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Polarization-Induced 3-Dimensional Electron Slabs in Graded AlGaN Layers

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Abstract

By compositionally grading AlGaN layers over different thicknesses, high mobility electron gases are produced by polarization-induced doping. Temperature dependent Hall and capacitance-voltage measurements were performed on these AlGaN layers, and two degrees of freedom are found for choosing the carrier concentration of these slabs. Carrier mobilities determined from Hall measurements are observed to be much higher than impurity doped structures of similar carrier densities. Alloy and phonon scattering are determined to be the major contributors limiting the mobility of the electron in the graded layers. This form of polarization-induced doping offers an attractive alternative to the traditional doping techniques, and may be used for highly conductive AlGaN layers with high Al composition, both for lateral and vertical transport.

1 Introduction

In recent years there has been a large interest in III-V nitride semiconductors for applications in high power electronic devices and short-wavelength optical devices. Optical devices have gained much popularity due to the large span in bandgaps ranging from 0.7 (InN) to 6.2 eV(AlN)[1]. Doping in most devices has been traditionally obtained by conventional methods, such as substitutional or modulation doping. Activation energies for traditional dopants in GaN are in the order of 10 meV (Si for n-type) and 160 meV[2] (Mg for p-type). P-type doping is more challenging than n-type in GaN. When the same dopants are introduced into the wider bandgap AlGaN, both the activation energies of n-type and p-type increase[3]. The need for high quality dopants in high aluminum composition AlGaN for UV-detectors/emmitters and heterojunction bipolar transistors (HBT's) has been a matter of extensive research.

Large polarization fields[4] have been observed in wurtzite III-V nitrides that are not present in other semiconductor materials. Both spontaneous and piezoelectric components of the polarization contribute to the total polarization charge in the crystal. By engineering these polarization fields it is possible to produce regions of fixed charge ρ_π given by:

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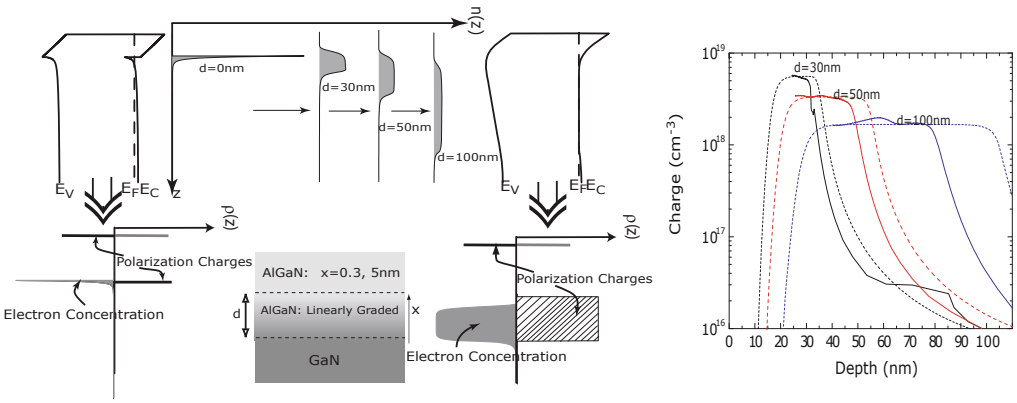

Figure 1: Sample structure of measured samples. Composition was linearly graded AlGaN over different thicknesses d. Positive polarization charges induce a 3-dimensional electron concentration in the graded layer. Room temperature Capacitance-voltage measurements performed on three AlGaN/GaN samples with 30 nm(black), 50 nm(red) and 100 nm(blue) linearly graded layer thickness. Solid lines represent the apparent carrier profile obtained from the experimental data and dashed line represents simulated data.

$$\rho_\pi = -\nabla \cdot \overrightarrow{P}, \tag{1}$$

where P is the polarization in the material. With a source of free charges present, these fixed polarization charges can then induce regions of 2 or 3 dimensional electron charges[5] with no need to provide any activation energy. This polarization-induced doping can be used to solve the doping problem in high Al-composition AlGaN. In this work the electrical properties of graded AlGaN is studied as a possible solution for the AlGaN doping problem.

2 Growth and Processing

The sample structure for the studied AlGaN samples is shown in FIG 1. Samples were grown by metal-organic vapor deposition (MOCVD) on c-sapphire employing the standard two-step growth, and the aluminum composition was graded linearly over different thicknesses, **d**. Trimethylgallium (TMGa), trimethylaluminum (TMAl), and ammonia (NH_3) were used as the sources for Ga, Al and N respectively. A 730 nm Fe doped semi-insulating buffer layer was grown at 1160^oC and 760 Torr followed by a 1830 nm unintentionally doped GaN layer. Then the aluminum composition was graded linearly from 0 to 30% at 1140^oC and 100 Torr, and capped by 5 nm Si_xN_y for reducing gate leakage[6]. Three samples with graded layer thicknesses of 30, 50, and 100 nm were studied. Polarization differences between the AlGaN and GaN layers form a positive polarization charge in the graded layer region, inducing regions of 3 dimensional electron concentration. X-ray diffraction and atomic force microscopy (AFM) performed on all samples showed coherently strained AlGaN layers with smooth surfaces.

