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S. C. Hung, C. W. Chen, C. Y. Shieh, G. C. Chi, R. Fan, and S. J. Pearton

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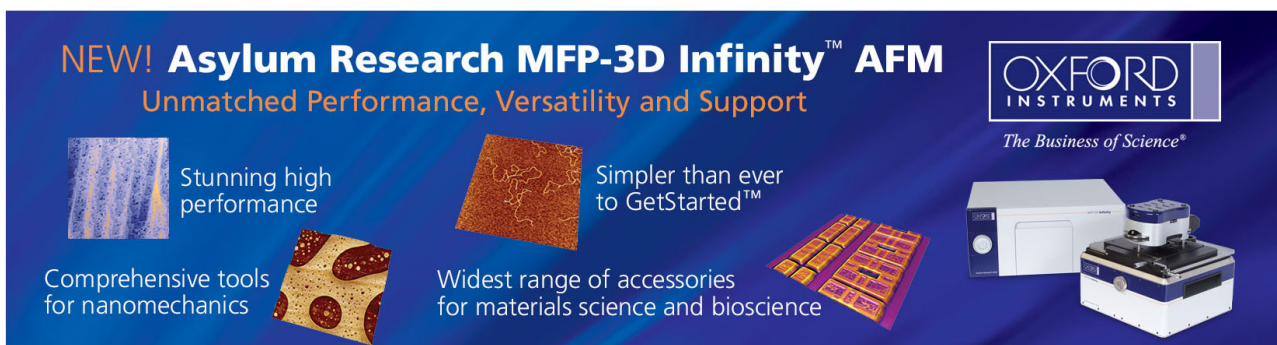
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High sensitivity carbon monoxide sensors made by zinc oxide modified gated AlGaIn high electron mobility transistors under room temperature

S. C. Hung,^{1(a)} C. W. Chen,² C. Y. Shieh,³ G. C. Chi,⁴ R. Fan,⁵ and S. J. Pearton⁶

¹Optical Science Center, National Central University, Jhong-Li 320, Taiwan

²Department of Physics, National Central University, Jhong-Li 320, Taiwan

³Department of Optics and Photonics, National Central University, Jhong-Li 320, Taiwan

⁴Department of Photonics, National Chiao Tung University, Hsinchu 300, Taiwan

⁵Department of Chemical Engineering, University of Florida, Gainesville, Florida 32611, USA

⁶Department of Material Science and Engineering, University of Florida, Gainesville, Florida 32611, USA

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AlGaIn/GaN high electron mobility transistors (HEMTs) with zinc oxide (ZnO) nanowires modified gate exhibit significant changes in channel conductance upon expose to different concentration of carbon monoxide (CO) at room temperature. The ZnO nanowires, grown by chemical vapor deposition (CVD) with perfect crystal quality will attach CO molecules and release electrons, which will lead to a change in surface charge in the gate region of the HEMTs, inducing a higher positive charge on the AlGaIn surface, and increasing the piezoinduced charge density in the HEMTs channel. These electrons create an image positive charge on the gate region for the required neutrality, thus increasing the drain current of the HEMTs. The HEMTs source-drain current was highly dependent on the CO concentration. The limit of detection achieved was 400 ppm in the open cavity with continuous gas flow using a $50 \times 50 \mu\text{m}^2$ gate sensing area. © 2011 American Institute of Physics. [doi:10.1063/1.3596440]

Recently, metal oxide semiconductors, such as SnO₂, In₂O₃, ZnO, indium tin oxide, and magnesium zinc oxide, play important roles in a lot of areas of chemistry, physics, and material science.^{1–5} In these candidates, ZnO is a semiconductor with direct band gap energy of 3.37eV at room temperature and large binding energy of 60 meV. So, it is a promising material for optoelectronics devices, such as light emitting diodes (LEDs), solar cell, and transparent contact layer, and gas sensors.^{6–9} The utilization of ZnO in gas sensor application has a long history. Devices composed of ZnO were studied as chemoresistive materials to detect gases like H₂, NH₃, CH₄, O₂, trimethylamine, ethanol, and CO.^{10–16}

