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Remote sensing system for hydrogen using GaN Schottky diodes

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Abstract

The characteristics and operation of a GaN Schottky diode-based remote sensing system for hydrogen is described. The detection mechanism is a change in effective barrier height of the Pt or Pd contact on the GaN in the presence of even 600 ppm of H_2 This translates to a change in forward current at fixed bias voltage or a change in voltage across diode at fixed bias current, which means a change in impedance. The change in sensor impedance is amplified and the signal is transmitted at 916 MHz to a remote receiver base station. The base station response can be set to many possibilities, including alarms for signals above a particular threshold. The sensor output increases with ambient temperature due to increased cracking efficiency of the hydrogen on the Pt or Pd surface.

1. Introduction

There is currently a strong interest in the development of wide bandgap semiconductor gas sensors for applications including detection of combustion gases, for fuel leak detection in spacecraft, automobiles and aircraft, fire detectors, exhaust diagnosis and emissions from industrial processes [1–23]. In addition, these detectors would have dual-use in automobiles and aircraft, fire detectors, exhaust diagnosis and emissions from industrial processes [1–14]. The high-temperature capabilities of 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 bandgap 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. 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 [1,7,24,25]. Gas sensors based on GaN could be integrated with high-temperature electronic devices on the same chip [26,27].

To enhance the utility of the hydrogen detection system it is desirable to have the capability for wireless remote transmission of the data, so that appropriate courses of action can be taken by a central monitoring team. In this paper, we describe the integration of a GaN Schottky diode sensor with a transmitter and receiver base station, operating at 916 MHz. The integrated system provides a robust combustion gas detection system capable of operating at high ambient temperatures.

2. Experimental

The starting sample were 6 μm thick n-GaN ($n \sim 3 \times 10^{17}\,cm^{-3}$) layers grown on Al_2O_3 sapphire substrates by metal organic chemical vapor deposition. Front-side ohmic contacts of Ti/Al/Pt/Au were formed by lift-off and subsequent annealing at 600 °C. The Schottky contacts were formed by lift-off of e-beam deposited Pd or Pt, 24 and 15 nm thick, respectively. The contact diameter was 80 μm in all cases. The devices were wire-bonded to a test fixture using Ti/Au bond-pads and Au wires for contact. The gas sensing experiments were performed in a tube furnace that contained electrical feedthroughs connected to an HP4145

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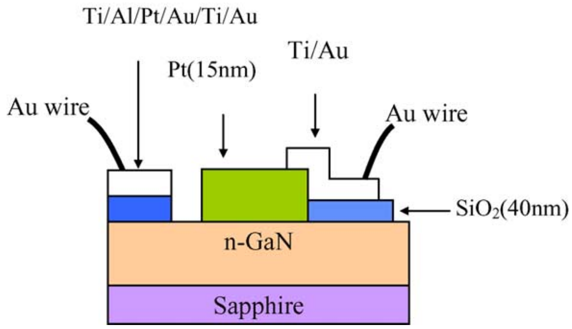

Fig. 1. Schematic of Pt/GaN Schottky diode for hydrogen gas sensing.

parameter analyzer. Measurements were performed at temperatures up to 300 °C in flowing gas ambients of N_2 or 10% H_2 in N_2. Fig. 1 shows a schematic of the completed device, while Fig. 2 shows a scanning electron micrograph of a completed diode (top) and the device packaged into a header (bottom).

Fig. 2. SEM micrograph of completed device, showing bond wire attached (top) and photograph of device bonded into header.

3. Results and discussion

Fig. 3 (top) shows the forward *I–V* characteristics of the Pd/GaN diode at 170 °C in pure N_2 and 10% H_2 in N_2 ambients. An advantage of these diodes is that they can be operated to large forward conduction currents, allowing very large signal differences resulting from different gas ambients. Note that the addition of 10% H_2 to the ambient produces a shift of 74 mV at a forward current of 0.2 A. At higher voltage and current, the signal change was even more discernable, e.g. 1 mA at a fixed forward bias of 1 V or equivalently, 100 mV at a fixed current of 6 mA. Similar magnitudes of current change were obtained for the Pt/GaN diodes and both Pd and Pt appear to be suitable contacts for these types of gas sensors. The GaN devices were also able to differentiate between various gases. The use of either air or CF_4 as the ambient produced significant increase in forward current. Since the H_2, O_2 and F_2 in these gases can affect the

