Over the past decade, the synthesis of various nanomaterials has attracted immense attention due to their potential to serve as building blocks for emerging nanoscale devices. Among them, the electronic and sensing properties of nanowires and nanotubes have been widely studied because of their nanoscale dimensions and enormous surface-to-volume ratios. For example, carbon nanotubes have been utilized to work as sensors for toxic gases and small molecules. Field-effect transistors (FETs) based on individual In$_2$O$_3$ nanowires have also been shown to offer superior performance as toxic gas sensors for NO$_2$ and NH$_3$, based on charge transfer between the toxic species and the nanowires. These devices were further observed to exhibit doping-dependent NH$_3$ sensing characteristics, as reduced conduction was observed for heavily doped nanowires and enhanced conduction was observed for lightly doped nanowires. Inspired by the afore-mentioned results, we have explored using our In$_2$O$_3$ nanowires to investigate the chemical gating effect of small organic molecules with amine or nitro groups. The electron-donating capability of amine groups and electron-withdrawing capability of nitro groups were found to induce dramatic changes in the nanowire conductance as well as significant shifts in the gate threshold voltages, as a result of the carrier concentration variation. In addition, adsorption of the nitro compound on partial lengths of the nanowires led to modulated chemical gating and intrananowire junctions exhibiting prominent rectifying behavior. Furthermore, biosensors for species like low-density lipoprotein (LDL) cholesterol, which is the major carrier of cholesterol in blood and the offending agent in coronary heart disease, have also been constructed based on the In$_2$O$_3$ nanowires.

Single-crystalline In$_2$O$_3$ nanowires with diameters around 10 nm were used in this study and a schematic diagram is shown in Fig. 1(a). Figure 1(b) inset shows a scanning electron micrograph (SEM) of an In$_2$O$_3$ nanowire bridging the source/drain electrodes with a channel length of ~3 µm. To avoid complications similar to the doping-dependent NH$_3$ sensing experiment, only lightly doped In$_2$O$_3$ nanowires were used for the chemical and biomolecule gating experiments described later. Several compounds were used for chemical gating measurements, including tert-

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**FIG. 1.** (a) Scheme for molecular absorption on an In$_2$O$_3$ nanowire device. The thickness of the SiO$_2$ layer is 100 nm. (b) $I$–$V$ curves of an In$_2$O$_3$ device before and after exposure to butylamine. Inset: SEM image of the device. (c) $I$–$V_g$ curves recorded before and after molecular absorption with the drain–source bias $V = 0.1$ V.
butylamine $[\text{CH}_3(\text{CH}_2)_3\text{NH}_2, \text{99.5\% from Aldrich}]$, 3′-aminopropyl triethoxysilane $[\text{APTES, NH}_2(\text{CH}_2)_3\text{Si(OEt)}_3, \text{99\% from Aldrich}]$ and butyl nitrite $[\text{CH}_3(\text{CH}_2)_3\text{NO}_2, \text{99\% from Aldrich}]$. The adsorption of the organic molecules was carried out by placing fully characterized In$_2$O$_3$ nanowire transistors facing the interior of a container with the organic compound for typically 5 min. The nanowires remained above the liquid organics and were exposed only to the molecular vapor. After the exposure, the device was dried with a stream of nitrogen. Electronic properties of the devices were characterized in ambient atmosphere and at room temperature both before and after the exposure.

