TEMPERATURE-DEPENDENT TRANSIENT BEHAVIOR OF AlGaIn/GaN HIGH ELECTRON MOBILITY PRESSURE SENSORS

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ABSTRACT

For the first time, the time-dependent response of an AlGaIn/GaN high electron mobility transistor (HEMT) pressure sensor is characterized at elevated temperatures. We show that temperature affects the sensitivity and the transient behavior of the sensor's response to pressure. At a temperature above 125°C, the drain current response after the application of pressure transitions from exponentially decaying to exponentially growing. Using an Arrhenius model of trap activation energy, we demonstrate that two traps in the AlGaIn/GaN heterostructure at 0.62 eV and 0.87 eV cause the temperature-dependent transient behavior. This work paves the way for creating reliable GaN-based sensing devices.

INTRODUCTION

Electronics and sensors have been developed using the gallium nitride (GaN) heterostructure platform. These devices leverage a conductive sheet of electrons that forms at the interface of GaN and III-nitride alloys (e.g., AlGaIn), known as a 2-dimensional electron gas (2DEG). The 2DEG is partially formed based on the piezoelectric nature of the materials and has thus been leveraged to develop strain [1] and pressure sensors [2]. There is a growing interest in engineering these GaN-based sensors to operate at high temperatures. This vision is supported by a recent demonstration of GaN HEMTs up to 1000°C [3]. However, transient effects of GaN-based strain/pressure sensors, which have plagued both transistor and optical device architectures [4], have been overlooked by researchers to date.

EXPERIMENT

To study the time-, pressure- and temperature-dependent response of the GaN 2DEG, a GaN-based micro-pressure sensor was microfabricated leveraging an AlGaIn/GaN high electron mobility transistor (HEMT) positioned at the center of a fully-suspended diaphragm. To microfabricate the device, an AlGaIn/GaN-on-silicon wafer grown via metal organic chemical vapor deposition (MOCVD) from DOWA Electronic Materials Co., Ltd. was used. The fabrication of the HEMT included a mesa-isolation etch (Figure 1b), Ohmic and Schottky contact depositions (Figure 1c), passivation with plasma-enhanced atomic layer deposition of Al₂O₃, etching vias, and bond metal deposition (Figure 1d). The pressure sensor is released by patterning a SiO₂ hard mask on the back side (Figure 1b) and etching the silicon with DRIE (Figure 1e).

The device was tested on a high-temperature probe station from 25°C to 200°C. Pressure was applied by placing the diaphragm over a vacuum port and pulling a vacuum of 6.9 ± 0.1 psi. At the center of diaphragm, the HEMT is in biaxial compressive strain in basal plane when the pressure is applied. The transient response (I_D - t) at $V_{DS} = 2.5$ V and $V_{GS} = -3$ V was measured using a semiconductor parameter analyzer (Agilent B1500A).

RESULTS AND DISCUSSION

The transient drain current (normalized by the current immediately before the first pressure application) response, I_D - t , is shown in Figure 2 at room temperature, 75°C, 150°C, and 200°C.

Figure 1: Microfabrication of AlGaIn/GaN-on-silicon micro-pressure sensor grown via MOCVD (a). Fabrication includes: mesa etch isolation, hard mask patterning (b) deposition of Ohmic and Schottky contact (c), passivation and deposition of metal for wire bonding. The device is released by etching the silicon with DRIE process.

Figure 2. Transient drain current (normalized) response of an AlGaIn/GaN pressure sensor at various temperatures under 6.9 psi of applied pressure (gray regions). The arrows highlight the increasing or decreasing behavior of the drain current during and after the pressure stimulus

The sensitivity is calculated based on measurements immediately before and after the application of pressure and the magnitude is plotted as a function of temperature in Figure 3. We observe that the magnitude of the sensitivity increases from room temperature to 150°C, 0.34 %/psi to 0.49 %/psi, and then shifts to a sharply decreasing trend reaching 0.34 %/psi at 200°C.

Additionally, at temperatures between 75°C and 125°C, when pressure is applied, there is an initial drop in current due to a

Figure 3: Magnitude of sensitivity of AlGaIn/GaN pressure sensor as function of temperature.

reduction in the piezoelectric effect, followed by a decay in the current. At temperatures above 125°C, the current increases after the initial drop in the current. The temperature-dependent transient behavior can be explained by the existence of two traps (caused by material defects) in different locations in the AlGaIn/GaN heterostructure (Figure 4). If the trap is at the top surface of the AlGaIn and above the Fermi level, the trap will be pulled below the Fermi level upon application of compressive strain due to a reduction in Schottky barrier height [5]. This causes a reduction in the 2DEG concentration and the current. Likewise, if the trap is near the AlGaIn/GaN interface, the trap will be pulled above the Fermi level and cause the 2DEG density and current to increase.

The time constant of the transient response, τ , is found by fitting the data to

$$I_D(t) = I_1 + I_2 \exp\left(-\frac{t}{\tau}\right)^\beta \quad (1)$$

where the sum of I_1 and I_2 are the steady state current and β is a stretching factor. The time constant is expected to be exponentially dependent on the energy level of the trap, E_T and the inverse of temperature, T , such that

$$\tau = \frac{1}{\sigma_T v_{th}(T) N_C(T)} \exp \frac{E_T - E_C}{kT} \quad (2)$$

where σ_T , v_{th} , N_C , E_C , k are the trap cross sectional area, the thermal velocity of the electron, the density of states in the conduction band, the conduction band energy, and the Boltzmann constant, respectively. By plotting the time constant on an Arrhenius plot, two trap energy levels are extracted at 0.62 eV and 0.87 eV, and their associated trap cross sectional areas are $8.9 \times 10^{-18} \text{ cm}^2$ and $1.9 \times 10^{-19} \text{ cm}^2$, respectively. These values match previously reported trap levels [6], [7]. The study of traps and their effect on the sensitivity and transient behavior is important for the development of reliable and sensitive high-temperature GaN-based pressure sensors. This work sets the foundation for further examination.

CONCLUSION

In this work, the transient response of a micro-pressure sensor was studied from room temperature to 200°C. The magnitude of the sensitivity of the device is seen to increase until 150°C from 0.49 %/psi to 0.70 %/psi, at which point it starts sharply dropping to 0.34 %/psi at 200°C. At 125°C, the transient response switches from decaying after the initial decrease in current due to the pressure

Figure 4: Schematic illustration of the conduction band of GaN heterostructure at lower temperatures showing a decay in current. A trap at the AlGaIn surface is pulled below the Fermi level, fills, and reduces the charge available to the 2DEG. (a) Schematic illustration of the conduction band of GaN heterostructure at high temperatures showing an increase in current. A trap at the AlGaIn/GaN interface is pulled above the Fermi level, empties, and increases the charge available to the 2DEG. (b)

application to exponentially growing. This change in the transient behavior is attributed to two traps at 0.62 eV and 0.87 eV.

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