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Effect of hydrostatic pressure on the dc characteristics of AlGaN/GaN heterojunction field effect transistors

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We report the effect of compressive hydrostatic pressure on the current-voltage characteristics of AlGaN/GaN heterojunction field effect transistors (HFETs) on a sapphire substrate. The drain current increases with hydrostatic pressure and the maximum relative increase occurs when the gate bias is near threshold and drain bias is slightly larger than saturation bias. The increase of the drain current is associated with a pressure induced shift of the threshold voltage by −8.0 mV/kbar that is attributed to an increase of the polarization charge density at the AlGaN/GaN interface due to the piezoelectric effect. The results demonstrate the considerable potential of AlGaN/GaN HFETs for strain sensor applications. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2161812]

AlGaN/GaN HFETs have demonstrated great potential for high power, high frequency, high temperature applications.[1] They have been shown to operate up to 600 °C without irreversible degradation.[2] In these devices, a two-dimensional electron gas (2DEG) with a sheet carrier density greater than 10^{13} cm^{-2} can be formed at the AlGaN/GaN interface without intentional doping of the structure, if the AlN molar fraction in the alloy layer is sufficiently large. The electron gas is induced by the difference in the spontaneous polarization of GaN and AlGaN (due to the compositional difference) and, to a lesser degree, by the piezoelectric polarization of the pseudomorphic AlGaN layer, which is strained.[3]

III-nitride based devices also are promising candidates for sensor applications at high temperature and in harsh environments. AlGaN/GaN HFETs have been investigated for gas and liquid sensing.[4,5] Recently, the piezoresistivity of AlGaN/GaN heterostructures has been measured for possible mechanical stress sensor applications.[6,7] In this letter, we report an increase in the drain current of AlGaN/GaN HFETs on a sapphire substrate under hydrostatic pressure. Pressure dependent threshold voltage (V_T) and low field mobility (μ) are extracted from the current-voltage characteristics.

The sample consists of a 2-μm-thick undoped GaN layer grown on a sapphire substrate by metalorganic chemical vapor deposition, followed by a 500-nm-thick undoped GaN layer, grown by molecular beam epitaxy (MBE). The gate barrier layer consists of 18 nm of undoped $Al_{0.3}Ga_{0.7}N$, grown by MBE, capped by a 2-nm-thick undoped GaN layer. A Ni/Au Schottky contact is used as the gate. The source-drain spacing is 5 μm, and a 2 μm gate is placed symmetrically between the source and the drain. Two HFET structures of different width (W) are studied: 150 and 40 μm. Both yield results that are consistent with one another. For brevity we only present the results from the 150-μm-wide HFET in the following. Hydrostatic pressure is applied through a commercial liquid pressure apparatus from the Polish Academy of Sciences. All measurements are performed at room temperature and without sample illumination.

Figure 1 shows the current-voltage and transfer characteristics of the 150-μm-wide HFET at zero applied pressure. The negative differential resistance at high gate bias ($V_{GS} \geqslant -1$ V) can be attributed to self-heating, exacerbated by the

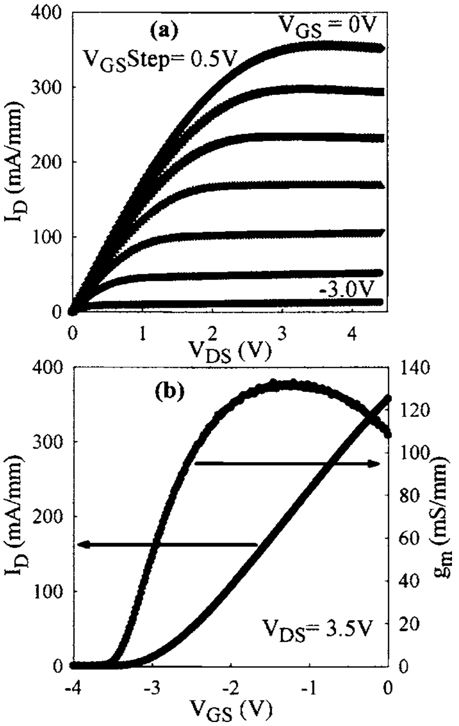

FIG. 1. (a) Output characteristics and (b) transfer characteristics of the AlGaN/GaN HFET at ambient pressure.