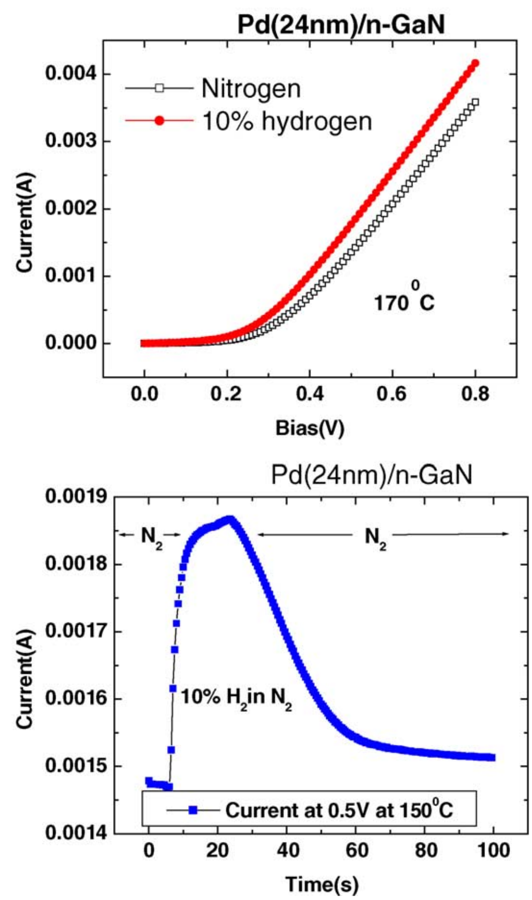

Fig. 3. Forward *I–V* characteristics from Pt/GaN diode at 170 C in either 10% H_2/90% N_2 or pure N_2 ambient (top) and forward current at fixed bias of 0.5 V at 150 C as a function of time as the ambient is switched from N_2 to 10% H_2/90% N_2 (bottom).

dipole layer at the Pt–GaN interface because of their reactivity, the electric field under the Pt gate is altered, producing the resulting change in diode forward current. The sensing mechanism in semiconductor gas sensors is thought to be creation of a polarized layer in the semiconductor surface by hydrogen atoms diffusing through the metal contact [15,16]. The adsorbed hydrogen is then assumed to change the work function of the metal [16]. Recent elastic recoil detection measurements on Pt–GaN Schottky diodes confirm the presence of hydrogen at the metal semiconductor interface after exposure to molecular hydrogen at 400 °C [8]. Other reports on Pt/GaN Schottky diode gas sensors have shown their ability to detect hydrogen and propane at temperatures up to at least 400 °C [3]. However, to date, there has been no quantification of the change in effective barrier height in GaN diodes after exposure to hydrogen-containing gases. The presence of hydrogen in the ambient is found to lower the effective barrier height of Pt on GaN by 50–70 meV in the temperature range 298–423 K and of Pd on GaN by 30–60 meV in the temperature range 443–473 K. The changes are

