

Communications

Realization of a Gas Sensor Using Ultrathin InAs Nanoribbon Membranes for NO₂ Detection at Parts-per-Billion Levels

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Sensors employing semiconductor materials as a sensing element typically use the configuration of field-effect transistors (FETs), to detect conductance changes in response to gas exposures. Such responses depend on how effectively the adsorption or reaction of gas molecules on the material surface can modulate the channel potential inside the materials. Thus, it makes semiconductor nanomaterials¹⁻⁵ with a large surface-to-volume ratio, which are suitable for the realization of high sensitivity gas sensors. Recently, indium arsenide (InAs)-based nanomaterials have garnered interest as a platform to realize high sensitivity gas sensors.³⁻⁵ Among them, the ultrathin InAs nanoribbon (NR) membrane⁵ is well suited to high sensitivity NO₂ gas sensor development due to its innate properties,⁶ such as the large Bohr radius of InAs (~34 nm), an electron accumulation layer on its surface due to Fermi level pinning above the conduction band edge, and uniformity and reproducibility of the process.

In this study we employed the 8 nm-thick InAs NRs transferred on a Si/SiO₂ substrate as a sensing element for the realization of the NO₂ sensor. Our study shows that the device is sensitive down to the parts-per-billion (ppb) level of NO₂ at room temperature, indicating effective modulation of the channel potential by the absorption of NO₂ gas on the InAs surface. Besides, comparative sensor response tests using different InAs thicknesses clearly demonstrated the role of channel thickness in obtaining higher sensor responses.

Figure 1(a) demonstrates the NR transfer process on a Si (*p*+)/SiO₂ (50 nm) substrate. First, InAs (thickness 8 nm) was epitaxially grown on a 60-nm thick Al_{0.2}Ga_{0.8}Sb layer, employing bulk GaSb as a growth substrate. Then, polymethylmethacrylate (PMMA) line patterns with a line-width of ~360 nm were transferred on the substrate using a soft-lithography, followed by etching of an InAs layer using a mixture of citric acid and hydrogen peroxide. After partially removing the InAs layer in line-patterns, the Al_{0.2}Ga_{0.8}Sb layer was selectively etched in 3% ammonium hydroxide, causing a negligible InAs layer etch rate. Next, a polydimethylsiloxane (PDMS) slab contacted the InAs NRs that

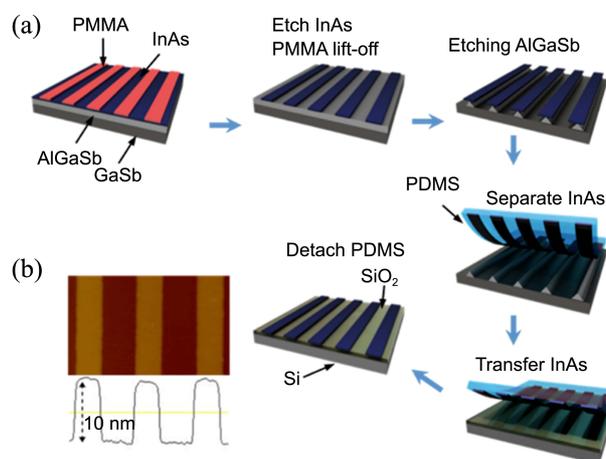


Figure 1. (a) Schematics of the transfer process of InAs NRs on a Si/SiO₂ substrate. (b) Atomic force micrograph (AFM) of transferred InAs NRs on a Si/SiO₂ substrate.

were weakly anchored to the Al_{0.2}Ga_{0.8}Sb layer after the sacrificial layer etching process. Finally, a PDMS slab with NRs was stamped on a Si/SiO₂ substrate. Figure 1(b) shows the atomic force micrograph (AFM) of the transferred InAs NRs on a Si/SiO₂ substrate with a layer thickness of 10 nm, where the native oxide thickness is ~2 nm.

Using the transferred InAs NRs on the Si/SiO₂, the sensor devices were fabricated as shown in Figure 2(a). Photolithography, a 40 nm-thick thermal evaporation of Ni, and lift-off complete the device fabrication. Highly doped (*p*+) Si substrate was used as a global back-gate, and a 50 nm-thick SiO₂ was used as a gate oxide. For the experiment, the device was wire-bonded on a chip carrier as shown in the inset of Figure 2(b), and placed in a 0.5 l chamber, which is electrically connected to an external measurement setup (Agilent B1500A).