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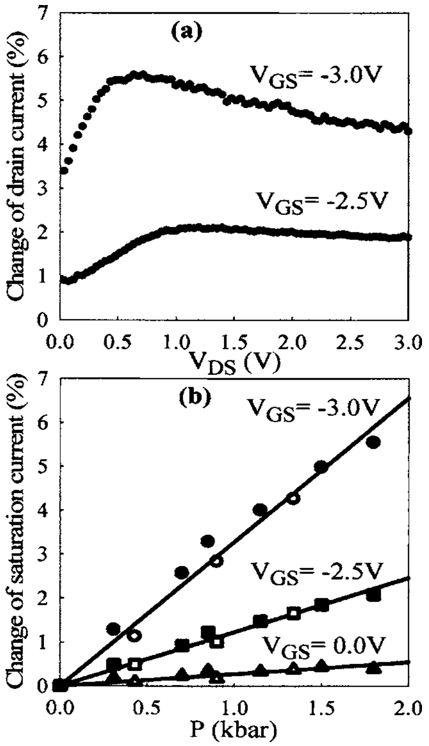

FIG. 2. (a) Relative change of the drain current under 1.8 kbar pressure as a function of V_{DS}. (b) Relative change of the saturation current with pressure. Solid symbols represent data collected under increasing pressure, and open symbols represent data taken while the pressure is reduced.

poor thermal conductance of the sapphire substrate.[8] The device has a maximum drain current of about 335 mA/mm at zero gate bias, and a maximum transconductance of about 135 mS/mm.

The drain current (I_D) increases with applied hydrostatic pressure. Figure 2 shows the relative change of the drain current at different drain and gate biases. The largest relative increase occurs at a gate bias (V_{GS}) near V_T and a drain bias (V_{DS}) slightly larger than the saturation bias (i.e., approximately V_{GS}-V_T). For a fixed gate bias, the drain saturation current increases linearly with pressure. With $V_{GS}=-3$ V, a least squares linear fit of $\Delta I_D/I_{D,0}$ versus pressure, where $I_{D;0}$ is the drain current at zero applied pressure, gives a percentage increase of 3.3%/kbar for the saturation current.

It is more difficult to understand the saturation current than the small bias drain current of AlGaN/GaN HFETs because of velocity saturation and self-heating at high fields.[8] As a result, we focus on the small bias drain current in the following analysis, even though the pressure effects are smaller in that regime.

In a simple model, the small bias drain current of an AlGaN/GaN HFET is given by[9]

$$I_D = \frac{W\varepsilon\varepsilon_0\mu}{L(d+\Delta d)}\left[(V_{\rm GS}-V_T)V_{\rm DS}-\frac{{V_{\rm DS}}^2}{2}\right]. \qquad (1)$$

Here μ is the field effect mobility and d is the distance from gate to the AlGaN/GaN heterojunction. Δd is the effective thickness of the 2DEG, ε is the static dielectric constant of the AlGaN layer, and ε_0 is the permittivity of free space. For AlGaN/GaN HFETs, Δd is about 4.5 nm.[1] We use $\varepsilon=9.7-1.2x$ as the dielectric constant of $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N}$.[10] The existence of the thin GaN cap layer can be accounted for by slightly modifying d[11]

