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Polarization effects, surface states, and the source of electrons in AlGaN/GaN heterostructure field effect transistors
Electron mobility in N-polar GaN/AlGaN/GaN heterostructures

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The drift mobility of two-dimensional electron gases in N-polar GaN/AlGaN/GaN heterostructures was measured with capacitance and resistance measurements using gated transmission line method structures. A decrease in mobility with increasing reverse bias of the gate was observed. A variational wave function was used to calculate the mobility limited by optical phonon, alloy disorder, and ionized impurity scattering as a function of gate bias, and found to match the experimental data well. Three distinct regimes where phonon, alloy, and impurity scattering were dominant were observed. © 2008 American Institute of Physics. [DOI: 10.1063/1.2965483]

N-polar GaN and its alloys are very promising due to the reversal of spontaneous and piezoelectric polarization charges at heterostructure interfaces.1 In GaN/AlGaN/GaN structures, these polarization charges lead to a fixed sheet of mobile electrons, or a two-dimensional electron gas (2DEG), at the top heterointerface, which forms the basis of N-polar high electron mobility transistors (HEMTs).2 Although N-polar HEMTs have been demonstrated,3-5 the transport properties have not been studied in great detail. Unlike Ga-polar HEMTs, the 2DEG charge is well confined in a deep triangular quantum well derived by Fang and Howard.6 In this work, we create a theoretical model for calculating electron mobility in 2DEGs confined to triangular quantum wells as a function of the electric field in the well and apply it to N-polar HEMTs grown by metal–organic chemical vapor deposition (MOCVD). Charge and drift mobility were measured as a function of electric field using capacitance-voltage (C-V) measurements and gated transmission line method (TLM) structures and found to fit the theoretical calculations well.

The HEMT structure shown in Fig. 1 was grown by MOCVD on a sapphire substrate misoriented 3° toward the c plane using a growth technique detailed in an earlier study.3 The structure was capped with 5 nm of SiN grown by MOCVD in order to reduce gate leakage. Measurement of the drift mobility was done using gated TLM structures. The structures were aligned parallel to the surface steps because the drift mobility of N-polar HEMTs grown by MOCVD is anisotropic with respect to the direction of the source current.7 The resistance of TLM patterns with gate lengths varying from 2 to 20 μm, and access region lengths of 2 μm, was measured. The slope of the resistance line with respect to the gate length multiplied by the gate width gave the channel sheet resistance $R_{sh}$ at each gate bias. A small source current of 25 μA was used to avoid high-field effects and pinch off of the channel. The 2DEG sheet charge $n_s$ as a function of gate bias was determined from capacitance-voltage measurements. The mobility was calculated by combining the two measurements using

$$\mu(V_g) = [eR_{sh}(V_g)n_s(V_g)]^{-1}.$$  

A variational wave function for mobile electrons confined in a triangular quantum well derived by Fang and Howard has been assumed that the triangular potential well was shaped entirely by depleted background dopants and the mobile charge confined to the well. However, a previous experiment observed a strong impact on the mobility of 2DEGs when the electric field in the well is modulated by an external voltage.8 The structure used in this study is shown in Fig. 1. It consists of an Al$_{0.33}$Ga$_{0.67}$N barrier grown on a semi-insulating GaN buffer. The structure has a 5 nm GaN channel layer, a 25 nm Al$_{0.33}$Ga$_{0.67}$N cap layer, and a 5 nm SiN gate insulator on top of the barrier. Material properties for the alloys were determined using Vegard’s law (Table I).

In a previous study, a variational wave function was derived for infinite triangular wells where $F$, the electric field, is known.8 A generalized form of the Fang–Howard wave function was used,

$$\psi(z) = Ce^{-z/\Gamma} \exp(-b\sqrt{z/2}), \quad z \geq 0,$$  

where $a$ and $b$ are variational parameters, $\Gamma$ is the gamma function, and $C = [b^{2a+1}/\Gamma(2a+1)]^{1/2}$. When $a = 1$ this is identical to the Fang–Howard wave function. Using this as a trial function, one can obtain the first subband energy as

$\mu (V_g) = [eR_{sh}(V_g)n_s(V_g)]^{-1}$.  

A decrease in mobility with increasing reverse bias of the gate was observed. A variational wave function was used to calculate the mobility limited by optical phonon, alloy disorder, and ionized impurity scattering as a function of gate bias, and found to match the experimental data well. Three distinct regimes where phonon, alloy, and impurity scattering were dominant were observed. © 2008 American Institute of Physics. [DOI: 10.1063/1.2965483]

FIG. 1. Epitaxial structure of the N-polar HEMT used for both theoretical calculations and experimental measurements in this study.
where the electron effective mass in the well, $m^*$ is the reduced Planck constant, and $\varepsilon$ is the electron charge. Mini-

m_h^* = 0.20 \ldots

m_h^* = 0.27 \ldots

$\Delta E_{C,1}$ = 0.59 eV

$\Delta E_{C,2}$ = 0.18 eV

$\sigma_{n,\text{net}}$ = -0.0086 C/m²

$\varepsilon$ = 8.9 \ldots

\begin{align}
E_0 &= \frac{\hbar^2}{2m_w^*} \frac{b^2}{4(2a - 1)} + \frac{eF}{b}(2a + 1). \\
&= \frac{\hbar^2}{2m_w^*} \frac{b^2}{4(2a - 1)} + \frac{eF}{b}(2a + 1) + \frac{eF}{b}(2a + 1). \\
&= \frac{eF}{b}(2a + 1) + \frac{eF}{b}(2a + 1). \\
\end{align}

Where $m^*_w$ is the electron effective mass in the well, $\hbar$ is the reduced Planck constant, and $\varepsilon$ is the electron charge. Mini-

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nant scattering mechanism because the centroid of the 2DEG charge becomes very close to the ionized donors in the barrier, and screening is reduced due to the decrease in charge density. Both the shape and the values of the theoretical curve had a good fit to the data collected experimentally, although temperature-dependent measurements should be done to verify that impurity scattering is dominant near pinch off, as the 2DEG may be more weakly degenerate at lower charge densities and high temperature.

In conclusion, theoretical calculations for the mobility of electrons confined to a triangular well by an arbitrary electric field were done, and applied to an N-Polar HEMT. The drift mobility was measured with gated TLMs as a function of gate bias and found to match the experimental data well. It was shown through theory and measurements that increasing the electric field in the channel of a 2DEG has a detrimental effect on the mobility because the wave function is pushed closer to the barrier alloy. This theoretical formalism can be applied to any other material system and device structure in which a 2DEG is confined to a triangular well by a strong electric field.

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FIG. 3. (Color online) Theoretical calculations for mobility limited by optical phonon, ionized impurity and alloy disorder scattering, the total mobility, and the experimentally measured data plotted vs 2DEG sheet charge and channel electric field as the gate is pinched off.