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AlGaN/GaN-based metal–oxide–semiconductor diode-based hydrogen gas sensor

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The characteristics of Sc_2O_3/AlGaN/GaN metal–oxide–semiconductor (MOS) diodes as hydrogen gas sensors are reported. At 25 °C, a change in forward current of ~6 mA at a bias of 2 V was obtained in response to a change in ambient from pure N_2 to 10% H_2/90% N_2. This is approximately double the change in forward current obtained in Pt/GaN Schottky diodes measured under the same conditions. The mechanism of the change in forward gate current appears to be formation of a dipole layer at the oxide/GaN interface that screens some of the piezo-induced channel charge. The MOS-diode response time is limited by the mass transport of gas into the test chamber and not by the diffusion of atomic hydrogen through the metal/oxide stack, even at 25 °C. These devices look promising for applications requiring sensitive, long-term stable detection of combustion gases. [DOI: 10.1063/1.1648134]

There is a strong interest in wide band gap semiconductor gas sensors for applications including fuel leak detection in spacecraft. In addition these detectors would have dual-use in automobiles and aircraft, fire detectors, exhaust diagnosis and emissions from industrial processes.[1–14] GaN electronics and sensors will reduce spacecraft launch weighs and increase satellite functional capabilities. Given the high cost per pound of launching payloads into earth orbit, the weight savings gained by using wide band gap devices could have large economic and competitive implications in the satellite industry. Existing commercial satellites require thermal radiators to dissipate heat generated by the spacecraft electronics. These radiators could be eliminated with GaN, and allow greater functionality (more transponders in a commercial satellite) by utilizing the space and weight formerly occupied by the thermal management system. In addition, the radiation hardness of these materials would reduce the weight of shielding normally used to protect spacecraft electronic components from radiation. GaN is capable of operating at much higher temperatures than more conventional semiconductors such as Si. Simple Schottky diode or field-effect transistor structures fabricated in GaN (and SiC)[15] are sensitive to a number of gases, including hydrogen and hydrocarbons.[1,7] One additional attractive attribute of GaN and SiC is the fact that gas sensors based on this material could be integrated with high-temperature electronic devices on the same chip.

There have already been reports of rad-hard (>300 Mrad Co-60 gamma ray tolerance) combustion gas detectors with extremely fast time response and capable of operating at high temperatures, eliminating bulky and expensive cooling systems. The device structures were mainly based on simple Schottky diodes with Pt contacts.[16–27]

In this regard gas sensors based on a metal–oxide–semiconductor (MOS) diode on an AlGaN/GaN high electron mobility transistor (HEMT) layer structure are of interest, because HEMTs are expected to be the GaN electronic device that is commercialized, as part of next generation radar and wireless communication systems. These structures have much higher sensitivity than Schottky diodes on the GaN layer, because they are true transistors and therefore operate with gain. In addition, the MOS-gate version of the HEMT has significantly better thermal stability than a metal–gate structure[28–33] and is well-suited to gas sensing. When exposed to changes in ambient, changes in the surface potential will lead to large changes in channel current.

HEMT layer structures were grown on C-plane Al_2O_3 substrates by metalorganic chemical vapor deposition. The layer structure included an initial 2-μm-thick undoped GaN buffer followed by a 35-nm-thick unintentionally doped $Al_{0.28}Ga_{0.72}N$ layer. The sheet carrier concentration was $\sim 1 \times 10^{13}\ cm^{-2}$ with a mobility of 980 $cm^2/V\,s$ at room temperature. Mesa isolation was achieved with 2000 Å plasma enhanced chemical vapor deposited SiN_x. The ohmic contacts were formed by lift-off of the electron (e)-beam deposited Ti (200 Å)/Al (1000 Å)/Pt (400 Å)/Au (800 Å). The contacts were annealed at 850 °C for 45 s under a flowing N_2 ambient in a Heatpulse 610T system. 400 Å Sc_2O_3 was deposited as a gate dielectric through a contact window of SiN_x layer. Before oxide deposition, the wafer was exposed to ozone for 25 min. It was then heat *in situ* at 300 °C cleaning for 10 min inside the growth chamber. 100 Å Sc_2O_3 was deposited on AlGaN/GaN by rf plasma-activated molecular beam epitaxy at 100 °C using elemental Sc evaporated from a standard effusion all at 1130 °C and O_2 derived from an Oxford rf plasma source.[34–36] 200 Å Pt Schokky contact was deposited on the top of Sc_2O_3. Then, the final metal of e-beam deposited Ti/Au (300 Å/1200 Å) interconnection contacts was employed on the MOS–HEMT diodes. Figure 1 shows a schematic (top) and photograph (bottom) of the completed device. The devices were bonded to electrical

