f_{\mathrm{top}}(E)\,\tau(E,V_a)\,dE, \tag{5}$$

where A^* is the effective Richardson constant, $f_{\mathrm{top}}(E)$ is the Fermi-Dirac distribution function with the quasi-Fermi level of the top n-GaN layer, and $E_{\min}$ is defined as the higher of the lowest conduction band energies for the top and bottom GaN layers:

$$E_{\min} = \max\{\min[E_C(x\leqslant 0)], \min[E_C(x\geqslant x_b)]\}. \tag{6}$$

The quasi-Fermi level in the bottom GaN layer is different from that of the top layer and the Fermi-Dirac distribution for the bottom layer is designated by $f_{\mathrm{bottom}}(E)$. The current density from the bottom to the top layer, J_{bottom}, may then be calculated in analogy to Eq. (5) and the total current density is obtained as $J = J_{\mathrm{top}} - J_{\mathrm{bottom}}$.

GaN grown on SiC is usually under compressive stress, but occasionally under tensile stress.[13–15] The exact in-plane stress in GaN on SiC depends strongly on growth conditions, film thickness, and AlN buffer layer, and the magnitude can be quite large.[13–15] Furthermore, the thin AlGaN layer should be pseudomorphically strained because of its mismatch to GaN. Hence, the interfacial polarization charge density at atmospheric pressure, σ_0, results from three contributions: the difference between spontaneous polarizations of AlGaN and GaN, the piezoelectric polarization due to lattice mismatch between AlGaN and GaN, and the piezoelectric polarization due to lattice (and thermal expansion) mismatches between the nitrides and the SiC substrates. It can be shown that the latter contribution is much smaller than the other two and can be neglected. For the calculations described in this work all parameters are taken from the paper by Ambacher *et al.*[16] Table I lists σ_0 for three GaN/$Al_xGa_{1-x}N$/GaN heterostructures (x=0.10, 0.15, and 0.20).

Under applied hydrostatic pressure, the in-plane strain tensor component $\varepsilon_{xx}=\varepsilon_{yy}$ of the GaN/AlGaN/GaN devices is determined by the thick SiC substrate. Using the elastic constants of SiC,[17] the pressure induced in-plane elastic strain is calculated to be -1.5044×10^{-4}/kbar.

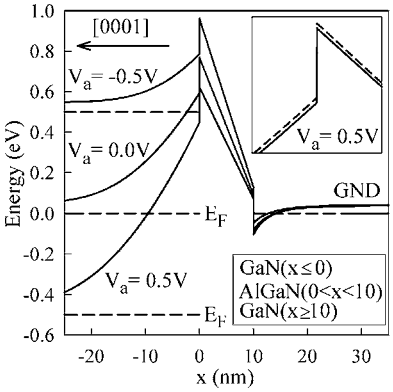

FIG. 2. Calculated band profiles for n-GaN/u-$Al_{0.15}Ga_{0.85}N$/n-GaN at room temperature. The effect of pressure is shown in the inset where the solid lines represent results at atmospheric pressure and the dotted lines represent results for 10 kbar pressure.

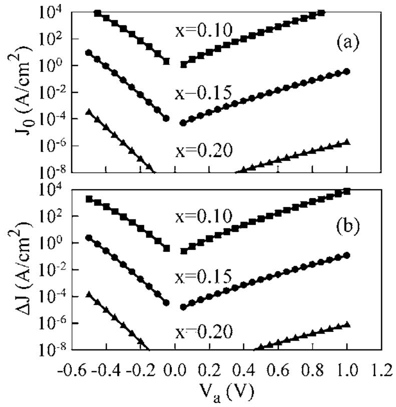

FIG. 3. (a) Calculated *I-V* characteristics of GaN/$Al_xGa_{1-x}N$/GaN devices at atmospheric pressure and at room temperature and (b) the corresponding change in current, ΔJ, for 10 kbar pressure.

