Development of GaN-based Micro Chemical Sensor Nodes

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***Abstract*— Sensors based on III-N technology are gaining significant interest due to their potential for monolithic integration of RF transceivers and light sources and the capability of high temperature operations. We are developing a GaN-based micro chemical sensor node for remote detection of chemical toxins, and present electrical responses of AlGaN/GaN HEMT (High Electron Mobility Transistor) sensors to chemical toxins as well as other common gases. Upon exposure to a chemical toxin, the sensor showed immediate increase in source-drain current (I_{ds}). The electrical response of the sensor was clear, reproducible and characteristic of the concentration of the analyte. This is the first time that electrical responses of chemical toxins are measured with a GaN-based microsensor. Detailed analysis on response time, sensitivity and temperature dependence will be discussed.**

I. Introduction

Large band-gap materials such as diamond, silicon carbide, and III-nitrides are promising materials for sensor applications. The robust chemical bonding in these structures resists deterioration or corrosion under extreme temperatures or harsh environmental conditions [1]. In addition, the large band-gap limits the generation of unwanted charge carriers due to optical or thermal excitation. This combination of electrical, thermal, and chemical stability is ideally suited for constructing electronic sensors for use under adverse environmental conditions where conventional silicon-based technologies are rendered useless. Wide band-gap materials are also of interest for applications in optoelectronics and high power and high frequency devices.

Electronics based on AlGaN/GaN structures have demonstrated great promise as broad band power amplifiers. The piezoelectric polarization of the strained AlGaN layer and polarization of the GaN film results in an interfacial two-dimensional electron-gas (2DEG) localized on the GaN side of the junction [2]. The charge redistribution in the GaN is similar to the hole-gas occurring at H-terminated diamond films. In the AlGaN/GaN structures, the microscopic dipoles at the interface result in the spontaneous polarization of the crystal lattices. An additional piezoelectric polarization can also occur due to mechanical distortions on the interface, which further influences the charge distribution in the inorganic layers. The resulting polarization induces a lowering of the conduction band edges in the GaN-side of the interface. Consequently, electron accumulation at the GaN side of the junction occurs forming the 2DEG. Changes in the polarization of the AlGaN layer affect the charge density and conductivity of the 2DEG. A gate electrode provides electronic control over the charge-transport properties of the GaN layer resulting in a high electron mobility transistor (HEMT), Fig 1.

In sensor applications, environmental perturbations of the AlGaN surface layer results in a change in the electron density of the 2DEG. The source-drain currents, i_{sd}, in the AlGaN/GaN device can then be used to monitor changes in the environment's composition. For example, a flux of anions reverses the polarization of the AlGaN and depletes the 2DEG in the GaN resulting in a decreased i_{sd} [3]. A

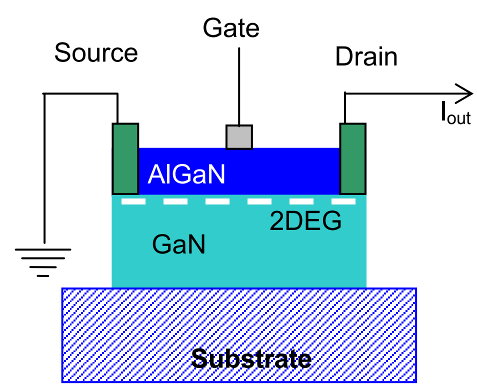

Fig 1. Cross-section of a gas sensitive AlGaN/GaN HEMT. In the fabricated devices, 4H-SiC substrate is employed with a nickel gate electrode. The AlGaN and GaN layers are 25 nm and 1 µm, respectively. Channel length is 2 µm and the gate width is 0.15 µm.

cation flux reestablishes the spontaneous polarization and i_{sd} returns to its original value. Minor variations in the electrostatic boundary conditions of the AlGaN-layer can also yield significant changes in source-drain currents. Polar organic liquids in contact with the AlGaN top surface modulate the polarization enough to cause significant changes in i_{sd} depending on the dielectric properties of the solvent [4].