Carbon monoxide (CO) is one of the most dangerous gases in air pollution and human daily life. CO is produced by incomplete combustion of fuels and commonly found in the emission of automobile exhausts, the burning of domestic fuels, etc. It is highly toxic and extremely dangerous because it is colorless and odorless. CO sensors are, therefore, needed in various situations including the detection of smoldering fires. It is believed that the sensing mechanism is based on the reaction between adsorbed oxygen molecules on the surface of ZnO and the gas molecules was detected by changing the electrical properties of ZnO. Thus, a lot of research groups are devoted in studying the relations between different surface morphology, such as nanowire, nanorods and nanobelts, and sensitivity. However, recently reports show a nano-ZnO sensor prepared by an arc plasma method did not show an expected high sensitivity even when exposed to CO at a concentration as high as 5000 ppm.¹⁷

Recently, AlGaIn/GaN high electron mobility transistors (HEMTs) have shown great potential for chemical and biochemical sensing applications.^{18–29} This is due to their high

electron sheet carrier concentration channel induced by both piezoelectric and spontaneous polarization. Unlike conventional semiconductor field effect transistors, there is no intentional dopant in the AlGaIn/GaN HEMTs structure. The electrons in the two-dimensional electron gas (2DEG) channel are located at the interface between the AlGaIn layer and GaN layer, and there are positive countercharges at the HEMT surface induced by the 2DEG. Slight changes in the ambient can affect the surface charge of HEMTs, thus changing the 2DEG concentration in the channel. Thus, nitride HEMTs may be excellent candidates for gas sensors applications.

In this letter, we study the effect of CO concentration on the drain current of AlGaIn/GaN HEMTs sensors with ZnO nanowire modified gate. We quantified the sensitivity, the temporal resolution, and the limit of detection of these sensors for CO detection.

The ZnO nanowire used to function the gate area were grown on c-plane GaN by chemical vapor deposition (CVD). Zinc shot (99.9999% pure) and O₂ (99.9999% pure) were used as precursors for Zn and O, respectively. The growth details were reported in Ref. 30. The characterization of ZnO nanowires were studied by photoluminescence (PL) measurement with a continuous wave He–Cd 325 nm laser, x-ray diffraction (XRD) using Cu K α_1 radiation, scanning electron microscope (SEM), and selected area diffraction patterns (SADPs), respectively. As shown in Fig. 1(a), the diameter and length of ZnO nanowires are very uniform and about 80 nm and 3.5 μm , respectively. Low temperature PL spectrum indicate strong band-edge emission with FWHM is 1.2 nm and weak impurity band emission, as shown in Fig. 1(b), Fig. 1(c) shows single (002) orientation of ZnO nanowires grown on (002) GaN by XRD. The SADP data shows an excellent crystalline quality and corresponds to ZnO (002).

^aElectronic mail: shengchun@ufl.edu.