In the [0001] direction, the strain is determined by the in-plane strain and by the elastic constants of GaN and AlGaN:

$$\varepsilon_{zz} = \frac{-p - 2C_{13}\varepsilon_{xx}}{C_{33}}, \tag{7}$$

where C_{13} and C_{33} are the elastic constants and p is the magnitude of applied pressure. In the numerical model we adopt the elastic constants and piezoelectric constants calculated in the generalized gradient approximation (GGA).[16,18] Because the piezoelectric parameters of AlGaN are reported to be nonlinear in the material composition, we calculate the change in the interfacial polarization charge density $\Delta\sigma$ by the approach suggested in Refs. 16 and 19. ε_{zz} for GaN with 10 kbar pressure is calculated to be -2.247×10^{-3}. Table I lists calculated values for ε_{zz} for $Al_xGa_{1-x}N$ layers and $\Delta\sigma$ and $\Delta\sigma/\sigma_0$ for GaN/$Al_xGa_{1-x}N$/GaN heterostructures with three different compositions (x=0.10, 0.15, and 0.20) on SiC under 10 kbar pressure. As GaN and AlGaN have almost the same band gap pressure coefficients,[20,21] the change of the conduction band offset with pressure is assumed to be negligible.

The bias direction in the calculations is defined by holding the bottom GaN layer at zero potential. Figure 2 shows the band profiles calculated for n-GaN/u-$Al_{0.15}Ga_{0.85}N$/n-GaN devices with a 10 nm thick undoped AlGaN layer and doping concentrations of 1×10^{18} cm^{-3} in both GaN layers. The depletion region in the top GaN layer is attributed to the negative polarization at the GaN/AlGaN interface, and the accumulation region in the bottom GaN layer is attributed to the positive polarization at the AlGaN/GaN interface. Due to the piezoelectric effect, polarizations of both GaN and AlGaN increase with pressure. Since the piezoelectric constants of AlGaN are larger than those of GaN, the net amount of the total polarization charges at the interfaces increases in magnitude. As a result, the band bending becomes stronger and the effective barrier height increases with pressure. The effect of 10 kbar pressure is clearly shown as a modulation of the band profile near maximum (see inset of Fig. 2).

I-V modeling was performed for a wide range of devices with different $Al_xGa_{1-x}N$ layer thicknesses, AlGaN compositions, and doping concentrations in the top and bottom GaN layers. Here, only representative results for doping concentrations of 1×10^{18} cm^{-3} and 10 nm thick AlGaN layers of different composition are presented. The *I-V* results at atmospheric pressure are shown in Fig. 3(a), and the corresponding change in current, ΔJ, for 10 kbar pressure is shown in Fig. 3(b), for Al compositions of 0.10, 0.15, and 0.20. The current is dominated by tunneling through these relatively thin barrier layers.

The model results indicate that the current at atmospheric pressure, J_0, decreases strongly with increasing AlN content in the barrier layer, thicker AlGaN layer, and lower doping concentration in the top GaN layer, while the effect of the doping concentration of the bottom GaN layer is small. The current is found to decrease with applied pressure in all cases. ΔJ is approximately proportional to J_0, in the voltage range where the currents are not dominated by thermionic emission (-0.5 V $\leqslant V_a \leqslant 1.0$ V). However, it is opposite for the relative change of current ($\Delta J/J_0$) with pressure, i.e., the larger J_0, the smaller $\Delta J/J_0$.

The effect of temperature on the devices is also investigated. The temperature dependence of band offset is calculated from the band gap temperature coefficients of GaN and AlN.[22] Although spontaneous polarization is very strong in GaN and AlGaN, the pyroelectric coefficients describing the change of the spontaneous polarization with temperature have been found to be very small.[23] (We neglect a possible temperature dependence of the piezoelectric constants.) Calculations have shown the temperature dependence of elastic constants of GaN and AlN to be negligible.[24] Therefore, the temperature dependence of the elastic constants, spontaneous polarization, and piezoelectric constants are neglected in the model. Calculations indicate that the relative change in current magnitude averaged over the voltage range of -0.5 to $+1.0$ V for a GaN/$Al_{0.15}Ga_{0.85}N$/GaN device at 300 K due to 1 kbar pressure is approximately equal to that resulting from a change in temperature by 0.65 K.[25] Increasing pressure reduces the current, but increasing temperature raises the current. However, the relative changes in current induced by pressure and temperature have different voltage dependencies. The current is most sensitive to pressure at moderately large reverse bias while the temperature dependence is

