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Pressure-induced changes in the conductivity of AlGaN/GaN high-electron mobility-transistor membranes

B. S. Kang, S. Kim, and F. Ren
Department of Chemical Engineering, University of Florida, Gainesville, Florida 32611

J. W. Johnson, R. J. Therrien, P. Rajagopal, J. C. Roberts, E. L. Piner, and K. J. Linthicum
Nitronex Corporation, Raleigh, North Carolina 27606

S. N.G. Chu
Multiplex, Inc., South Plainfield, New Jersey 07080

K. Baik, B. P. Gila, C. R. Abernathy, and S. J. Pearton[a]
Department of Materials Science and Engineering, University of Florida, Gainesville, Florida 32611

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AlGaN/GaN high-electron-mobility transistors (HEMTs) show a strong dependence of source/drain current on the piezoelectric-polarization-induced two-dimensional electron gas. The spontaneous and piezoelectric-polarization-induced surface and interface charges can be used to develop very sensitive but robust sensors for the detection of pressure changes. The changes in the conductance of the channel of a AlGaN/GaN high electron mobility transistor (HEMT) membrane structure fabricated on a Si substrate were measured during the application of both tensile and compressive strain through changes in the ambient pressure. The conductivity of the channel shows a linear change of $-(+)6.4\times 10^{-2}$ mS/bar for application of compressive (tensile) strain. The AlGaN/GaN HEMT membrane-based sensors appear to be promising for pressure sensing applications. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1800282]

There is renewed emphasis on development of robust solid-state sensors capable of uncooled operation in harsh environments. The sensors should be capable of detecting chemical, gas, biological or radiation releases as well as be able to send signals to central monitoring locations. AlGaN/GaN high electron mobility transistors (HEMTs) have demonstrated extremely promising results for use in broadband power amplifiers in wireless base station applications,[1–8] while AlGaN high voltage rectifiers show promise for power flow control in hybrid electric vehicles.[9–12] The high electron sheet carrier concentration of nitride HEMTs is induced by piezoelectric polarization of the strained AlGaN layer and spontaneous polarization is very large in wurtzite III nitrides.[8,13–16] These characteristics suggest that the nitride HEMTs have potential as solid-state pressure sensors and some initial work has shown reproducible changes in channel conductance during application of both tensile and compressive strain.[14]

In this letter we demonstrate that a AlGaN/GaN membrane fabricated on Si substrate shows linear changes in channel conductance with changes in pressure. The sign of the conductance change is reversed when vacuum is applied to the membrane.

The piezoelectric polarization induced sheet carrier concentration, n_s, of undoped Ga-faceAlGaN/GaN can be calculated by following equation: [13,17,18]

$$n_s(x) = \frac{\sigma(x)}{e} - \left(\frac{\varepsilon_0\varepsilon(x)}{d_d e^2}\right)[e\phi_b(x) + E_F(x) - \Delta E_C(x)], \quad (1)$$

where $\varepsilon(x)$ is the dielectric constant, σ is the conductance, e is the electronic charge, d_d is the AlGaN layer thickness, $e\varphi_b$ is the Schottky barrier of the gate contact on AlGaN, E_F is the Fermi level and ΔEc is the conduction band discontinuity between AlGaN and GaN. The sheet carrier concentration induced by the piezoelectric polarization is a strong function of Al concentration. If an external stress can be applied to the AlGaN/GaN material system, the sheet carrier concentration can be changed significantly and devices fabricated in this fashion could be used in sensor-related applications.

The sensors used to monitor the differential pressure are made of a circular membrane of AlGaN/GaN on a Si substrate by etching a circular hole in the substrate, as illustrated in Fig. 1 (left). A deflection of the membrane away from the

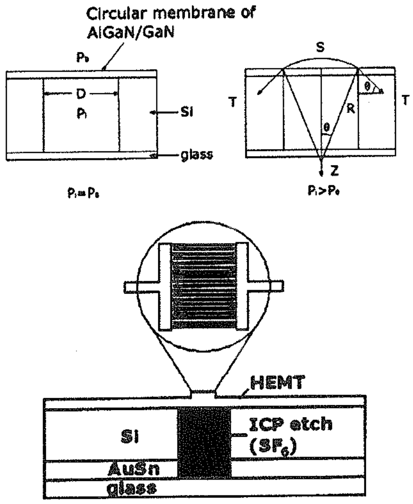

FIG. 1. Circular membrane of AlGaN/GaN on a Si substrate fabricated by etching a circular hole in the substrate (left). A deflection of the membrane away from the substrate due to differential pressure on the two sides of the membrane produces a tensile strain in the membrane (right).