II. Device Fabrication and Testing

The AlGaN/GaN HEMT devices were fabricated with $Al_{0.25}Ga_{0.75}N$/GaN heterostructures grown on a semi-insulating 4H-SiC substrate using RF-assisted nitrogen plasma molecular beam epitaxy, Fig 1. The thickness of the AlGaN and GaN layers were ~25 nm and 1 μm, respectively, and both layers were undoped. Typical sheet charge density is ~$1\text{x}10^{13}$ /cm^2 for these structures, which is induced by the spontaneous polarization and piezoelectric effect. Electron mobility is ~ 1500 cm^2/Vs. Mesa isolation of devices was accomplished with chlorine-based reactive ion etching. Ohmic contacts for the source and drain electrodes were made with Ti/Al metal schemes, yielding specific contact resistance of ~ 0.2 ohm-mm. The excellent ohmic contact resistance results in a lower knee voltage, allowing the sensor operation at source-drain potential difference of less than 3 V. For initial sensor characterization, Ni-based Schottky contacts were employed as gate electrodes. In the tested devices, the source-drain distances were 2 μm and the gate lengths and widths were 0.15 μm and 200 μm, respectively. Sensor evaluation was performed at V_{ds} = 1 - 1.5 V and I_{ds} on the order of 10 mA, which corresponds to dissipating power of 75 mW/mm.

The source drain current I_{sd} was measured for the AlGaN/GaN sensors upon exposure of various gaseous environments at a constant V_{sd} (1 – 1.5 V). Initially, a background signal was obtain with nitrogen or compressed air. Subsequently, a dilute sample of analyte is added to the sensor chamber. Changes in I_{sd} indicate a positive response. Analyte gases included a variety of chemicals including oxygen, volatile organics, and toxics. Nitrogen or air saturated with the organics was diluted with pure N_2 or air in a proscribed fashion using mass flow controllers. In all cases, the background currents were linear. On occasion, a slight drift or slope was noticeable on the background currents. In these cases, a straight line was subtracted from the raw data. Otherwise, the data is unmodified.

III. Sensor Response

Modulation of the source-drain currents in the AlGaN/GaN HEMTs provides the transduction mechanism for detecting chemical analytes in the gas or liquid phase. Specific and nonspecific interactions can occur between the top AlGaN layer and Ni-gate with the molecules in the localized environment. Nonspecific interaction such as changes in the dielectric continuum will alter the polarization of the AlGaN layer and, consequently, affect the polarization of the GaN and 2DEG. Specific gas-AlGaN interactions include coordination of the organic molecules to Al or Ga atoms (chemical bonding), dipole interactions, or non-chemical bonding such as hydrogen bonding with Lewis basic sites on nitrogen-rich surfaces. Each of these modes will alter the surface potential of the AlGaN layer and cause a measurable redistribution of electron density in both the AlGaN and GaN layers. Similarly, the metal-gate electrode can interact with gas molecules in both specific and nonspecific means. For example, gate electrodes composed of gold readily adsorb halide ions which induce a mirror charge (positive) in the gate electrode [5]. This localized polarization of the gold electrode is transmitted through the AlGaN layer lowering the barrier height at the AlGaN/GaN interface. These specific interactions will be highly dependent on the thickness of the metal layer and more effective with thinner films.

In the present work, the gate electrodes are comprised of thin films (a few tens nm) of nickel. The total exposed area between the source and drain contacts is 400 μm^2 with the gate electrode occupying only 30 μm^2 or less than 10% of this area. Thus, both the surfacial AlGaN and nickel gate electrode are free to interact with analyte molecules and transduce their presence into an electrical signal. With an applied V_{sd} bias of 1 V under a steady atmosphere, a constant I_{ds} on the order of 10 mA results. Variations in the atmosphere composition result in measurable changes in I_{ds}. Positive responses have been recorded with noise levels that are typically less than 10 μA.

Exposure of an AlGaN/GaN HEMT to a nitrogen flux containing 1% acetone results in an immediate increase in the I_{sd}, Fig 2. Response times are within a few seconds and the magnitude of I_{sd} change is consistent over multiple

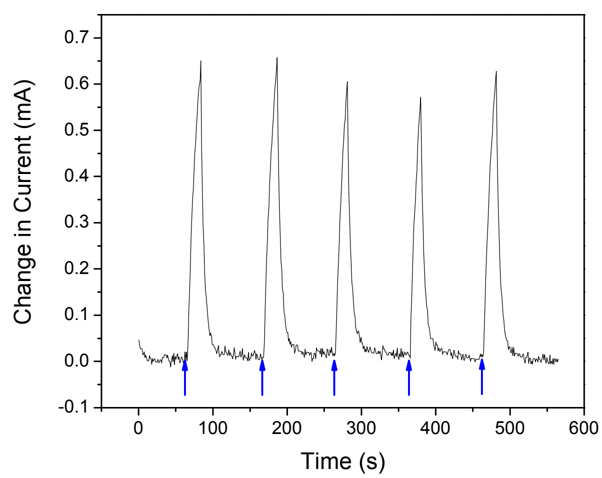

Fig 2. Response of source-drain currents for an AlGaN/GaN HEMT sensor exposed to mixtures of 1% acetone in nitrogen. The background consists of pure nitrogen and the acetone mixture was added in 10 s exposures (blue arrow). Operating temperature is 22°C and V_{sd} is 1 V.

exposures of similar duration and concentration. A slight variation of I_{sd} of 20% is observed over the five exposures. However, much of this difference is likely due to small variations in the exposure time. Interestingly, the changes in I_{ds} do not plateau out within the ten second exposure suggesting that sensor response is under kinetic limitations. Changes in flow rate, temperature, and concentration of analyte will likely affect the sensor response.