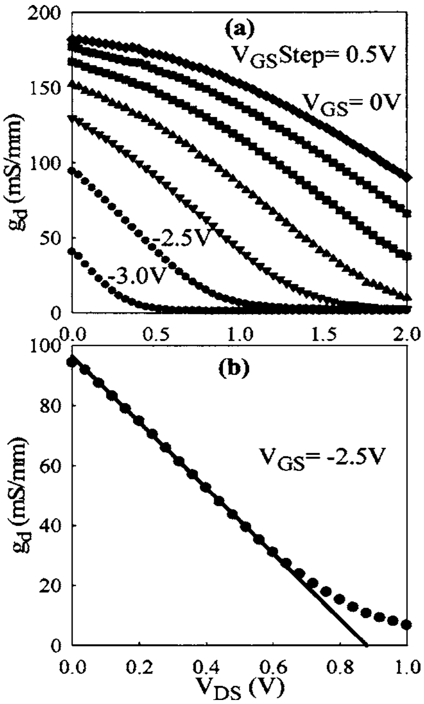

FIG. 3. (a) Channel conductance vs drain bias plots for different gate bias voltages and (b) linear fit to the channel conductance for $V_{\rm GS}=-2.5$ V, both for zero applied pressure.

$$d = d_d + d_t\varepsilon/\varepsilon_t. \qquad (2)$$

Here d_t and ε_t are the thickness and dielectric constant of the GaN cap layer, and d_d is the thickness of the AlGaN layer.

The differential channel conductance is given by

$$g_d = \frac{\partial I_D}{\partial V_{\rm DS}} = \frac{W\varepsilon\varepsilon_0\mu}{L(d+\Delta d)}[(V_{\rm GS}-V_T)-V_{\rm DS}]. \qquad (3)$$

A plot of g_d vs $V_{\rm DS}$ is expected to be linear for fixed $V_{\rm GS}$ and μ and V_T can be calculated from the slope and the y-axis intercept, respectively. Figure 3 shows plots of g_d vs $V_{\rm DS}$ at different gate biases. The plots are not completely linear, especially when $V_{\rm GS}$ is large, presumably due to series resistances.

Assuming source and drain series resistances to be equal, a fit of the drain current curves for $V_{\rm GS}$ of -2 V, -1.5 V and -1 V yields a total series resistance (R) of about 11 Ω, corresponding to a normalized source resistance of $R_s=0.08$ Ω cm. For $V_{\rm GS}$ larger than -1 V, R is larger, presumably due to self-heating. R has little effect if the channel resistance is large, i.e., if $V_{\rm GS}$ is not much greater than V_T. As can be seen from Fig. 3, the I_D curves for $V_{\rm GS}$ of -2.5 and -3.0 V are indeed quite linear.

R is not independent of μ and V_T. Rather than extracting three correlated parameters (i.e., R,μ, and V_T) from the experimental data, we focus on the g_d curves for $V_{\rm GS}=-2.5$ V, where the effect of R is negligible, to obtain μ and V_T. These results are plotted as functions of pressure in Fig. 4. V_T is found to be -3.38 V at zero pressure and it changes linearly with pressure by -8 mV/kbar; μ is 647.6 cm^2/V s at zero pressure and its rate of change with pressure is -2.6 cm^2/V s/kbar. Although the relative changes with pressure in the extracted parameters are small, they are very re-

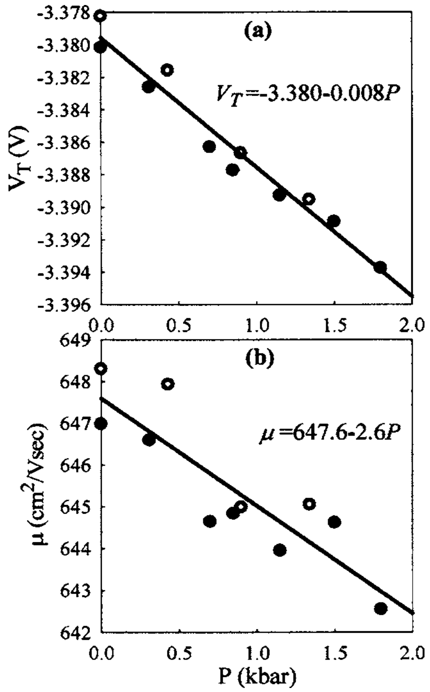

FIG. 4. Threshold voltage (a) and mobility (b) vs pressure extracted from −2.5 V gate bias data.

producible as indicated by the distinction between data obtained with increasing pressure (solid symbols) and with decreasing pressure (open symbols).