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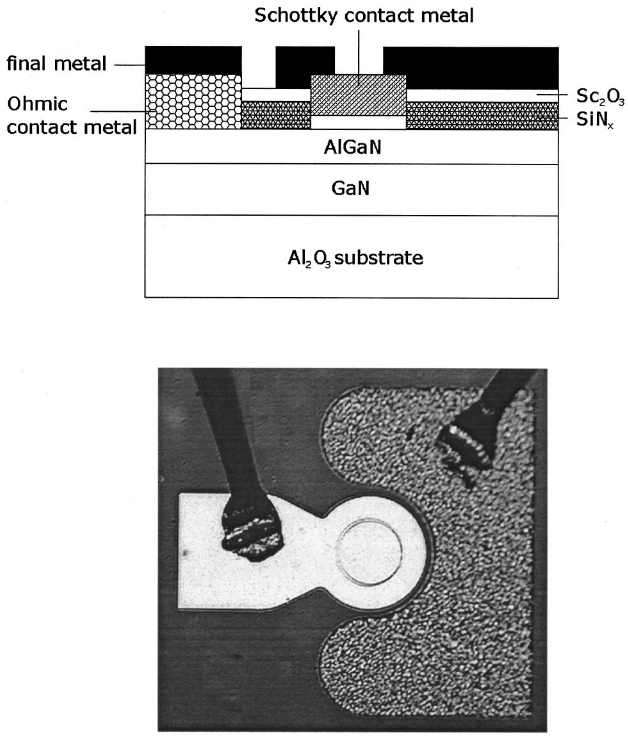

FIG. 1. Cross-sectional schematic of the completed MOS diode on the AlGaN/GaN HEMT layer structure (top) and plan-view photograph of device (bottom).

feed through and exposed to different gas ambients in an environmental chamber.[24–26]

Figure 2 shows the forward $I-V$ characteristics at 25 °C of the MOS–HEMT diode both in pure N_2 and in a 10% H_2/90% H_2 atmosphere. At a given forward bias, the current increases upon introduction of the H_2, through a lowering of the effective barrier height. The H_2 catalytically decomposes on the Pt metallization and diffuses rapidly though the underlying oxide to the interface where it forms a dipole layer.[23] At 2.5 V forward bias the change in forward current upon introduction of the hydrogen into the ambient is ~6 mA or equivalently 0.4 V at a fixed current of 10 Ma. This is roughly double the detection sensitivity of comparable GaN Schottky gas sensors tested under the same

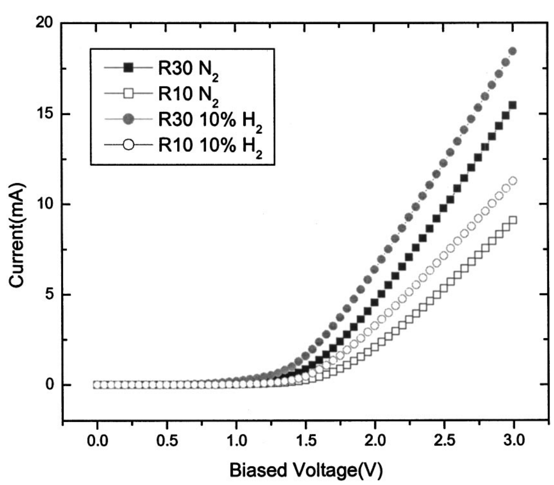

FIG. 2. Forward $I-V$ characteristics of MOS–HEMT based diode sensors of two different dimensions at 25 °C measured under pure N_2 or 10% H_2/90% N_2 ambients.

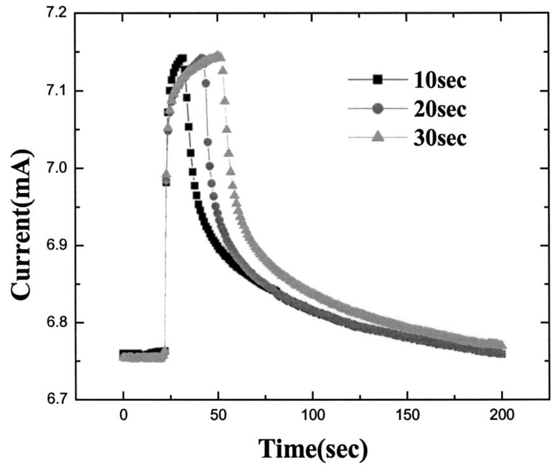

FIG. 3. Time response at 25 °C of MOS–HEMT based diode forward current at a fixed bias of 2 V when switching the ambient from N_2 to 10% H_2/90% N_2 for periods of 10, 20, or 30 s and then back to pure N_2.

conditions,[26] confirming that the MOS–HEMT based diode has advantages for applications requiring the ability to detect combustion gases even at room temperature. As the detection temperature is increased, the response of the MOS–HEMT diodes increases due to more efficient cracking of the hydrogen on the metal contact.