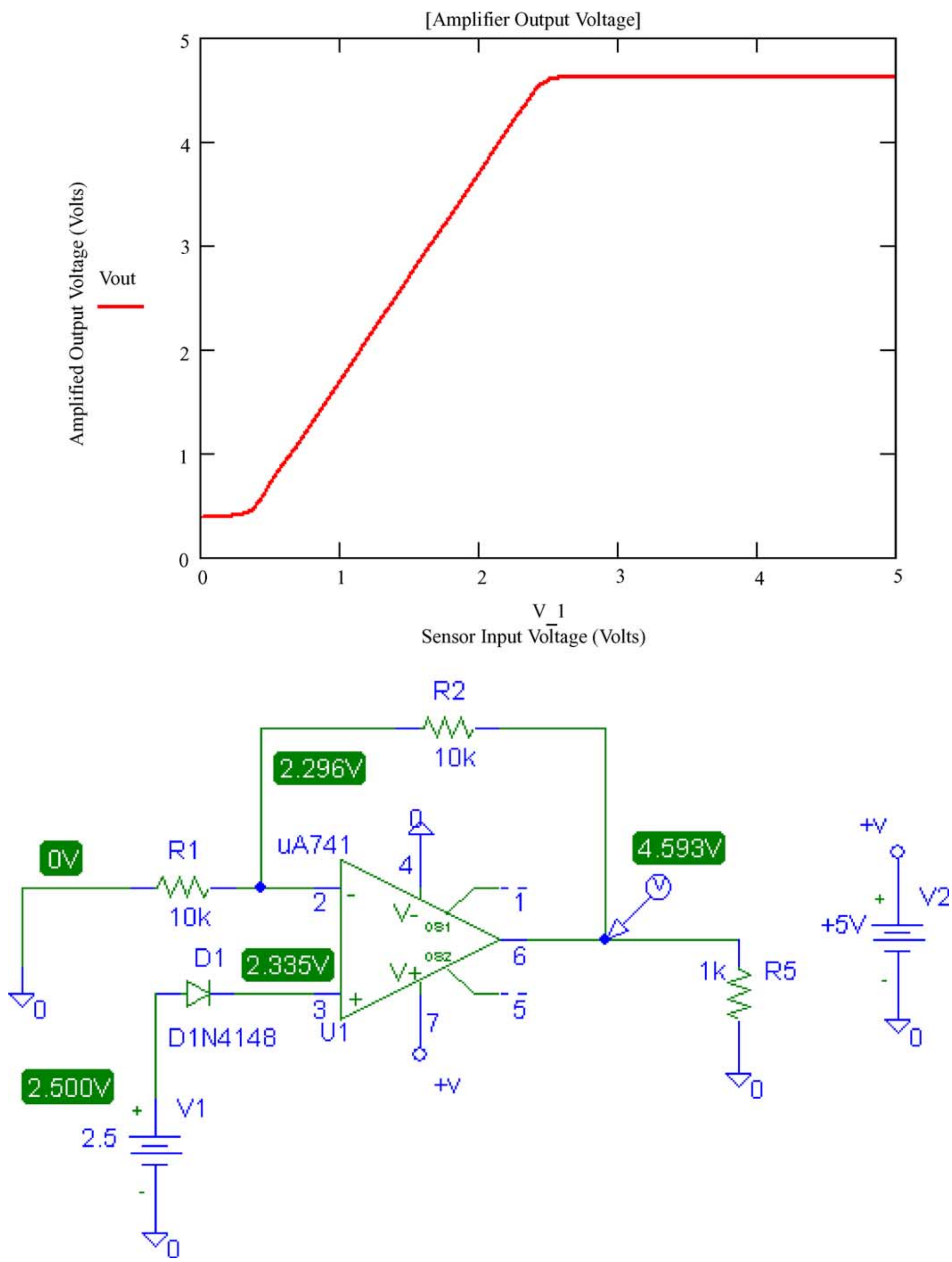

Fig. 4. Output of amplifier in response to change in sensor input voltage (top) and schematic of amplifier (bottom).

larger as temperature increases, consistent with more effective catalytic cracking of the H_2.

A very clear demonstration of the reversibility of the effect is shown in Fig. 3 (bottom). In this case, Pd/GaN diodes were biased at a constant forward bias of 0.5 V at 150 °C and the resulting forward current measured as a function of time as the ambient was cycled from N_2 to 10% H_2 in N_2 and then back to N_2. Note the increase in forward current of ∼0.3 mA as H_2 is introduced and the subsequent decay back towards the initial current as N_2 is introduced into the measurement system. The increase in forward current is very rapid after switching in the 10% H_2 in N_2 gas. From careful observation of this initial rise in current, we believe that diffusion of hydrogen through the metal contact is not the limiting factor in the time response of the diodes but rather the mass transport of gas into the enclosure. Similarly, the longer recovery times are at least partially caused by the time needed to completely flush the H_2 out of the measurement enclosure. Once again, the Pt/GaN diodes showed similar results.

When the sensor is exposed to hydrogen-containing ambients, the impedance of the sensor decreases as a function of the amount of gas present. Therefore, assuming constant bias current, this causes a decrease in the voltage drop across the sensor,—which can be then amplified and transmitted to remote locations.

The voltage variation is driven through a low noise operational amplifier (NE5532P, Texas Instruments) with a set gain = $((1 + R_2)/R_1)$. Since the voltage reading across the diode is about 1.0–1.5 V with gas detected (assuming bias current = 4–6 mA), a gain = 2 ($R_2 = R_1 = 10\,\text{k}\Omega$) will be enough for the micro-controller to read the voltage and to avoid saturation of the amplifier ($V_{sat} = 4.6$ V, $V_{dd} = 5$ V) as seen in Fig. 4, which also shows the amplifier schematic. The output voltage of the amplifier is then sampled and converted to digital form by the micro-controller (PIC16F876, Microchips). The micro-controller is preset to generate samples every 50 us and analog voltage is converted into an 8-bit data string.