In a simple charge control model, the threshold voltage of an undoped AlGaN/GaN HFET is given by[9]

$$V_T = \phi_B - \frac{\Delta E_C}{q} - \frac{\sigma}{\varepsilon\varepsilon_0} d. \tag{4}$$

Here, ϕ_B is the Schottky barrier height, ΔE_C is the AlGaN/GaN conduction band offset, σ is the polarization charge density at the AlGaN/GaN interface, and the very thin GaN cap layer has again been neglected.

Because the band gaps of AlGaN and GaN increase with almost equal pressure coefficients,[12] the change in conduction band offset due to pressure can be assumed to be negligible. The change of V_T with pressure is thus given by

$$\delta(V_T) = \delta(\phi_B) - \frac{\delta(\sigma)}{\varepsilon\varepsilon_0} d. \tag{5}$$

The change of the polarization charge density under pressure, $\delta(\sigma)$, is determined by the strain and the piezoelectric constants of the GaN and $Al_{0.3}Ga_{0.7}N$ layers. In order to calculate the strain components due to the applied pressure, we assume that the strain in the basal plane is the same as that in the thick sapphire substrate. In the direction perpendicular to the substrate, (0001), the strain can be calculated from the strain in the basal plane and the elastic constants of GaN and $Al_{0.3}Ga_{0.7}N$.

There is still controversy regarding the elastic and piezoelectric constants of GaN and AlGaN. Here we use values calculated in the local density approximation.[13] Because the piezoelectric parameters of AlGaN are reported to be nonlinear in the material composition, we calculate $\delta(\sigma)$ by the approach as suggested;[14] $\delta(\sigma)$ for a pressure of 1 kbar is calculated to be 3.74×10^{-9} C/cm^2. From the measured change in threshold voltage, the change in barrier height $\delta(\phi_B)$ is then determined to be 1.0 mV/kbar [Eq. (5)].

Previously, we observed an increase of the Schottky barrier height of Ga-polarity n-GaN on a sapphire substrate with pressure by 4.2 mV/kbar.[15] The calculated $\delta(\phi_B)$ from the HFETs is smaller. This discrepancy may be due to the cap layer, possible changes of the ionized background donor density, although the structure is nominally undoped, or to the fact that we made many simplifying assumptions in our analysis and used several material parameters of uncertain accuracy.

Several factors can contribute to the observed decrease of μ with pressure. First, the change of the band gaps of GaN and AlGaN with pressure by about 3.8 meV/kbar[12] increases the effective mass by about 0.1%/kbar and thus reduces the mobility. Second, the decrease of V_T and the concomitant increase of the 2DEG density, along with the increasing effective mass, bring the 2DEG closer to the AlGaN/GaN interface, which may result in stronger interface scattering, also decreasing the mobility.

In summary, the drain current of AlGaN/GaN HFETs is found to increase with pressure, with the relative effect being largest just above threshold and near saturation. In order to explore the pressure dependence of the threshold voltage and the mobility, the device pressure response at low source-drain voltage is analyzed in the framework of a simple charge control HFET model. In that bias regime velocity saturation, self-heating, and series resistance effects are avoided and the increasing drain current can be attributed to a shift of the threshold voltage by −8 mV/kbar that is offset in part by a mobility decrease of approximately −2.6 cm^2/V s/kbar. The results demonstrate the potential of AlGaN/GaN HFETs for strain sensor applications.

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