GaN-based Micro Pressure Sensor for Extreme Environments

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Abstract—n-GaN/$Al_xGa_{1-x}N$/n-GaN (n-I-n) heterostructure devices are investigated for potential applications as pressure sensors in extreme environments. Theoretical modeling of n-I-n sensors performed with various compositions (x = 0.1, 0.15, & 0.2) and thicknesses (10 nm and 20 nm) of $Al_xGa_{1-x}N$ suggests that electrical currents will decrease with increasing pressure and this effect becomes more significant with higher AlN compositions in the $Al_xGa_{1-x}N$ layer and thicker $Al_xGa_{1-x}N$ layer. The effects of hydrostatic pressure on the electrical properties of n-GaN/$Al_{0.15}Ga_{0.85}N$/n-GaN structures were also measured over the range of 0-6 kbar at a fixed forward bias. The current was found to decrease linearly and reversibly with increasing pressure. The normalized change in current with pressure is consistent with our modeling studies. The linearity and reversibility in pressure response suggest that these newly investigated n-GaN/$Al_xGa_{1-x}N$/n-GaN devices are promising candidates for high-pressure sensor applications.

I. Introduction

The III-nitride compounds based on the AlGaN alloy have large band gaps (3.4 - 6.1 eV) and strong atomic bonds. Consequently, these semiconductors exhibit favorable thermal, mechanical, and chemical stabilities and radiation hardness with minimal problems arising from the unwanted optical or thermal generation of charge carriers [1,2]. Therefore they are ideal materials for constructing sensors for applications in extreme and harsh environments. One of the unique advantages of GaN-based devices is that AlGaN/GaN heterostructures develop sheet charges at the hetero-interfaces due to the differences in spontaneous polarizations between AlGaN and GaN layers and piezoelectric polarization of the pseudomorphic AlGaN layer [3-5]. Applied stress modulates this interfacial polarization charge due to differences in the piezoelectric coefficients of AlGaN and GaN, and therefore the barrier height (that controls transport across the interface) is modulated [6-8]. The stress-induced modulation of the barrier height in AlGaN/GaN structures has been recently investigated with heterojunction field effect transistors (HFETs), resulting in promising results for potential use in pressure or stress sensing [6-9]. In this work, the pressure response of an n-GaN/$Al_xGa_{1-x}N$/n-GaN (n-I-n) vertical transport device is investigated using both theoretical modeling and electrical (current-voltage) measurements. The n-I-n device is chosen for our work due to the high sensitivity of barrier height to stress and the high stability of device operation expected at increased temperatures. While higher pressure sensitivity will be achieved with the devices fabricated on a GaN membrane or on free-standing GaN [8,10], we investigated the devices fabricated on a standard substrate with the objective of determining the most promising AlGaN/GaN heterostructure for pressure sensing.

II. Theoretical modeling

For theoretical modeling of the vertical transport current in the n-GaN/$Al_xGa_{1-x}N$/n-GaN single barrier heterostructure device, we first calculated a conduction bandedge profile with a self-consistent semiclassical approach incorporating interfacial polarization charges, ionized dopant charges, and mobile electron charges. Figure 1 shows the bandedge profile calculated for n-GaN/$Al_{0.13}Ga_{0.87}N$/n-GaN devices with a 10 nm thick undoped AlGaN layer and doping concentration of $2x10^{17}$ cm^{-3} in both n-GaN regions. Polarization charge (σ) formed at the $Al_{0.13}Ga_{0.87}N$/n-GaN interface near the substrate, due to spontaneous and piezoelectric polarizations, is estimated to be 7.24 $x10^{12}$ ecm^{-2} (e: electronic charge) [3-5]. With this polarization charge, a barrier height of 1.33 eV is calculated for the GaN/$Al_{0.13}Ga_{0.87}N$/n-GaN system. The calculation indicates that 1% reduction of polarization charge will result in a decrease of the barrier height by 12 meV, which corresponds to a 60% increase in thermionic emission current over the barrier (Fig. 1b).