Figure 1(b) shows two $I-V$ curves with the gate bias $V_g=0$ of an In$_2$O$_3$ nanowire transistor before and after exposure to butylamine. Before the chemical exposure, the device showed very little conduction with a zero-bias resistance of 250 MΩ. After exposure to butylamine, the device exhibited significantly enhanced conduction with a zero-bias resistance of 17 MΩ. In addition to the conductance variation, the sensing properties of our devices can also be studied by monitoring the current dependence on the gate bias. Figure 1(c) shows two $I-V_g$ curves recorded before and after exposure to butylamine with a constant drain–source bias $V=0.1$ V. Both curves confirm In$_2$O$_3$ nanowires are n-type-doped semiconductors, however, a $-3$ V shift in the threshold voltage (from 0.5 to $-2.5$ V) was observed after the exposure. This indicates an increase of electron concentration in the nanowire, which can be estimated to be $1.1 \times 10^{18}$ cm$^{-3}$ following $C \Delta V_T/eL$, where $C$ is the nanowire capacitance, $\Delta V_T$ is the shift in threshold voltage, $e$ the electron charge, and $L$ the channel length. This increase in electron concentration and conductance is attributed to the chemical gating effect of the amino groups in butylamine, consistent with our previous observation that lightly doped nanowires exhibited enhanced conduction upon NH$_3$ exposure. Similar results (not shown) were obtained with other In$_2$O$_3$ devices exposed to APTES, where a dramatic increase in conductance and a negative shift in the gate threshold voltage were consistently observed. This further confirms the electron-donating effect of the amino groups.

In sharp contrast to butylamine and APTES, our In$_2$O$_3$ nanowire devices exhibited a totally different behavior when exposed to butyl nitrite. Figure 2(a) shows two $I-V$ curves recorded before and after the butyl nitrite adsorption at a fixed gate bias $V_g=0$ V. This device was relatively conductive before the exposure; however, after the exposure, the device showed a reduction in conductance around five orders of magnitude for $V=0.3$ V. Furthermore, we also observed a significant positive shift in the gate threshold voltage from $-0.6$ V before the exposure [shown in Fig. 2(b) inset] to $5-10$ V after the exposure [shown in Fig. 2(b)], indicating a decrease in the electron concentration. This can be understood as nitro groups are highly oxidative and are thus expected to withdraw electrons from our nanowires, subsequently leading to reduced conduction for our n-type In$_2$O$_3$ nanowire. Similar behavior was observed when In$_2$O$_3$ nanowire transistors were exposed to NO$_2$ gas.9

Armed with our understanding about the chemical gating effects, we have further created intranowire junctions by exposing part of an In$_2$O$_3$ nanowire device to butyl nitrite. This was achieved by using photolithography to cover up the right half of a nanowire device with a thick layer of photo-resist, while the left half remained exposed, as shown in the Fig. 3(b) inset. Electronic measurements were performed both before and after the molecule adsorption. To eliminate the asymmetry caused by the local gating effect, a “symmetric” bias scheme was used for data shown in Fig. 3, with $V/2$ applied to the drain and $-V/2$ applied to the source, thus giving a total bias of $V$. Fig. 3(a) shows a family of $I-V$ curves recorded with the device before the butyl nitrite ad-

FIG. 2. (a) $I-V$ curves of an In$_2$O$_3$ device before and after exposure to butyl nitrite. (b) $I-V_g$ curve of the device after exposure. Inset: $I-V_g$ curve of the device before exposure. Here, $V=50$ mV.

FIG. 3. (a) $I-V$ curves of the device before molecule absorption. Rather symmetrical $I-V$ curves were observed. (b) $I-V$ curves recorded after exposure to butyl nitrite molecules. Pronounced rectifying curves were observed with all gate biases. Inset: Scheme for molecular absorption on a device partially covered by photo-resist.
A drop of pure ethanol was first applied to the device and after applying one drop of the LDL suspension onto our nanowires, thus leading to the enhanced carrier concentration.

In conclusion, chemical gating effects of both organic molecules and bio species have been studied with In$_2$O$_3$ nanowire transistors. The amino groups in both butylamine and APTES were found to donate electrons to the n-type In$_2$O$_3$ nanowires and resulted in enhanced carrier concentrations and also conductance, whereas the nitro groups in butyl nitrite withdraw electrons from the nanowires, and led to reduced carrier concentration and conduction. Intrananowire junctions have been constructed by exposing part of a nanowire to butyl nitrite, leading to n$^-$$^-$$^n$ junctions and pronounced rectifying diode behavior with rectification ratios ~400. In$_2$O$_3$ nanowires were further demonstrated to work as LDL sensors via interaction with the amino groups carried by LDL particles. Our work clearly demonstrates the potential of using In$_2$O$_3$ nanowires as both chemical and biosensors.

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