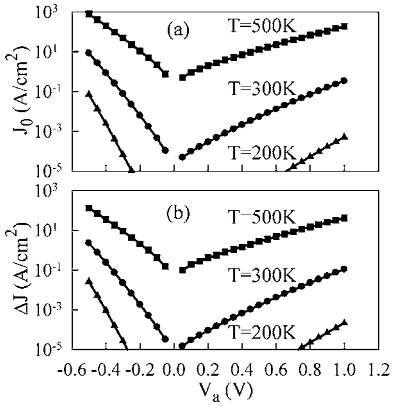

FIG. 4. (a) Calculated *I-V* characteristics of a $GaN/Al_{0.15}Ga_{0.85}N/GaN$ device at atmospheric pressure and three different temperatures and (b) the corresponding change in current, ΔJ, for 10 kbar pressure.

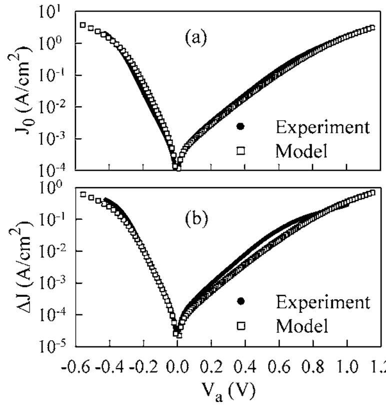

FIG. 6. (a) Measured *I-V* characteristics of the sample at atmospheric pressure and (b) the change in current, ΔJ, for 5 kbar pressure, along with the model results.

strongest at zero bias. Hence, the relative sensitivities to pressure and temperature may be controlled by the voltage.

Figures 4(a) and 4(b) show the calculated *I-V* results and the corresponding ΔJ, again for 10 kbar pressure, for a $GaN/Al_{0.15}Ga_{0.85}N/GaN$ device at 200, 300, and 500 K. Both J_0 and ΔJ are strongly temperature dependent. As temperature increases, J_0 and ΔJ increase, while $\Delta J/J_0$ decreases. Optimized sensing of these devices at different temperatures may be achieved by a judicious choice of the AlGaN layer composition and thickness and the GaN doping concentrations.

Gauge factors for the devices may be defined as $\Delta J/J_0$ divided by the in-plane strain.[26] Because the piezoelectric constants of GaN and AlGaN are only known with limited accuracy, it is useful to examine the sensitivity of gauge factors to the induced piezoelectric polarizations. Making conservative assumptions, based on a review of the reported values for III-nitride piezoelectric constants,[16,18,22] we estimate that a pressure of 10 kbars will induce relative changes in the interface polarization charges of between 1% and 3%. Figure 5 shows calculated $(\Delta J/J_0)/\varepsilon_{xx}$ of a $GaN/Al_{0.15}Ga_{0.85}N/GaN$ device on SiC for $\Delta\sigma/\sigma_0$ of 1%, 1.5%, and 2%, assuming an in-plane strain corresponding to a pressure of 10 kbars. Clearly, the value of the gauge factor depends strongly on the change in the polarization charges induced by the strain.

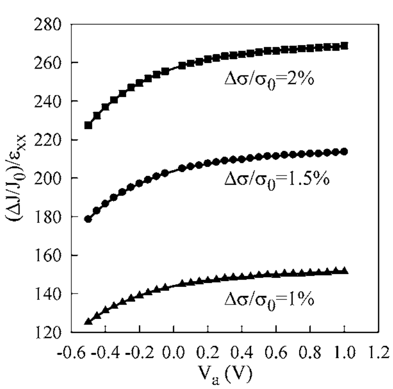

FIG. 5. Calculated gauge factors, $(\Delta J/J_0)/\varepsilon_{xx}$, of a $GaN/Al_{0.15}Ga_{0.85}N/GaN$ device for $\Delta\sigma/\sigma_0$ of 1%, 1.5%, and 2%, assuming an in-plane strain corresponding to 10 kbar pressure.