Ohmic contacts were created by depositing Ti/Al/Ni/Au contacts of 200/1200/375/500 $\mathring{A}$ thickness respectively, and then annealed in N_2 ambient at 860^oC. Van der Pauw and

capacitance-voltage patterns were then etched by reactive ion etching (RIE) in a Cl_2 plasma. 200 / 4000 $\mathring{A}$ of Ni/Au. Schottky metal is then deposited for C-V measurements.

3 Experimental Results

3.1 Carrier confinement

Carrier concentration as a function of position was extracted from capacitance-voltage measurements. Measurements were performed using an Agilent 4294A precision impedance analyzer. The capacitance (C) measurements were performed at 1MHz under various reverse biases. Carrier profiles can then be extracted by:

$$n(z) = \frac{C^3}{q\varepsilon\varepsilon_0 A^2 \frac{\partial C}{\partial V}}, \tag{2}$$

where ε is the relative permittivity of the sample, and A is the total area of the C-V diode. Room temperature carrier profile for the three samples is shown in FIG 1 by the solid lines. The theoretical carrier profile estimate obtained by a simultaneous solution to Schrodinger's and Poisson's equation[7] is shown by the dashed lines.

Carrier confinement is seen to be limited to the graded layer region. This gives two degrees of freedom in determining a desired volume carrier density when using polarization-induced doping. By changing the material composition and/or the graded layer thickness the desired carrier density can be produced. The deviation between the theoretical and experimental carrier profiles is due to the homogeneous model used to determine the electron concentration from the capacitance-voltage measurements. A heterojunction model may be used to determine a more accurate carrier profile[8].

3.2 Transport

3.2.1 Hall Measurements

Temperature dependent Hall measurements were performed on the studied samples by placing them in a helium closed-cycle refrigerator and varying the temperature from 10 K to 300 K with a resistive heater. Low field ($< 1T$) Hall measurements were performed. FIG 2(b) shows the volume density as a function of temperature for three different samples graded over 30, 50, and 100 nm.

No carrier freeze out is seen at lower temperatures. A very slight decrease ($< 10\%$) in sheet carrier density is observed with increasing temperature. This is attributed to the change of spontaneous polarization with changing temperature. A more detailed analysis of this change will be studied in a future work.

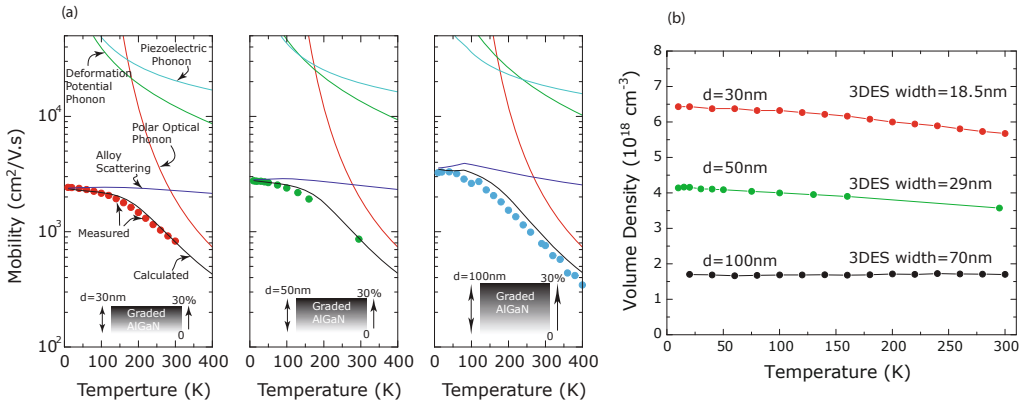

Figure 2: Measured and calculated mobility(a) and measured Hall densities(b) vs temperature for three graded AlGaN layers with the 3D electron slabs spread over 30, 50, and 100 nm. The various scattering mechanisms included show that room temperature mobility is limited by a combination of optical phonon and alloy scattering, whereas alloy scattering dominates at low temperatures for all three samples. Unlike normal impurity doped samples, no carrier freeze out is seen at lower temperatures.

3.2.2 Scattering mechanisms

FIG 2 shows the measured low-field electron Hall mobility as a function of temperature. The Hall mobility is seen to vary from $\sim 900 cm^2/Vs$ at room temperature to $\sim 3000 cm^2/Vs$ at 10 K. The high conductivity of polarization-induced charges as compared to impurity doped charges has been studied in an earlier work [5]. In this work the scattering mechanisms that determine the carrier transport properties are identified. The contributions of individual scattering mechanisms, the calculated total mobilities, and the experimentally measured mobility are shown in FIG 2(a). The calculated and experimental values seem to agree reasonably.