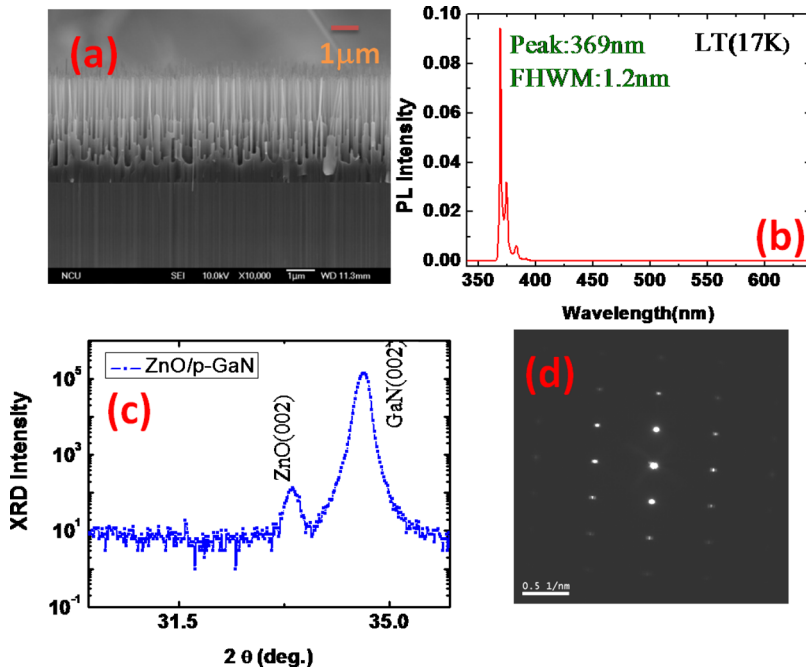


FIG. 1. (Color online) (a) SEM image of ZnO nanowires on GaN template. (b) PL spectrum of ZnO nanowires under 17 K. (c) XRD spectrum of ZnO nanowires on GaN template. (d) SADP data of ZnO nanowires.

The HEMT structures consisted of a 2 μm thick undoped GaN buffer and 250 \AA thick undoped $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ cap layer. The epilayers were grown by metal-organic CVD on thick GaN buffers on sapphire substrates. Mesa isolation was performed with inductively coupled plasma (ICP) etching with Cl_2/Ar discharges at -90 V dc self-bias, ICP power of 300 W at 2 MHz, and a process pressure of 5 mTorr. $50 \times 50 \mu\text{m}^2$ Ohmic contacts separated with gap of 50 μm consisted of e-beam deposited Ti/Al/Pt/Au patterned by lift-off and annealed at 850 $^\circ\text{C}$ for 45 s under a flowing N_2 . AZ 1818 positive photoresist was used as the mask to define the gate area for ZnO nanowires coating, and the gate dimension was $50 \times 50 \mu\text{m}^2$.

For coating ZnO nanowires on the gate area, the ZnO nanowires on GaN template were put into the ethanol solution and the solution was stirred and ultrasonic for 10 min in order to break the connection between ZnO nanowires and GaN template. After ultrasonication, the homogenous ZnO nanowires ethanol solution was dripped onto the gate area by micropipette and dried at 85 $^\circ\text{C}$ for 5 min using a hot plate. Figure 2 shows the schematics of HEMTs sensor coated with ZnO nanowires. For the CO sensing measurement, the HEMTs sensor was mounted on a carrier and put in a gas chamber which filled by N_2 gas. The temperature of chamber was kept at room temperature and a constant drain bias voltage of 500 mV was applied to the drain contact of the sensor. Finally, different amounts of CO gas were injected into the chamber. Figure 3 shows the real time CO detection with ZnO modified gate HEMTs. The drain current of the HEMT sensor showed a rapid increase when the CO concentration

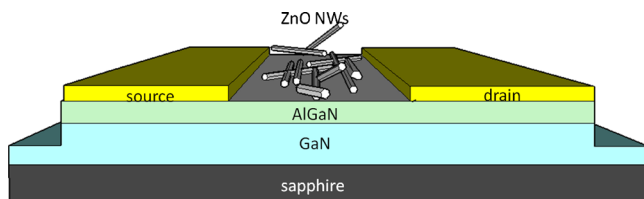


FIG. 2. (Color online) Schematic of ZnO nanowires gated HEMT sensor.

was changed to 1600 ppm in the open cavity with continuous gas flow. A further decrease in the drain current for the HEMT sensor was observed when the CO concentration decreased to 400 ppm. These abrupt drain current increases were due to the change in charges in the ZnO nanowires upon a shift in CO concentration. A HEMT sensor without the ZnO nanowires on the gate area was loaded in the gas chamber, and there was no change in drain current observed.