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[a] Author to whom correspondence should be addressed; electronic mail: spear@mse.ufl.edu

substrate due to differential pressure on the two sides of the membrane produces a tensile strain in the membrane, as shown in Fig. 1 (right). The differential piezoelectric responses of AlGaN and GaN layers creates a space charge or depletion region which induces two-dimensional electron gas (2DEG) at the AlGaN/GaN interface. The concentration of 2DEG is expected to be directly correlated with the tensile strain in the membrane and hence with the differential pressure. The radial strain, ε_r, is given by[19,20]

$$\begin{aligned}\varepsilon_r &= (S-D)/D = (2\theta R - 2R\sin\theta)/(2R\sin\theta)\\ &= \theta/\sin\theta - 1,\end{aligned}\tag{2}$$

where S is the radius of curvature, D is the diameter of the via hole and R is defined in Fig. 1. The total tensile force, T, around the edge of the circular membrane is

$$T = \pi D t_{\mathrm{GaN}}\sigma_r = \pi D\, t_{\mathrm{GaN}}[E_{\mathrm{GaN}}/(1-v)]\varepsilon_r,\tag{3}$$

where t_{GaN} is the film of thickness, $\sigma_r=[E_{\mathrm{GaN}}/(1-v)]\varepsilon_r$, E_{GaN} is the Young's modulus and v is the Poisson's ratio of the GaN film. The component of T along z direction is balanced by the force on the membrane due to a differential pressure P_i-P_0, where P_i and P_0 are the inside and outside pressure, respectively. Hence $T\sin\theta=(P_i-P_0)\pi D^2/4$ and the radial strain, ε_r, in the nitride film can be expressed as a function of the differential pressure P_i-P_0

$$(\theta - \sin\theta) = (P_i - P_0)[(1-v)D]/(4E_{\mathrm{GaN}}t_{\mathrm{GaN}}),\tag{4}$$

where E_{GaN} is the Young's modulus, D is the diameter of the via hole, t_{GaN} is the film of thickness and v is the Poisson's ratio of the GaN film. If θ is measured, the differential pressure P_i-P_0 can be estimated with Eq. (4). We also derive the relationship between conductance, σ, of AlGaN/GaN HEMT and radial strain, ε_r

$$\sigma = \alpha(r_{\mathrm{AlGaN}}) + \beta(f_{\mathrm{GaN}}) \times \varepsilon_r,\tag{5}$$

where

$$\begin{aligned}\alpha(r_{\mathrm{AlGaN}}) = \mu_s\{1/[1 + (\varepsilon_0\varepsilon(x)/t_{\mathrm{AlGaN}}\, e^2)h^2/4\pi m^*(x)]\}\\ \times\{-|\Delta P_{\mathrm{SP}}| - |e_{\mathrm{eff}}|\Delta\varepsilon_{\mathrm{AlGaN}}r_{\mathrm{AlGaN}}\\ - [\varepsilon_0\varepsilon(x)/t_{\mathrm{AlGaN}}\, e][e\phi_b(x) - \Delta E_c(x)]\}\end{aligned}\tag{6}$$

and

$$\begin{aligned}\beta(f_{\mathrm{GaN}}) = \mu_s\{1/[1 + (\varepsilon_0\varepsilon(x)/t_{\mathrm{AlGaN}}e^2)h^2/4\pi m^*(x)]\}\\ \times\{|e_{\mathrm{eff}}(\mathrm{GaN})| - |e_{\mathrm{eff}}(\mathrm{AlGaN})|\},\end{aligned}\tag{7}$$

where μ_s is the mobility of 2DEG, ε_0 the electric permittivity, $\varepsilon(x)=9.5-0.5x$ is the relative permittivity, $e\phi_b(x)=0.84+1.3x(\mathrm{eV})$ is the Schottky barrier height, $e_{\mathrm{eff}}=(e_{31}-e_{33})C_{13}/C_{33}$, h is Planck's constant, e is the electron charge, $m^*(x)\sim 0.228\, m_e$. By monitoring the conductance of the HEMT on membrane, the pressure difference, P_i-P_0, can be obtained.

