Measurement of piezoelectrically induced charge in GaN/AlGaN heterostructure field-effect transistors

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Electron concentration profiles have been obtained for $Al_xGa_{1-x}N/GaN$ heterostructure field-effect transistor structures. Analysis of the measured electron distributions demonstrates the influence of piezoelectric effects in coherently strained layers on III-V nitride heterostructure device characteristics. Characterization of a nominally undoped $Al_{0.15}Ga_{0.85}N/GaN$ transistor structure reveals the presence of a high sheet carrier density in the GaN channel which may be explained as a consequence of piezoelectrically induced charges present at the $Al_{0.15}Ga_{0.85}N/GaN$ interface. Measurements performed on an $Al_{0.15}Ga_{0.85}N/GaN$ transistor structure with a buried $Al_{0.15}Ga_{0.85}N$ isolation layer indicate a reduction in electron sheet concentration in the transistor channel and accumulation of carriers below the $Al_{0.15}Ga_{0.85}N$ isolation layer, both of which are attributable to piezoelectric effects. © *1997 American Institute of Physics.* [S0003-6951(97)01245-X]

III-V nitride heterostructure field-effect transistors (HFETs) have been a subject of intense recent investigation, and have emerged as attractive candidates for high-voltage, high-power operation at microwave frequencies.[1–4] Contributing to the outstanding performance of nitride-based HFETs is the ability to achieve sheet carrier concentrations of $\sim 1 \times 10^{13}\ \mathrm{cm}^{-3}$ or higher in the channel region of the transistor—well in excess of those achievable in other III-V material systems. It has been shown previously that piezoelectric effects can exert a substantial influence on charge density and electric field distributions in zincblende semiconductors grown in the (111) orientation,[5,6] and more recently in III-V nitride heterostructures with the wurtzite crystal structure grown in the (0001) orientation.[7,8]

In this letter we describe experimental measurements and analysis of carrier density distributions in $GaN/Al_xGa_{1-x}N$ HFET structures grown by both molecular-beam epitaxy (MBE) and metalorganic vapor phase epitaxy (MOVPE). Carrier distributions measured in these structures are interpreted as consequences of piezoelectrically induced electric polarization charges at the $GaN/Al_xGa_{1-x}N$ heterojunction interfaces. These studies demonstrate the influence of piezoelectric effects on carrier distributions in HFET structures, and the importance of proper inclusion of these effects in the design and analysis of high-performance nitride-based HFET structures.

The epitaxial structures used in these experiments were grown on c-plane (0001) sapphire substrates. Details of the growth procedures and epitaxial layer characteristics for samples grown by MBE[9] and by low-pressure MOVPE[10] have been provided elsewhere. Schottky diodes were fabricated using evaporated Ti/Al annealed at 950 °C to form large-area Ohmic contacts to the HFET layers, and Ni to form Schottky contacts consisting typically of 320 μm diam dots.

Initial studies were performed using a nominally undoped 300 Å $Al_{0.15}Ga_{0.85}N/GaN$ heterostructure, shown schematically in Fig. 1. Despite the absence of intentional doping in this structure, a high sheet carrier concentration is observed at the $GaN/Al_{0.15}Ga_{0.85}N$ interface, which can be explained as a consequence of the presence of piezoelectrically induced polarization charge at the $GaN/Al_{0.15}Ga_{0.85}N$ interface. The piezoelectrically induced charges shown schematically in Fig. 1(c) arise from the lattice mismatch between the $Al_xGa_{1-x}N$ barrier layer and the underlying GaN epilayer. For growth in the (0001) orientation of III-V nitrides with the wurtzite crystal structure, there will be present

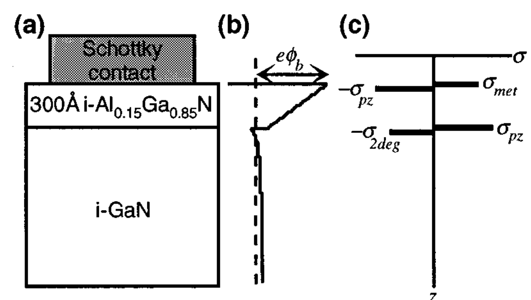

FIG. 1. (a) Schematic diagram of a nominally undoped $Al_{0.15}Ga_{0.85}N/GaN$ HFET structure. (b) Conduction-band energy diagram (solid line) calculated for this structure; the dotted line represents the Fermi level, and $e\phi_b$ is the Schottky barrier height. (c) Schematic diagram of piezoelectrically induced and free-carrier charge distribution.