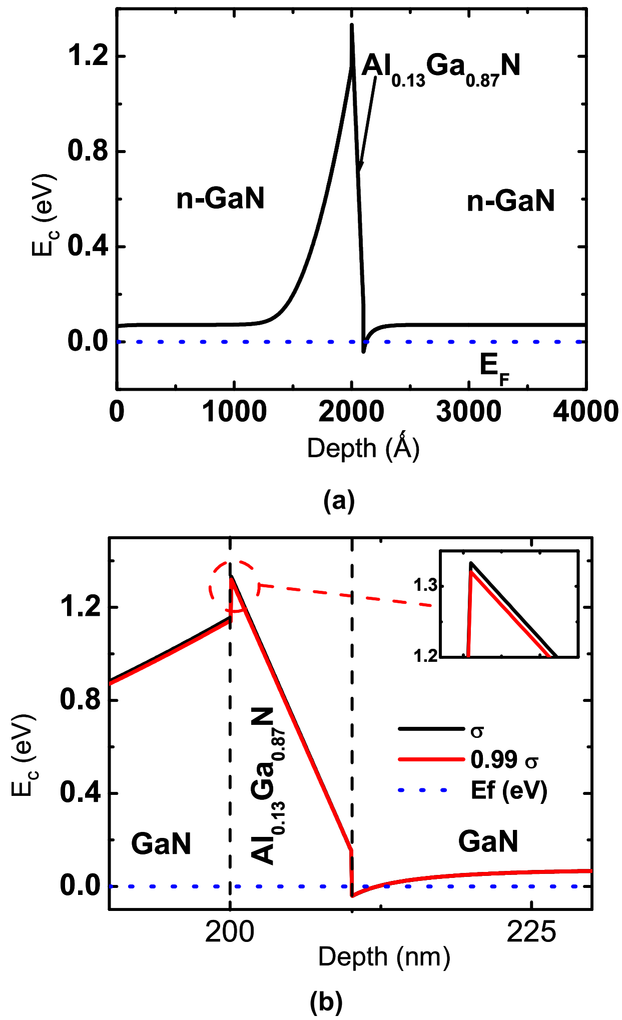

Figure 1. Schematic of a conduction band diagram of n-GaN/$Al_{0.13}Ga_{0.87}N$/n-GaN heterostructure (a) 10 nm thick undoped $Al_{0.13}Ga_{0.87}N$ layer and doping concentration of $2x10^{17}$ cm^{-3} in both n-GaN regions are assumed. The estimated polarization charge (σ) formed at the $Al_{0.13}Ga_{0.87}N$/n-GaN due to spontaneous and piezoelectric polarization is 7.24 $x10^{12}$ ecm^{-2} (e: electronic charge). With this polarization charge, a barrier height of 1.33 eV is calculated. The enlarged $Al_{0.13}Ga_{0.87}N$ barrier region (b) shows that 1% reduction of polarization charge will result in a decrease of the barrier height by 12 meV.

To estimate the vertical transport current in the n-GaN/$Al_xGa_{1-x}N$/n-GaN heterostructures under pressure, we developed a new model incorporating thermionic emission, thermionic field emission, and tunneling as the current transport mechanisms. Modeling was performed for devices with variable thickness and AlN composition of the $Al_xGa_{1-x}N$ layer (10 nm & 20 nm; x=0.1, 0.15, & 0.2) under 10 Kbar hydrostatic pressure. Figure 2 presents the modeling results where normalized changes of both total and thermionic current densities, $(J-J_0)/J_0$, are shown. GaN layers with a doping concentration of 5 x 10^{17} cm^{-3} and an undoped $Al_xGa_{1-x}N$ layer are assumed. The modeling results indicate that the current will decrease with increasing pressure, and the amount of current change due to the applied pressure increases as the AlN compositions and $Al_xGa_{1-x}N$ thickness increase within the ranges examined. Applied pressure modulates the polarization charge density at the AlGaN/GaN interfaces resulting in an increased barrier height and thus reduced current. The modeling data presented here are for heterostructures grown on a sapphire substrate, but very similar results are obtained with heterostructures grown on a SiC substrate.