This 8-bit data string is then stored in a variable and encoded with a Convolutional Encoder for better error detection and correction at the receiver side. Then, the encoded variable is transmitted serially at a baud rate equal to 9600 symbols/s through pin 21 (RB0) to pin 2 (Data In) on the transmitter. The 8-bit serial input data to the transmitter is then modulated (ASK OOK) and transmitted at a radio frequency equal to 916 Mhz using TLP916A Transmitter module (Laipac). The schematic of the transmitter sensor device is shown in Fig. 5.

The 916 Mhz receiver module RLP916A (Laipac) filters the incoming signal, demodulates it, and serially outputs

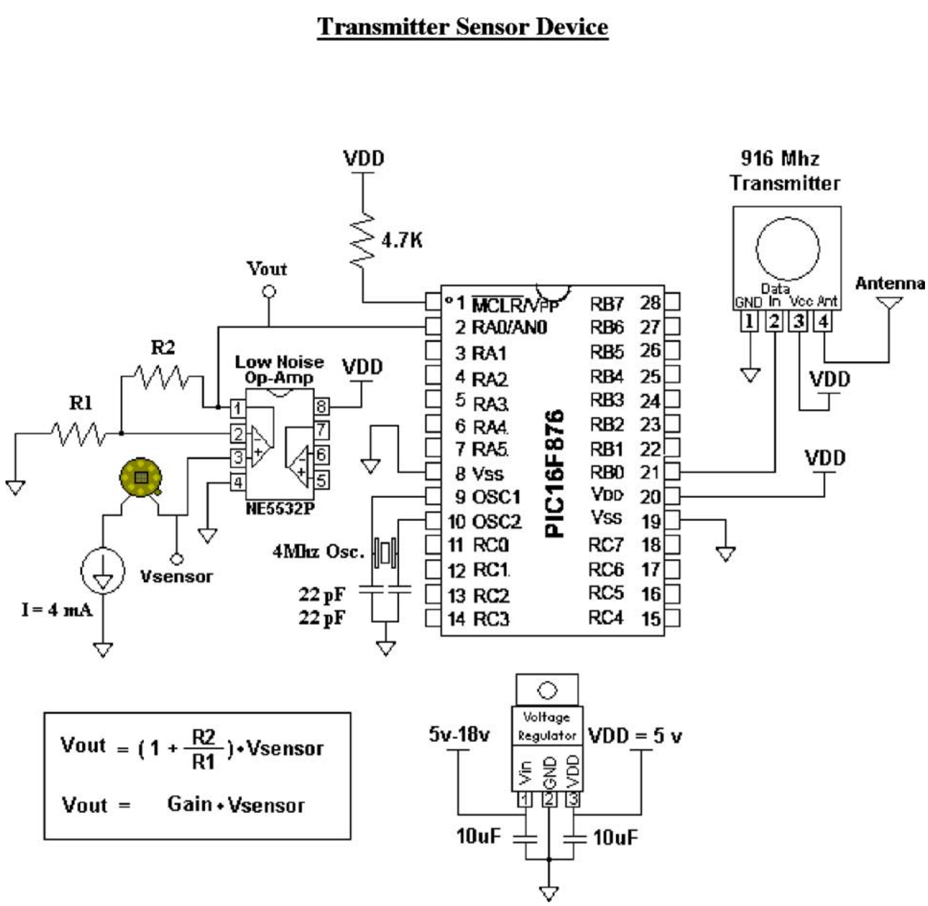

Fig. 5. Circuit diagram for transmitter sensor (top) and specifications (bottom).

the encoded data to pin 11 (RC0) on the micro-controller at the same baud rate it was originally sent. The encoded signal is then decoded using hard decision Viterbi decoder algorithm for error detection and correction due to noise and interference. Since the encoded signal was the actual voltage reading of the output voltage on the sensor, the decoded signal is therefore the 8-bit ADC voltage reading of the sensor. At this point, the user has many options that can be specified and activated by the microcontroller according to the voltage reading received (example: set off a siren alarm, flash a hazardous light, inform other parties, etc.). For simplicity in experiment, the received output voltage of the sensor was displayed on a 16×1 LCD screen to verify, indeed, successful transmission of data.

4. Summary and conclusions

A robust combustion gas sensor with remote data transmission capability has been demonstrated. The system is versatile, radiation-hard and capable of operating to high local sensor temperatures, and offers many response variants.

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