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# AlGaN/GaN high electron mobility transistor structures for pressure and pH sensing

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Nitride High Electron Mobility Transistor(HEMT) structures are excellent candidates for polar liquid detectors, pressure sensors and piezoelectric-related applications. The changes in conductance of the channel of AlGaN/GaN high electron mobility transistor structures during application of both tensile and compressive strain are reported. For fixed Al mole fraction, the changes in conductance were roughly linear over the range up to 2.7x $10^8$ N.cm$^{-2}$**,** with coefficients for planar devices of –6.0 +/–2.5 x $10^{-10}$ S.N$^{-1}$ m$^{-2}$ for tensile strain and +9.5+/–3.5 x$10^{-10}$ S.N$^{-1}$m$^{-2}$ for compressive strain. The large changes in conductance demonstrate that simple AlGaN/GaN heterostructures are promising for pressure and strain sensor applications. A gateless HEMT structure was also used for sensing different liquids present in the gate region. The forward current showed significant decreases upon exposure of the gate area to solvents (water, acetone) or acids (HCl). Milli ampere changes in the source-drain current are observed relative to the value measured in air ambient. The pH sensitivity is due to changes in net surface charge that affects the relative depletion in the channel of the transistor.



## 1 Introduction

AlGaN/GaN high electron mobility transistors(HEMTs) have shown great promise for broad-band wireless communication systems and advanced radar [1–5]. More recently these same structures have demonstrated the ability to perform as combustion gas sensors, strain sensors and also chemical detectors [5–11]. In most cases, the application of some external change in surface conditions changes the piezoelectric-induced carrier density in the channel of the HEMT, which in turn alters the drain-source or gate current. Ambacher et al. [5–11] have shown the strong sensitivity of AlGaN/GaN heterostructures to ions, polar liquids, hydrogen gas and even biological materials. In particular they have shown that it is possible to distinguish liquid with different polarities.

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In this paper we report on the sensitivity of gateless AlGaN/GaN heterostructures to different polar liquids and the effect of external strain on the sheet resistance of the two dimensional electron gas channel in AlGaN/GaN HEMTs. The sensors can also be used to monitor the differential pressure, by forming a circular membrane of AlGaN/GaN on a Si substrate and then etching a circular hole in the substrate. 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. The differential piezoelectric responses of AlGaN and GaN layers creates a space charge which induces 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.

## 2 Experimental

The HEMT structures were grown by Metal Organic Chemical Vapor Deposition at 1040 °C on C-plane $Al_2O_3$ substrates. The layer structure consisted of a low temperature GaN nucleation layer, a 3 μm undoped GaN buffer and a 30 nm $Al_{0.3}Ga_{0.7}N$ undoped layer. Silicone rubber was used to encapsulate the source/drain regions, with only the gate region (with dimension 1x100 micron)open to allow the polar liquids to access the surface. The source-drain current-voltage characteristics were measured at 25 °C using an Agilent 4156C parameter analyzer with the uncontacted gate region exposed either to air, or ~3 $mm^2$ of water, 50 or 75% acetone or 5–10% HCl.The true transistor (ie.gate region contacted) structures for pressure sensing were fabricated in a similar fashion. These devices with gate dimension 1x100 microns were fabricated on half of 2" wafer ,sawed into 2 mm wide stripes and wire bonded on the test feature. Lucite blocks secure the sample and PCB board for testing. The contact pads were connected to the PCB board, which had BNC connectors on the end for signal outputs, with 1 mil thick gold wire. A high precision single axis traverse was used to bend the sample. For HEMTs grown on Si substrates, Via holes were fabricated from the back side 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. 2000 Å of AuSn was deposited on the backside of the sample and a glass slice. A RD automation flip-chip bonder was used to bond the glass slice and the sample at 400 °C to seal off the via holes.

## 3 Results and discussion

Figure 1 shows the I-V characteristic from gateless HEMTs exposed to air, $H_2O$ or 50% and 75% acetone. The results are similar to those reported previously by Neuberger et al. [6]. The current is significantly reduced upon exposure to any of the polar liquids relative to the value in air. As seen previously, acetone has the largest effect [6], which correlates with its high dipole moment(2.7 Dy). The data in Figure 1 also shows that the HEMT sensor is sensitive to the concentration of polar liquid and therefore could be used to differentiate between liquids into which a small amount of leakage of another substance has occurred. The I-V characteristics of HEMTs in either air or 5 or 10% HCl showed that at a bias of 30 V, there is a difference in current of ~8 mA for exposure to 5 versus 10% HCl. There is still much to understand about the mechanism of the current reduction in relation to the adsorption of the polar liquid molecules on the AlGaN/GaN surface. It is clear that these molecules are bonded by van der-Waals type interactions and that they screen surface change that is induced by polarization in the AlGaN/GaN heterostructure. This leads to changes in the induced electron density in the two dimensional electron gas that resides just below the AlGaN/GaN interface. Different chemicals are likely to exhibit degrees of interaction with the AlGaN surface. Steinhoff et al. [8] found a linear response to changes in the pH range 2-12 for ungated GaN-based transistor structures and suggested that the native metal oxide in the semiconductor surface is responsible.