Longer exposure times and higher acetone content in the analyte gas results in an increase of the observed I_{ds} change, Fig 3A. As the acetone content is raised from 1% to 5%, the source-drain current increases by more than a factor of 10. The I_{ds} increase is nonlinear over this acetone concentration. In these sets of experiments the exposure time was extended from 90 seconds (low acetone concentrations) to three minutes (high acetone concentrations). The I_{ds} for the lower

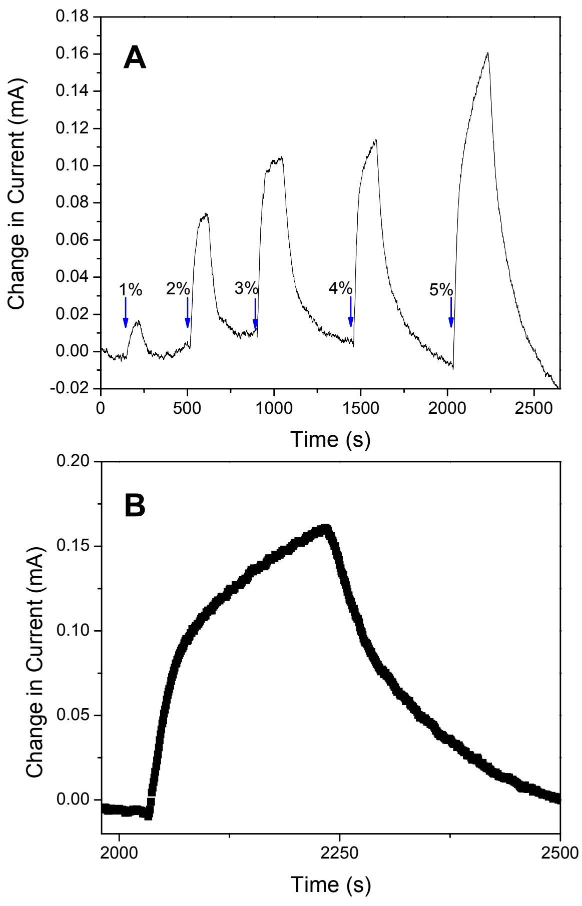

Fig 3. (A) Source-drain current response of an AlGaN/GaN HEMT sensor exposed to nitrogen with 1-5% acetone vapor. Exposure times range from 90 s for the lower acetone concentrations to 3 min for the higher concentrations. Initiation times for the exposure are indicated with blue arrows. Operational temperature for these experiments was 22°C. The V_{ds} was 1.5 V. (B) Blow up of 5% exposure in (A). Notice the fast and slow process of the I_{ds} change.

acetone concentrations begins to plateau in the shorter duration. By contrast, the increased current with the higher acetone concentrations (4 and 5%) continues to increase after thee minutes. Immediately after exposure, the source-drain current raises dramatically in the first 30 s followed by a much slower increase in I_{ds}, Fig 3B. This bimodal increase indicates that the acetone is affecting the polarization of the AlGaN/GaN HEMT with two different mechanisms. Two specific or nonspecific interactions or a combination can lead to the observed two step process.

Similar responses were obtained for AlGaN/GaN HEMT sensors exposed to the chemical toxin diethylcyanophosphonate (DECNP), Fig 4. Even after a 90 s exposure to a 0.1% DECNP mixture in nitrogen, the I_{ds} failed to plateau. The increased chemical reactivity of DECNP compared to acetone provides additional analyte-AlGaN and analyte-Ni interactions that may yield I_{ds}-changing byproducts. For example, DECNP can lose an anionic cyanide group which can then associate/coordinate to the metal centers in the gate electrode or AlGaN layer. In both cases, the barrier height of the GaN film will be affected by this process.