It is well accepted that the sensitivity of semiconductor gas sensors is attributed to the chemisorptions of oxygen on the oxide surface and the subsequent reaction between adsorbed oxygen and tested gas, which caused the resistance change. The same mechanism may be applied for the CO-sensing of the present ZnO nanowires gated HEMTs. Thus, more CO molecules can react with more oxygen species on the ZnO nanowire surface, and in this letter, we emphasis the electrical change via measuring the change in drain current in the HEMTs instead of measuring the change in resistance. Takata *et al.*³⁰ found that the stable oxygen ion were O_2^-

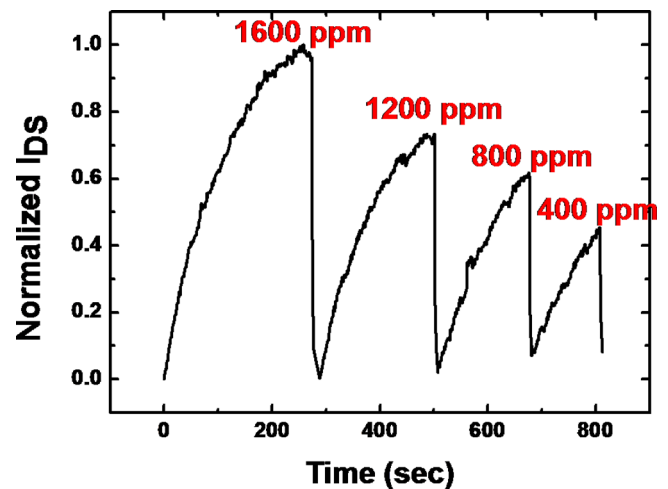


FIG. 3. (Color online) Drain current of a ZnO nanowires gated AlGaIn/GaN HEMT as a function of different CO gas flow rate.

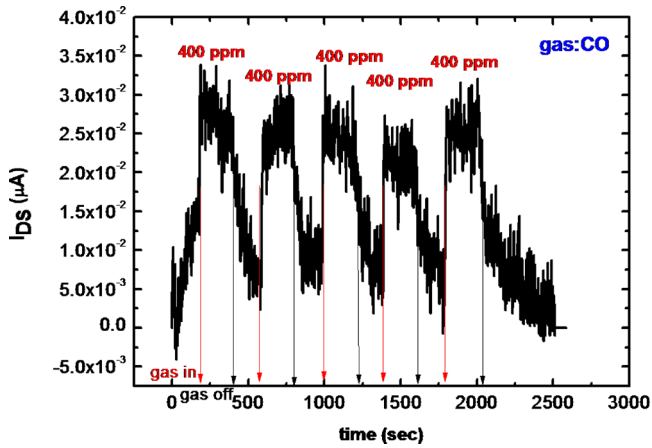


FIG. 4. (Color online) Drain current of a ZnO nanowire gated AlGaIn/GaN HEMT as a function of different CO gas flow rate.

below 100 °C, O^- between 100 and 300 °C, and O^{2-} above 300 °C. The relevant reactions on the surface area could be as follows:



From the knowledge of the catalytic activity, it is anticipated that reducing agents will react rapidly with O^- presented on the surface but very slowly with O_2^- . So, normally at a low temperature below 150 °C, the ZnO based CO sensor show low response in previous work.^{31–33} In this work, we utilize ZnO nanowires with excellent crystal quality to adsorb CO species and release electron on the ZnO nanowire surface, which will induced more positive charge on the AlGaIn surface and enhance the current going through the drain and source contact even at room temperature.

The CO sensor showed a good repeatability, as illustrated in Fig. 4, the drain current response of the ZnO nanowires gated HEMT sensor to CO gas flow rate was switching from 0 to 400 ppm. The change in drain current for the HEMT exposed between 0 to 400 ppm was still considerably larger than the background noise. Thus, HEMTs could be used to detect small difference in CO concentration.

In conclusion, ZnO nanowires gated AlGaIn/GaN HEMTs showed rapid change in the source-drain current when exposed to different CO concentration ambient at room temperature. These results show the potential of ZnO nanowire gated AlGaIn/GaN HEMT for CO sensing applications.

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