Figure 2(b) shows the I_{ds}-V_{bg} characteristics of the sensor device, which was measured at V_{ds} = 10 mV in an ambient with different NO₂ concentrations (0, 5, 10, 50 ppm). The device was measured after exposure to each NO₂ concent-

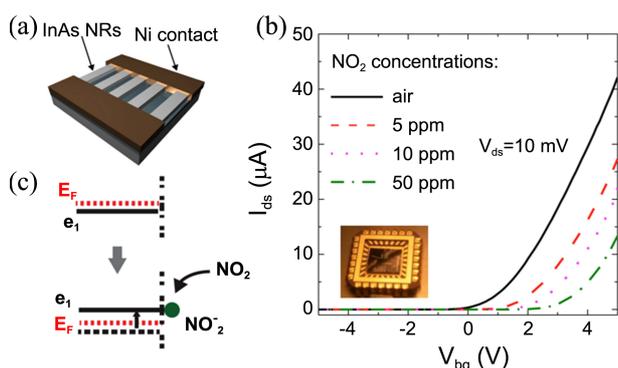


Figure 2. (a) Schematic representation of the InAs NR gas sensor. (b) I_{ds} - V_{bg} characteristics of NO_2 sensor measured after exposing the devices to different NO_2 concentrations for 5 minutes. (inset) The device mounted on a chip carrier. (c) Schematic energy band diagram of InAs NR membrane before (top) and after (bottom) NO_2 exposure. E_F (red dash lines) and e_1 (solid black lines) denote the Fermi level and the first sub-band energy level of the quantized InAs membrane, respectively.

ration for 5 minutes, which is sufficient time to ensure absorption of NO_2 molecules onto the InAs NR surface. Several observations are apparent from the data in Figure 2(b). First, the threshold voltage (V_T) moves toward a positive direction with increasing NO_2 concentrations, where the oxidation process dominates. Second, the device characteristics exhibit a unipolar behavior even at the highest NO_2 concentration, indicating strong Fermi level pinning above the conduction band edge.

Lastly, the negligible changes of the slopes in the linear region of I_{ds} - V_{bg} at different NO_2 concentrations suggest that gas absorption at the InAs NR surface does not significantly affect the mobility of the sensor device. Note that the slope (a conductance) in the I_{ds} - V_{bg} plot is related to the mobility by the equation $C_{ox}^{-1}(dG/dV_{bg})$, where C_{ox} , G , and V_{bg} are the NRs to back-gate capacitance, conductance, and the back-gate bias, respectively. Thus, it can be deduced that the observed sensor response originates mainly from the electrostatic coupling between the absorbed NO_2 on the NR surface and the charge centroid in the channel (as represented by the V_T shift) rather than interferences of electron transport. Figure 2(c) shows the schematic energy band diagrams of ultrathin InAs NR before (top) and after (bottom) NO_2 exposures. At the initial state, the first sub-band in the quantized InAs is located near Fermi level (E_F) due to Fermi level pinning above the conduction band edge. With NO_2 absorption, the first sub-band moves to a high energy level, increasing V_T as shown in Figure 2(b).

To explore the detection limits of the sensor, sensor responses were measured at different NO_2 concentrations as a function of time, focusing on concentrations below 5 ppm. The sensor response was defined as $\Delta R/R_0$, where ΔR is the change of resistance upon NO_2 exposure from its initial value (R_0) in the dry air. Figure 3(a) shows the sensor response of the 8 nm-thick InAs NR device. During the measurement, each NO_2 concentration was introduced at given times (red arrows) while the constant biases $V_{ds}=10$ mV and $V_{bg}=0$ V

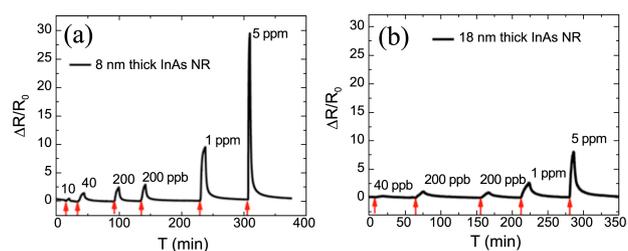


Figure 3. Sensor responses of the ultrathin InAs NR gas sensors in different NO_2 concentrations. (a) Sensor responses of the 8 nm-thick InAs NR gas sensor, showing a clear response at concentrations below 100 ppb. (b) Sensor responses of the 18 nm-thick InAs NR gas sensors. Red arrows indicate the NO_2 gas injection.

were applied. The sensor was capable of detecting levels below 100 ppb, and demonstrated a monotonic rise of $\Delta R/R_0$ with increasing NO_2 concentrations. Next, to highlight the role of size effects in sensor responses, the sensor was fabricated using the 18 nm-thick InAs NRs. The results in Figure 3(b) demonstrate the approximately 4-fold lower sensor responses in the 18 nm-thick InAs NR sensor, exhibiting negligible sensor responses below 100 ppb. As reported previously,⁶ the sub-band energy spacing in a 8 nm-thick InAs is larger than 300 meV due to the quantization effect, resulting in electron occupation of only the first sub-band. Thus, the charge centroid is pushed into the center of the channel thickness due to the structural confinement effect, enhancing an electrostatic coupling. However, in 18 nm-thick InAs NRs, the charge centroid is closer to the interface between the InAs and SiO_2 layers, spatially separated from the top InAs surface where the absorption occurs. Therefore, the absorbed NO_2 on the NR surface becomes weakly coupled to the charge centroid compared with the sensor with 8 nm-thick InAs NRs.

In summary, we have experimentally demonstrated the performance of ultrathin InAs NR NO_2 gas sensors. The sensor responses below 100 ppb were clearly observed at room temperature. Besides, the roles of thickness scaling effects were experimentally shown. This work can be used to realize energy efficient 2-D semiconductor-based gas sensors with low detection limits.

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