Scattering processes from polar optical phonons [9] $\hbar\omega_0 = 92$ meV (GaN) and 100 meV (AlN), acoustic phonons due to deformation potential and piezoelectric interactions, ionized impurity scattering (N_{imp} $=10^{17}\text{cm}^{-3}$), charged dislocation scattering [10, 11, 12] ($N_{disl} = 10^9 cm^{-2}$), and alloy disorder scattering are included in the calculation. In order to model the measured mobility theoretically, a constant volume density of the 3-dimensional electrons (this is approximately true for all three samples, as seen in Figure 1) is assumed. The Fermi energy is then determined as a function of temperature from the Joyce-Dixon approximation[13]. This enables us to use exact ensemble-averaged forms for the scattering rates for each scattering process considered. Appropriate Hall factors are used to convert the drift mobility to Hall mobility, and the scattering rates are evaluated for the whole graded layer, taking into account the spatially varying dielectric constant, alloy composition, and optical-phonon energy. The size of the unit cell is assumed to be the same as that of unstrained GaN, since the AlGaN layers are coherently strained. The total mobility is then calculated by a Matheissen's rule sum of the individual components.

The results in FIG 2 show that Coulombic scattering processes arising from ionized impurities and charged dislocations are weak (compared to alloy disorder and phonon scattering) due to heavy screening. In fact, the whole temperature dependence of mobility may be ex-

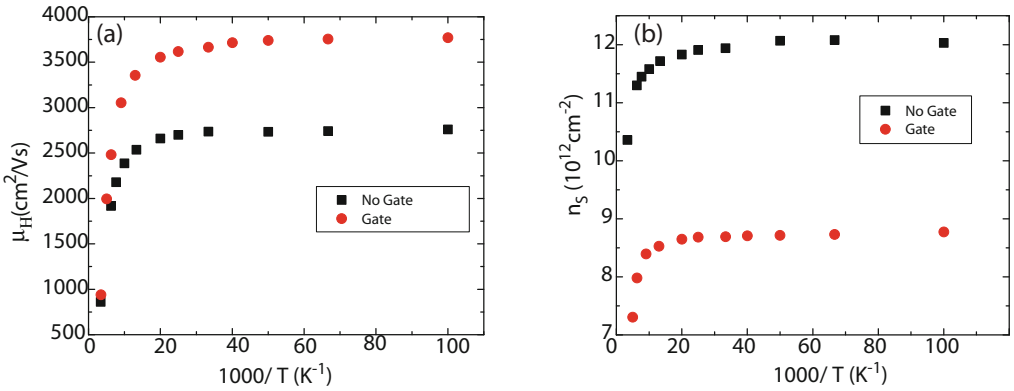

Figure 3: Measured Hall mobility(a) and carrier density(b) vs temperature for the graded AlGaN layer over 50 nm. The mobility with a gate on top is seen to be larger due to the depletion from the top, confining the electrons to the lower aluminum composition regions, lowering alloy scattering in the system.

plained by considering two scattering processes only - that due to alloy disorder and due to polar optical phonons. Alloy scattering is identified as the dominant scattering mechanism at low temperatures, and is rather strong even at high temperatures. A short-range alloy scattering potential[14] $V_0 = 1.5$ eV is found to explain the mobility variation of all three samples, which is smaller than the conduction band discontinuity of $\Delta E_C = 2.1$ eV between GaN and AlN. The fact that alloy scattering in the 3DES is dominant at low temperatures supports recent reports[15] of intrinsic mobility limits in AlGaN/GaN 2DEGs as well.

The contribution of alloy scattering is confirmed by introducing a gate on the top of the samples. At zero bias, due to a high Schottky barrier height, the metal gate depletes electrons from the high aluminum composition regions of the slabs. FIG 3 shows the Hall mobilities for the 50nm graded AlGaN layer with and without gate metals. An increase in mobility is seen with the gate on top due to the lowering of alloy scattering by confining the electrons to the lower aluminum composition regions of the AlGaN slab.

Thus, the mobility obtained might be close to the intrinsic limits set by the stasticial disorder in the alloy system. If this is true, the conductivity of such layers may be further improved upon by switching to a "digital" $(AlN)_n$—GaN_m superlattice alloy growth scheme[16] which removes the spatial disorder in the alloy composition. However, the in-plane electron transport properties of such digital alloy layers have not been looked into for III-V nitrides till date.

4 Conclusions

The use of polarization fields in III-V nitrides to produce 3-DES has been demonstarted. These slabs have higher mobilities compared to impurity doped structures of similar densities. The two degrees of freedom to established the desired polarization-doping density

was confirmed. Higher mobilities of carriers as compared to impurity doped structures of similar doping are observed. This might offer an alternative to the problem associated with the doping of large Al-composition AlGaN, as is required for HBT's and UV optical devices. No carrier freeze out at lower temperatures is observed. Experimental fittings done to Hall mobility versus temperature show a clear dependence of the mobility on alloy and phonon scattering. We gratefully acknowledge financial support from the Office of Naval Research (Dr. C. Wood), and the University of Notre Dame research funds.

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