IV. TEMPERATURE DEPENDENCE

One advantage of wide band-gap semiconducting devices is their ability to operate at high temperatures. The large energy gap limits the generation of thermally excited charge carriers which can negate the semiconducting properties of the solid and compromise the electronics. High temperature (400°C) capabilities of AlGaN/GaN HEMT sensors have been demonstrated [6]. However, the temperature

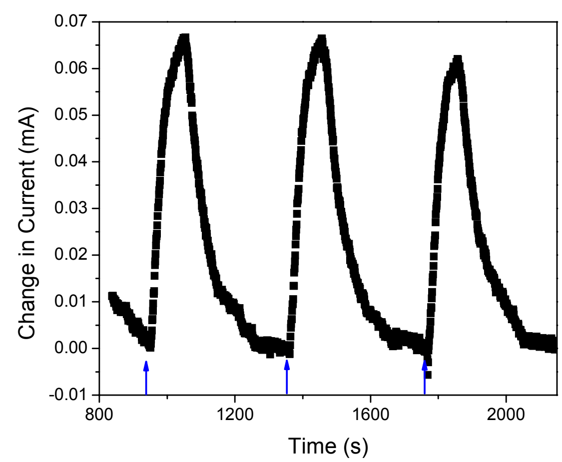

Fig 4. Source-drain current response of an AlGaN/GaN HEMT sensor exposed to 0.1% diethyl cyanophosphonate in nitrogen. Exposure times are 90 seconds and initiation times are indicated with blue arrows. Measurements were performed at 22°C with a V_{ds} of 1.5 V.

dependence of the sensor response has not been reported in great detail to date.

The temperature dependent I_{sd} response for a AlGaN/GaN HEMT sensor exposed to 4% O_2 in nitrogen reveals a strong increase in sensitivity with temperature, Fig 5A. Interestingly, the signal increases by a factor of 10 when the temperature is increased from 22°C to 300°C. These results are consistent with a kinetically limited sensor response. The higher currents are not due to thermally generated charge carriers as the magnitude of the background current decreases with temperature, Fig 5B. This decrease in background current is likely due to phonon scattering. Thus, the energetics of the AlGaN/GaN are not significantly altered by the higher temperatures. Rather, these results suggest that the response of the AlGaN/GaN sensors is largely limited by the kinetics of the analyte-surface interaction. Kinetic limitations imply that a specific analyte/substrate interaction is responsible for the majority of I_{ds} change rather than a nonspecific process. Furthermore, these results suggest that the performance of AlGaN/GaN HEMT sensors can be optimized by strategies that target the kinetics of the analyte-sensor interactions.

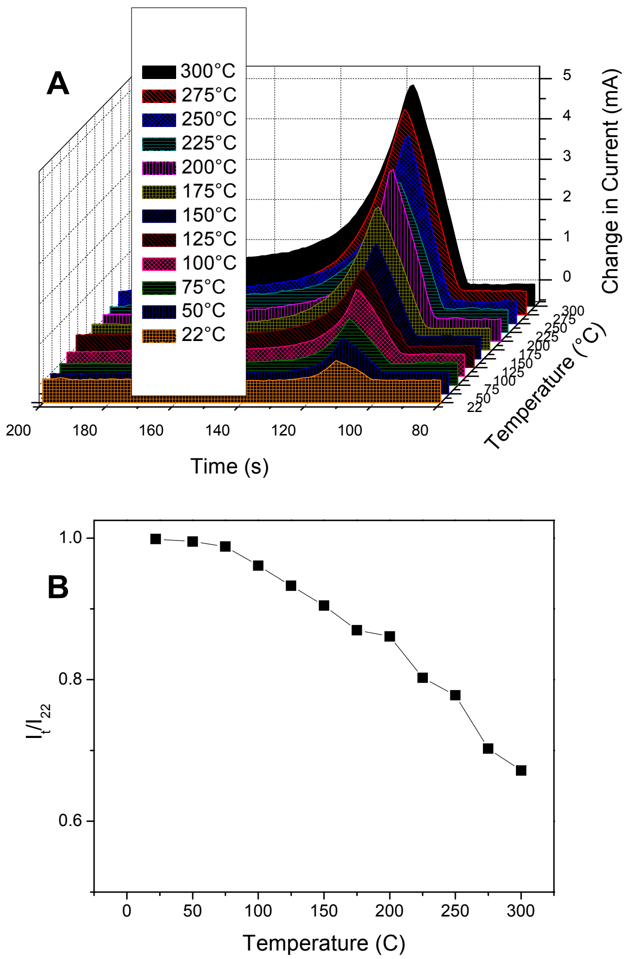

Fig 5. (A) Source-drain current response of AlGaN/GaN HEMT sensor exposed to 4% O_2 in nitrogen at temperatures from 22°C to 300°C. V_{sd} is 1 V. (B) Relative source-drain currents for AlGaN/GaN HEMT under a nitrogen atmosphere. Currents are normalized to the I_{sd} obtained at room temperature (22°C). V_{sd} is 1 V.

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References