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in a strained layer a polarization field P_z aligned along the [0001] direction, given by[7]

$$P_z = 2d_{31}(c_{11} + c_{12} - 2c_{13}^2/c_{33})\epsilon_{xx}, \tag{1}$$

where d_{31} is the relevant piezoelectric constant, c_{ij} are the elastic constants, and $\epsilon_{xx} = a_{\text{GaN}}/a_{\text{AlGaN}} - 1$; a_{GaN} and a_{AlGaN} are the lattice constants of GaN and $Al_xGa_{1-x}N$, respectively.

For AlN, a value of -2×10^{-10} cm/V has been reported for d_{31},[11] and negative values of slightly smaller magnitude are expected for GaN and $Al_xGa_{1-x}N$ alloys.[12] For $Al_xGa_{1-x}N$, which when grown pseudomorphically on a strain-relaxed GaN layer is under tensile strain, the polarization field will point in the $[000\bar{1}]$ direction, i.e., from the A (cation-terminated) face to the B (*N*-terminated) face in the crystal. This direction is opposite to that found in III-V zincblende semiconductors grown in the (111) orientation, but is the same as that observed in CdS, which forms in the wurtzite crystal structure and has piezoelectric coefficient $d_{31} < 0$.[11] That the polarization field is in the opposite direction for nitride compounds compared to other III-V semiconductors is not unexpected given the greater ionicity of the nitrides compared to other III-V materials.[13]

Associated with the polarization field given by Eq. (1) is a piezoelectrically induced charge density ρ_{pz} given by $\nabla\cdot\mathbf{P} = \rho_{pz}$. In the $Al_xGa_{1-x}N$/GaN heterostructure shown in Fig. 1, a positive piezoelectric sheet charge density σ_{pz} will be present at the GaN/$Al_xGa_{1-x}N$ interface, and a corresponding negative sheet charge $-\sigma_{pz}$ at the top of the $Al_xGa_{1-x}N$ layer. We see immediately that any strain component common to both the GaN and $Al_xGa_{1-x}N$ layers, or slowly varying in comparison to the strain induced by pseudomorphic growth, will not contribute significantly to ρ_{pz}—the lattice-mismatch-induced component of strain will exert the dominant influence. Variations in composition or strain distribution near an interface will alter the local distribution of piezoelectrically induced charge; however, the total piezoelectric sheet charge density associated with the interface will be very nearly equal to that present at an abrupt interface between materials with the same compositions as those found away from the immediate vicinity of the interface. And finally, local process-induced variations in strain arising from, for example, etching for mesa isolation or recessing for Ohmic or Schottky contacts in FET structures will produce corresponding local variations in ρ_{pz} and, consequently, free-carrier concentrations.

Using values reported in the literature for the piezoelectric coefficient[11] and elastic constants,[14] we estimate that σ_{pz} in Fig. 1 is $\sim4\times10^{12}\ e\ \text{cm}^{-2}$. The electric field in the $Al_{0.15}Ga_{0.85}N$ layer implied by this value is far too large to be consistent with reasonable values for the Schottky barrier height $e\phi_b$ for $Al_{0.15}Ga_{0.85}N$ and the conduction-band offset ΔE_c at the GaN/$Al_{0.15}Ga_{0.85}N$ interface. Thus, a two-dimensional electron gas (2DEG) is formed at the GaN/$Al_{0.15}Ga_{0.85}N$ interface, the negative charges from which act to cancel partially the electric field arising from the piezoelectrically induced charges. At the top of the $Al_{0.15}Ga_{0.85}N$ layer, the negative piezoelectric charge density will induce the formation in a Schottky barrier structure of a positive sheet charge in the metal at the metal-nitride interface, or at a free surface of a positive sheet charge that most likely arises from charging of surface states.