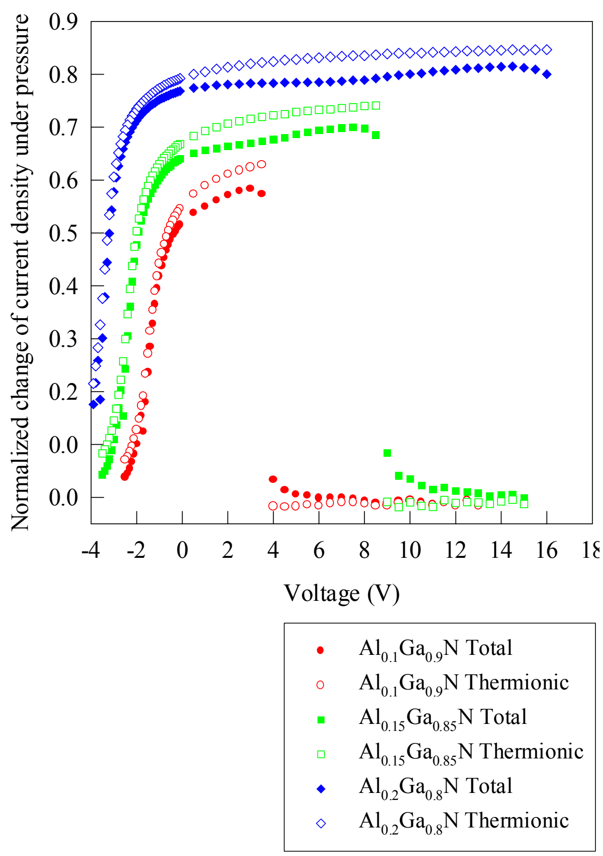

Figure 2. Modeling of normalized change of total and thermionic current densities, $(J-J_0)/J_0$, of n-GaN/$Al_xGa_{1-x}N$ /n-GaN heterojunction under 10 Kbar hydrostatic pressure. Both GaN layers are assumed to have a doping concentration of 5 x $10^{17}/cm^3$, and 10 nm thick undoped $Al_xGa_{1-x}N$ is assumed. The bottom GaN surface is set as ground.

III. EXPERIMENTAL RESULTS

Single barrier heterostructures of n-GaN/$Al_{0.15}Ga_{0.85}N$/n-GaN (Fig. 3) are used to measure pressure response. The n-I-n structures are grown on a 400 µm thick 6H-SiC substrate using Metalorganic Chemical Vapor Deposition (MOCVD) [11]. The $Al_xGa_{1-x}N$ layer is 10 nm thick and undoped. Theoretical modeling performed for this structure with ΔE_c=0.25 eV (conduction band offset) and σ=8.9 $x10^{12}$ ecm^{-2}

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(polarization charge) estimates a conduction barrier height of 1.1 eV [12]. Circular shape n-I-n mesa structures 250 μm diameter are created with BCl_3 reactive ion etching (Fig. 4). Ohmic contacts are made with a stack of Ti/Al/Ti/Au layers deposited with e-beam evaporation. The contacts (200 μm diameter) are formed on the highly doped (N_d~3x $10^{18}/cm^3$) top and the bottom n-GaN layers by rapid thermal annealing at 900 °C in nitrogen environments. During the measurements of vertical current transfer, the bottom contact is set at ground and a bias voltage is applied to the top contact.

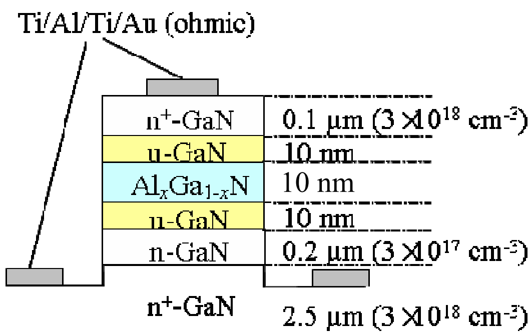

Figure 3. Schematic of the n-GaN/$Al_xGa_{1-x}N_x$/n-GaN (nIn) devices investigated.

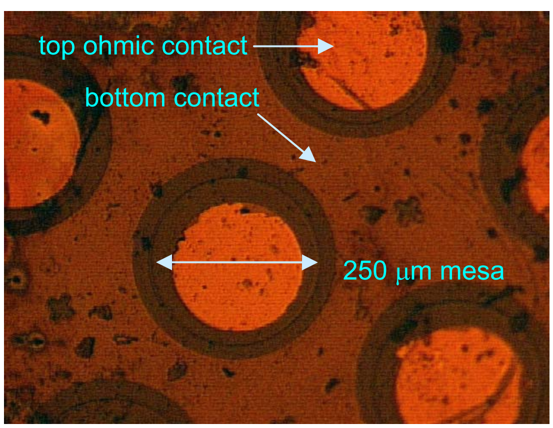

Figure 4. Optical image of n-GaN/Al0.15Ga0.85N /n-GaN heterojunction devices used for pressure measurements. The heterostructure was grown on a SiC surface using MOCVD. The Al0.15Ga0.85N layer was undoped and 10 nm thick. The diameter of the heterojunction mesa structure is 250