The threshold voltage for a MOSFET is given by[37]

$$V_T = V_{\mathrm{FB}} + 2\phi_B + \left(\frac{4eN_D\phi_B\varepsilon_S}{C_i}\right)^{0.5},$$

where V_{FB} is the voltage required for flatband conditions, ϕ_B is the barrier height, e is the electronic charge, and C_i is the Sc_2O_3 capacitance per unit area. In analogy with results for MOS gas sensors in other materials systems,[19] the effect of the introduction of the atomic hydrogen into the oxide is to create a dipole layer at the oxide/semiconductor interface that will screen some of the piezo-induced charge in the HEMT channel.

To test the time response of the MOS diode sensors, the 10% H_2/90% N_2 ambient was switched into the chamber through a mass flow controller for periods of 10, 20, or 30 s and then switched back to pure N_2. Figure 3 shows the time dependence of forward current at a fixed bias of 2 V under these conditions. The response of the sensor is rapid (<1 s), with saturation taking almost the full 30 s. Upon switching out of the hydrogen-containing ambient, the forward current decays exponentially back to its initial value. This time constant is determined by the volume of the test chamber and the flow rate of the input gases and is not limited by the response of the MOS diode itself.

Figure 4 shows the time response of the forward current at fixed bias to a series of gas injections into the chamber, of duration 10 s each (top) or 30 s each (bottom). The MOS diode shows good repeatability in its changes of current and the ability to cycle this current in response to repeated introductions of hydrogen into the ambient. Once again, the response appears to be limited by the mass transport of gas into and out of the chamber and not to the diffusion of hydrogen through the Pt/Sc_2O_3 stack.

In conclusion, AlGaN/GaN MOS–HEMT diodes appear well-suited to combustion gas sensing applications. The

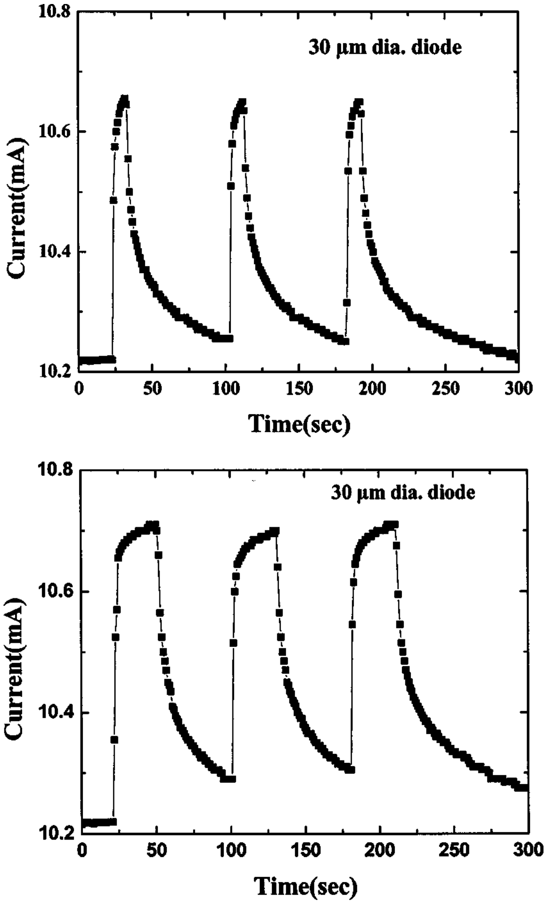

FIG. 4. Time response at 25 °C of MOS–HEMT based diode forward current at a fixed bias of 2 V for three cycles of switching the ambient from N_2 to 10% H_2/90% N_2 for periods of 10 (top) or 30 (bottom) s and then back to pure N_2.

changes in forward current are approximately double those of simple GaN Schottky diode gas sensors tested under similar conditions and suggest that integrated chips involving gas sensors and HEMT-based circuitry for off-chip communication are feasible in the AlGaN/GaN system.

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