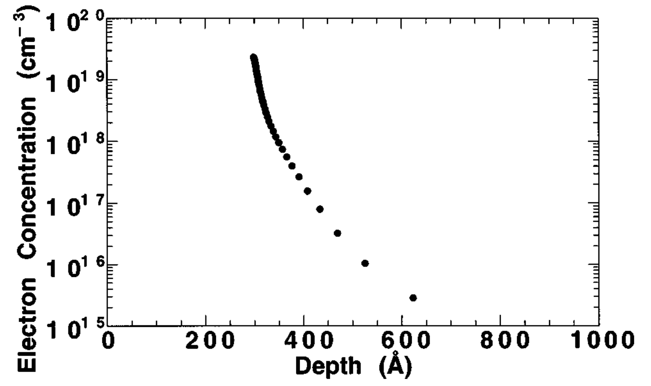

FIG. 2. Profile of electron concentration vs depth obtained from $C-V$ measurements performed on the device structure shown in Fig. 1, showing that the electrons are present primarily at the GaN/$Al_{0.15}Ga_{0.85}N$ interface.

The piezoelectric effect therefore leads to the formation of a 2DEG with a high sheet charge density even in $Al_xGa_{1-x}N$/GaN HFET structures without intentional doping. The sheet carrier densities in nominally undoped nitride HFET structures can in fact be comparable to those achievable in doped-channel structures, but without the degradation in mobility resulting from the presence of ionized impurities in the channel. A simple electrostatic analysis shows that the sheet carrier concentration n_s in the 2DEG at the $Al_xGa_{1-x}N$/GaN interface for a nominally undoped HFET structure should be given by

$$n_s = \sigma_{pz}/e - (\epsilon_{\text{AlGaN}}/de^2)(e\phi_b + E_F - \Delta E_c),$$
$$\sigma_{pz}/e = 2d_{31}(c_{11} + c_{12} - 2c_{13}^2/c_{33})(a_{\text{GaN}}/a_{\text{AlN}} - 1)x_{\text{Al}}, \tag{2}$$

where ϵ_{AlGaN} is the dielectric constant of $Al_xGa_{1-x}N$, d is the width of the $Al_xGa_{1-x}N$ barrier, E_F is the Fermi level with respect to the GaN conduction-band-edge energy at the GaN/$Al_xGa_{1-x}N$ interface, and x_{Al} is the Al concentration. An analysis of carrier concentrations measured in several nominally undoped $Al_xGa_{1-x}N$/GaN HFET structures grown by both MBE and MOVPE has provided quantitative confirmation of this behavior.[8]

Figure 2 shows the carrier concentration profile versus depth measured in the HFET structure shown in Fig. 1. The carriers are located primarily at the GaN/$Al_{0.15}Ga_{0.85}N$ interface, and we obtain a sheet carrier concentration n_s of $3.8\times10^{12}\ \text{cm}^{-2}$ at zero bias. Furthermore, we do not see significant evidence of electron transfer into the $Al_{0.15}Ga_{0.85}N$ layer, as would be expected if a high level of unintentional doping were present in that barrier layer. The absence of electron transfer into the $Al_{0.15}Ga_{0.85}N$ layer can be shown to imply that any uniformly distributed space charge in the $Al_{0.15}Ga_{0.85}N$ layer must be confined to within a distance d_0 of the $Al_{0.15}Ga_{0.85}N$/GaN interface, where

$$d_0 \leqslant \left(\frac{2\epsilon_{\text{AlGaN}}}{e^2 n_s}\right)(\Delta E_c - E_F). \tag{3}$$

For the structure shown in Fig. 1, an estimate using $n_s = 3.8\times10^{12}\ \text{cm}^{-2}$ as determined from our capacitance volt-

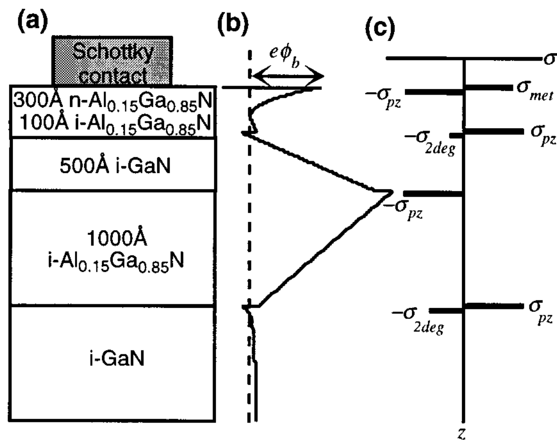

FIG. 3. (a) Schematic diagram of a doped $Al_{0.15}Ga_{0.85}N$/GaN HFET structure with a buried $Al_{0.15}Ga_{0.85}N$ isolation layer. (b) Conduction-band energy diagram (solid line) calculated for this structure; the dotted line represents the Fermi level, and $e\phi_b$ is the Schottky barrier height. (c) Schematic diagram of piezoelectrically induced and free-carrier charge distribution.