The HEMTs were grown by metalorganic chemical vapor deposition on 100 mm (111) Si substrates at Nitronex Corporation. The structures consisted of an (Al,Ga)N-based transition layer, ~0.8 μm undoped GaN buffer, and 300 Å undoped AlGaN barrier layer. Mesa isolation was performed with an inductively coupled plasma (ICP) etching with Cl_2/Ar based discharges at −90 V dc self-bias, ICP power of 300 W at 2 MHz and a process pressure of 5 mTorr. Ti/Al/Pt/Au based inter-digitated finger pattern separated by 4 μm was formed with e-beam deposition and standard lift-off. The fingers were annealed at 850 °C, 45 s under flowing N_2. Plated Au was subsequently deposited on the ohmic metal pads for wire bonding on the samples. Via holes were fabricated from the backside of the Si substrate and stopping on the GaN layer using ICP etching with SF_6/Ar. The etch selectivity is more than 1000:1. Two thousand angstroms of AuSn were deposited on the backside of the sample and a glass slice. A reflectance difference (RD) automation flip-chip bonder was used to bond the glass slice and the sample at 400 °C to seal off the via holes.

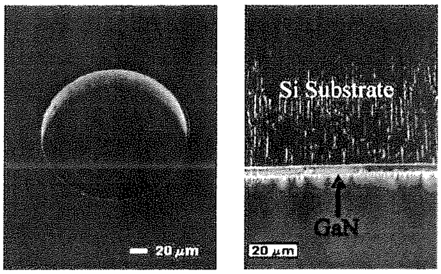

FIG. 2. SEM micrographs of via through the Si wafer (left) and cross sectional view of a via hole (right).

Figure 2 shows scanning electron microscopy (SEM) photos of the via through the Si wafer (left) and cross sectional view of the via (right). The dc current–voltage (I–V) characteristics were obtained from measurements on an Agilent 4156C parameter analyzer while the device was measured at 25 °C under either vacuum (10 m Torr) or pressure (40–200 psi) conditions.

Figure 3 shows the drain-source I–V characteristics from the membrane HEMT structure as a function of the ambient pressure. This current increases with increasing pressure and decreases under vacuum conditions. The resulting channel conductance derived from this data is shown as a function of differential pressure in Fig. 4. In the case of applied positive pressure, which corresponds to compressive strain induced in the HEMT layers, the conductivity decreases with a coefficient of -6.4×10^{-2} mS/bar. For the case of applied negative pressure (vacuum), the conductivity shows a positive coefficient of the same value within experimental error, given the limited data for vacuum conditions. These trends are similar to those observed with actual bending of HEMT samples on a cantilever beam to produce tensile or compressive strain,[14] but exhibit sensitivities to the induced tensile or compressive strain of almost two orders of magnitude larger. This is due to the absence of the thick

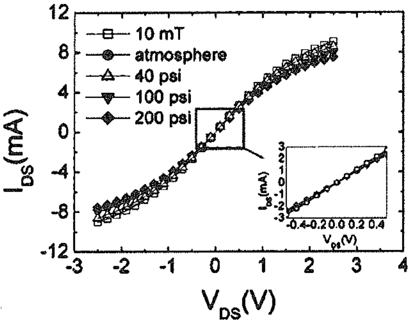

FIG. 3. I_{DS}-V_{DS} characteristics at 25 °C from AlGaN/GaN HEMT membrane as a function of applied pressure.

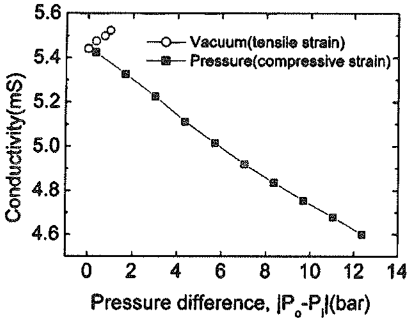

FIG. 4. Channel conductivity of the AlGaN/GaN HEMT membrane as a function of differential pressure.

sapphire substrate that is present in the cantilever structures. The new membrane structures are particularly sensitive to changes in differential pressure.

In summary, an AlGaN/GaN HEMT membrane on Si shows large changes in channel conductivity as a result of changes in ambient pressure. These structures appear promising for use in integrated sensors in which the HEMTs can also be used for gas, chemical and biological detection combined with on-chip transmission of the data.

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