III. EXPERIMENTAL RESULTS

The concept of pressure sensing with an *n*-GaN/*u*-AlGaN/*n*-GaN heterostructure device was verified experimentally. The sample used for this study consists of a 2.5 μm thick GaN layer grown by metal organic chemical vapor deposition (MOCVD) on a (0001) 6*H*-SiC substrate. On top of the GaN layer, several layers were grown by molecular beam epitaxy (MBE): first a superlattice buffer of 20 AlN/GaN layers, then a 0.5 μm thick highly doped n^+-GaN layer, the unintentionally doped 30 nm GaN/10 nm $Al_{0.2}Ga_{0.8}N$/30 nm GaN heterostructure, and finally a 0.2 μm thick highly doped n^+-GaN layer. Circular mesa structures of 250 μm diameter were created with BCl_3 reactive ion etching. Ohmic contacts were made with a stack of Ti/Al/Ti/Au layers deposited by e-beam evaporation. Contacts were formed on the highly doped GaN layers by rapid thermal annealing at 900 °C in a nitrogen atmosphere. The pressure response of the devices at room temperature was measured with a U11 compressor and a GC10 gas pressure cell from the Polish Academy of Sciences.

Figures 6(a) and 6(b) show the measured *I-V* characteristics at atmospheric pressure and ΔJ with 5 kbar pressure, both along with the model results. In order to agree with the experimental results, we find it is necessary to reduce σ_0 in the calculation by a factor of 0.57. The decrease in σ_0 could result from compensating charges due to interface states and/or uncertainty in the spontaneous polarizations.[22] This reduction is similar to the reduction of the interface polarization charges introduced by Hermann *et al.* in their discussion of AlN/GaN resonant tunneling diodes.[10] In addition, doping concentrations of 9.0×10^{17} cm^{-3} (or electron concentrations of 4.4×10^{17} cm^{-3}) are assumed for the nominally undoped GaN spacer layers directly adjacent to the AlGaN barrier. This assumption is reasonably consistent with the growth conditions employed and the highly doped n^+-GaN layers outside the GaN/AlGaN/GaN structure. In the model the highly doped GaN layers above and below GaN/AlGaN/GaN structures were neglected. Lastly, a series resistance of 100 Ω is added to the model to account for the experimentally observed leveling off of the current at high bias.

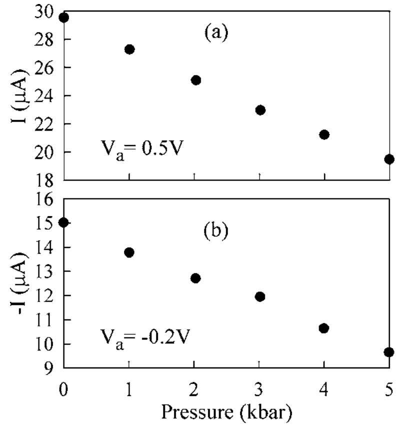

FIG. 7. Measured pressure dependence of the current at (a) 0.5 V and (b) −0.2 V.

Figures 7(a) and 7(b) show the measured pressure dependence of the current at −0.2 and 0.5 V, where $\Delta J/J_0$ are largest. Clearly, the change in current is nearly linear in the applied pressure. A voltage dependent gauge factor in the range of 240–500 may be extracted from the data of the measured sample.

IV. CONCLUSION

In conclusion, we have investigated the effect of hydrostatic pressure on the *I*-*V* characteristics of *n*-GaN/*u*-AlGaN/*n*-GaN heterostructure devices. Theoretical modeling indicates a decrease in current with pressure due to the piezoelectric effect. Our model predicts that the relative change in current with pressure becomes more significant with increasing thickness of the AlGaN layer and increasing AlN content. The pressure response of the devices at high and low temperatures was studied. The current is shown to be highly sensitive to pressure induced changes in the interfacial polarization charge densities. Based on the model results, $GaN/Al_{0.2}Ga_{0.8}N/GaN$ heterostructure devices were fabricated and the pressure response was measured over the range of 0–5 kbars. The current showed an approximately linear decrease with applied pressure. A maximum gauge factor approaching 500 was obtained. The experimental results are consistent with our model predictions and clearly demonstrate the considerable potential of GaN/AlGaN/GaN heterostructure devices for strain sensing applications.

ACKNOWLEDGMENTS

Partial support from NASA/PIDDP and NSF/ECS is gratefully acknowledged. One of the authors (H.M.) acknowledges fruitful discussions with Dr. V. Litvinov and also funding from the Air Force Office of Scientific Research monitored by Dr. G. L. Witt.

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