age ($C-V$) measurements and $\Delta E_c - E_F = 0.2$ eV yields $d_0 \approx 58$ Å. Space charge arising from the piezoelectric effect would be located at or very close to the interface, consistent with this limit.

The presence of piezoelectrically induced charges must be properly accounted for in nitride heterostructure device design. Figure 3 shows a schematic diagram, the calculated energy band structure, and the distribution of piezoelectric and free-carrier charges expected for an $Al_{0.15}Ga_{0.85}N$/GaN HFET structure incorporating a buried $Al_{0.15}Ga_{0.85}N$ isolation layer below the GaN channel. Figure 4 shows the carrier concentration profile versus depth measured for such a structure grown by MOVPE. The 2DEG carrier concentration at the upper GaN/$Al_{0.15}Ga_{0.85}N$ interface is considerably reduced compared to that in the structure without the buried $Al_{0.15}Ga_{0.85}N$ layer. We attribute this reduction to the presence of a negative piezoelectrically induced sheet charge at the top of the buried $Al_{0.15}Ga_{0.85}N$ layer, which as shown in Fig. 3 acts to deplete carriers from the 2DEG. In the absence of the piezoelectric effect the lower $Al_{0.15}Ga_{0.85}N$ layer should have little influence on this carrier density. Furthermore, there is evidence in the carrier concentration profile shown in Fig. 4 for the formation of a second 2DEG below the lower $Al_{0.15}Ga_{0.85}N$ layer, arising from the presence of positive piezoelectrically induced charge at the bottom of that layer, as indicated in Fig. 3(c). These results provide a clear demonstration of the influence of piezoelectric effects on III-V nitride device characteristics, and the importance of incorporating these effects in nitride device design.

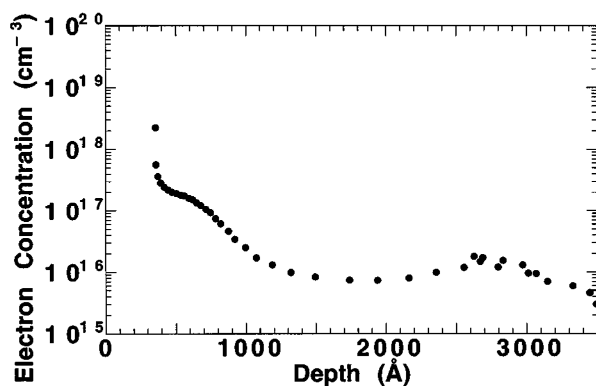

FIG. 4. Profile of electron concentration vs depth obtained from $C-V$ measurements performed on the device structure shown in Fig. 3, showing a reduction in electron concentration in the channel of the HFET structure and accumulation of electrons below the $Al_{0.15}Ga_{0.85}N$ isolation layer.

In summary, we have performed measurements of carrier concentration profiles in two $Al_xGa_{1-x}N$/GaN HFET structures. Analysis of a nominally undoped $Al_{0.15}Ga_{0.85}N$/GaN HFET structure revealed the presence of a high sheet carrier density in the HFET channel, which we interpret as a consequence of piezoelectrically induced polarization charges present at the GaN/$Al_{0.15}Ga_{0.85}N$ interface. $C-V$ profiling of an $Al_{0.15}Ga_{0.85}N$/GaN HFET structure with an $Al_{0.15}Ga_{0.85}N$ isolation layer located beneath a 500 Å GaN channel demonstrated that piezoelectrically induced polarization charges in the $Al_{0.15}Ga_{0.85}N$ isolation layer act to reduce the sheet carrier density in the HFET channel and to induce the accumulation of electrons at the GaN/$Al_{0.15}Ga_{0.85}N$ interface at the bottom of the isolation layer. These results confirm the importance of including piezoelectric phenomena in the design and analysis of III-V nitride heterostructure devices.

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