Pressure response of the n-I-n devices is measured in a liquid pressure cell from the Polish Academy of Sciences, where hydrostatic pressure is applied to the devices through a liquid (i.e. n-hexane) medium while measuring current of the devices via built-in electrical feedthroughs [13-14]. Vertical transport current of the devices is measured at a constant bias voltage with both increasing and decreasing pressures. Hydrostatic pressure in the pressure cell was measured using an InSb pressure gauge.

As predicted by the modeling studies, the current decreases with increasing pressure. Figure 5 shows current measured with an 0.8 V forward bias at room temperature while cycling the pressure between 0 and 6 kbar. The solid dots correspond to the measurements made with increasing pressure while the open dots are for the data taken with decreasing pressure. The change in the current is ~ 10 % over a 6 kbar range in pressure (Fig. 5), resulting in a sensitivity of 0.12 uA/kbar. This sensitivity is mainly limited by the rigidity of the thick SiC substrate and can be increased by as much as two orders of magnitude if the device is fabricated on a GaN membrane [8] or on a free-standing GaN bulk sample [10]. One very important fact to note is that the n-I-n response to applied pressure is highly linear and reversible over the pressure range examined, which is crucial for pressure sensing applications.

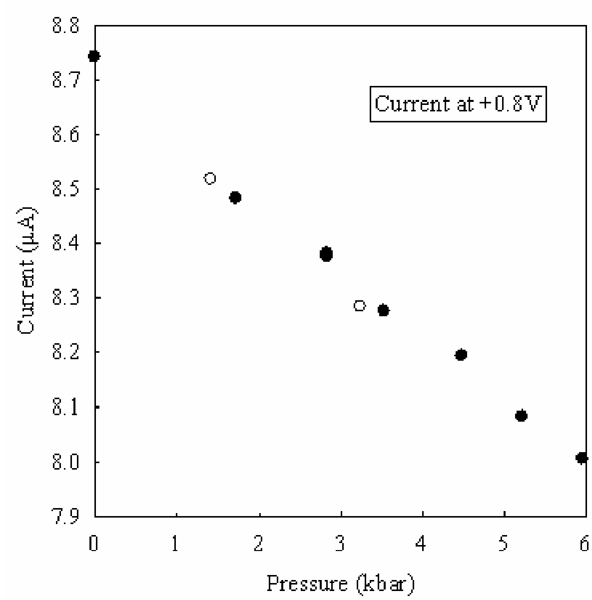

Figure 5. Pressure response measured for the n-GaN/$Al_{0.15}Ga_{0.85}N$ /n-GaN single barrier vertical transport device. Current was measured under hydrostatic pressure at a fixed forward bias (+0.8 V) while the pressure was increased (solid dots) and decreased (open dots) as well. Linear decrease of the current with increasing pressure was observed and the response was reversible.

IV. Summary

We have investigated n-GaN/$Al_xGa_{1-x}N$/n-GaN (n-I-n) heterostructural vertical transport devices for potential use as pressure sensors in extreme environments. Theoretical modeling performed for the n-I-n devices indicates that electrical currents will decrease with increasing pressure due to the increase of polarization charge. The modeling carried out with various compositions (x = 0.1, 0.15, & 0.2) and thicknesses (10 nm and 20 nm) of $Al_xGa_{1-x}N$ predicts that the current decrease will become more significant with higher AlN compositions in the $Al_xGa_{1-x}N$ layer and for the thicker $Al_xGa_{1-x}N$ layer. Based on the modeling results, vertical transport n-GaN/$Al_{0.15}Ga_{0.85}N$/n-GaN structures were fabricated and vertical transport current was measured over the range of 0-6 kbar at room temperature. The current showed a linear decrease with increasing pressure and the response was reversible. The normalized change in current with pressure is consistent with our modeling studies. The linearity and reversibility in pressure response suggest that these newly investigated n-GaN/$Al_xGa_{1-x}N$/n-GaN devices are promising candidates for high-pressure sensor applications.

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