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 nanomaterials 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. Among them, the ultrathin InAs nanoribbon (NR) membrane is well suited to high sensitivity NO₂ gas sensor development due to its innate properties, 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 Al₀.2Ga₀.8Sb 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 Al₀.2Ga₀.8Sb 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 were weakly anchored to the Al₀.2Ga₀.8Sb 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 transferred InAs NRs on a Si/SiO₂ substrate.
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 $C_{ox}(dG/dV_{bg})$, 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, 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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References