Figure 2 shows the effects of external tensile and compressive strain on the conductivity of AlGaN/GaN HEMT samples without mesa. In the case of applying external tensile strain on the HEMT sample, a decrease of conductivity was observed. The lattice constant of AlGaN is smaller than that of GaN. Since the AlGaN layer is on the top of GaN layer, applying a tensile stress on the HEMT sample, the AlGaN will be stretched more than the GaN. Thus the internal strain and piezoelectric polarization from the strained AlGaN layer were reduced and conductivity decreased. By contrast, applying a compressive stress on the sample, the AlGaN atoms were pushed together more than that of GaN. The strain and piezoelectric polarization of the AlGaN layer increased, therefore the conductivity increased as the bending increased.

In the membrane structures, the channel 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. 3. In the case of applied positive pressure, which corresponds to compresssive strain induced in the HEMT layers, the conductivity decreases with a coefficient of $-6.4\text{x}10^{-2}$ mS/bar. For the case of applied negative pressure (vacuum),the conductivity shows a positive coefficient

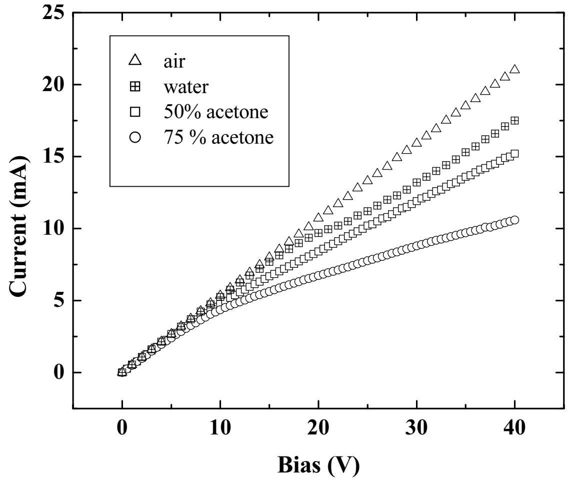


**Fig. 1** Drain-source I-V characteristics of HEMT exposed to air, water or various concentrations of acetone in the gate region.

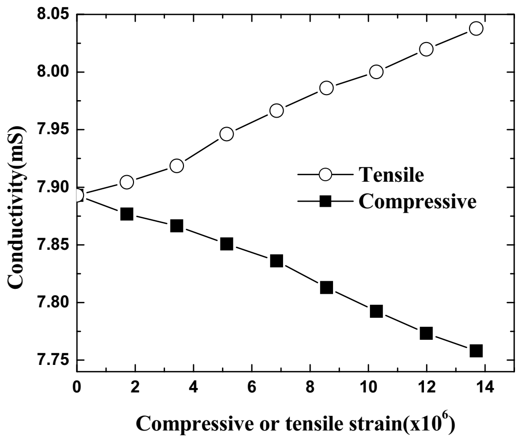


**Fig. 2** The effect of tensile or compressive stress on the conductivity of the AlGaN/GaN HEMT without mesa etching.

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

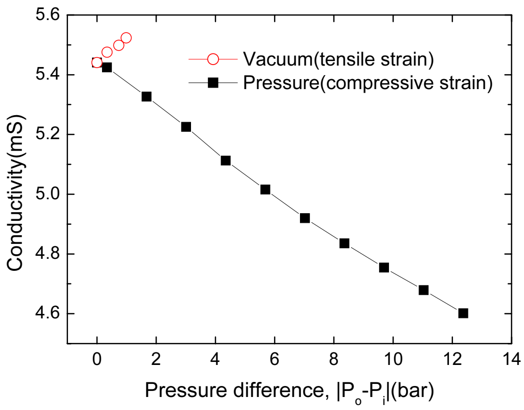


**Fig. 3** Channel conductivity of the HEMT membrane as a function of differential pressure.

## 4 Summary and conclusions

AlGaN/GaN ungated HEMTs show dramatic changes in drain-source current upon exposure to polar liquids in the gate region. Bonding of polar liquid molecules appear to alters the polarization-induced positive surface change, leading to changes in the channel carrier density and hence the drain-source current. In addition, the bending or flexing of a HEMT structure leads to changes in channel conductivity that can be used for strain sensing and using a sealed membrane geometry allows for measurement of differential pressure. The results show the potential of AlGaN/GaN transistor structures for a variety of sensing applications.

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