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NO_2 Sensor on Ambipolar Si-Junctionless Nanowire Transistor

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Summary:

We demonstrate highly effective ambipolar Si-junction less nanowire transistors (JNTs) with a distinct dual reaction to oxidative pollutant NO_2. DFT study reveals NO_2 acts as an electron acceptor and produces holes; acting as pseudo dopant for Si JNTs; significantly altering different JNT parameters. Different Si-JNT characteristics showed dynamic change on both the p- and n-sides, i.e. dual response; of the ambipolar transistor devices upon exposure to NO_2 in a wide mixing ratio (250 ppb-50 ppm). Additionally, we have improved the discrimination between different gases (NO_2, NH_3, SO_2 and CH_4) by using multivariate calibration.

Keywords: Silicon nanowire, Junction less transistor, Ambipolar device, Machine Learning, NO_2 sensor

Introduction

NO_2 plays an important role in the chemistry of the atmosphere. Long-term exposure to high levels of NO_2 can also cause respiratory problems and has been linked to increased risk of heart and lung disease.

The current techniques to detect NO_2 are based on spectroscopy, electrochemical process, and electrical methods based on metal oxides. They do, however, have limitations in terms of selectivity, sensitivity, portability, high temperature [1]. Due to their high surface-to-volume ratio, the ability to interact chemically with analytes on the surface, and operation at ambient temperature, Si nanowires (NWs) offer unique opportunities as efficient sensor material [2]. Additionally, Si NW also offers benefits from their ease in fabrication, compatibility with existing semiconductor technology, high carrier mobility, and great sensitivity to analytes adsorbed on their surface. In this regard, Si NW Junction-less Transistor (Si JNT); a nanowire transistor with no gate junction [3]; are interesting proposition as NO_2 sensor. JNTs are much simpler to manufacture as the source and drain areas do not need to be separately doped[16]. Additionally, the bulk conductance in JNTs is near the center of the channel promoting extreme sensitivity to any variation in the electrostatic potential on the Si-JNT channel surface with variation in electrical parameters. Incidentally, ambipolar transistors, a type of transistors that allow for simultaneous transit of both positive (holes) and negative (electrons) charge carriers within the semiconducting channel, can provide a dual response to a single analyte using a single device [4]. Thus, a variety of electrical parameters could be explored for a single ambipolar Si-JNT upon analyte interaction, offering variety of sensing properties and extremely selective gas detection.

In this work, we show how NO_2 can alter different Si-JNT properties and function as a pseudo dopant for Si JNTs. This NO_2-Si interaction effectively influence different electrical parameters in ambipolar Si-JNTs with a distinct and selective dual response to oxidative pollutant NO_2.

Matarials and Methods

The Si-JNT (20 nm NW width) devices were fabricated from ultra-thin silicon-on-insulator (SOI) substrates. Si-JNTs were fabricated following a top-down approach using electron beam lithography (EBL) and reactive ion etching (RIE). Flash lamp annealing (FLA), which leads to form Nickel Silicide at the interface of Silicon and Nickel controls the unipolar or ambipolar nature. Fig. 1.a shows top-view SEM image of the representative Si-JNT device.

Electrical and sensor characterization of Si-JNTs was performed by using an electrical analysis system (two Keithley 2450 Source Meter) interfaced with the Nextron gastight probe station. Si-JNTs were tested and compared towards different mixing ratios of NO_2 at room temperature and at atmospheric pressure.

Results and Discussion

The transfer curve of the Si NW JNT measured under ambient conditions exhibits typical ambipolar characteristics (Fig. 1b). The transport characteristics involve both electron (or hole) depletion and hole (or electron) accumulation. A clear change in on-current (I_{on}) is observed upon NO_2 exposure (25 and 50 ppm NO_2) to the Si-JNTs (Fig. 1b). The I–V curves retained ambipolar characteristics upon exposure to NO_2.

However, current in both p and n conduction channels (left: p-type, right: n-type) shifted with the exposure of NO_2 at different concentrations. An increase in the drain current has been observed with increasing mixing ratios of NO_2 in the p-side (from 25 ppm to 50 ppm) whereas a decrease in the n-type current was observed with NO_2 exposure of same concentrations. This is classified as dual interaction. Interaction with NO_2 alters the carrier concentration in the JNT channel, with NO_2 acting as an electron acceptor and inducing holes, as supported by Density Functional Theory (DFT) calculations, providing a pathway for charge transfer and "pseudo" molecular doping in ambipolar Si-JNTs.

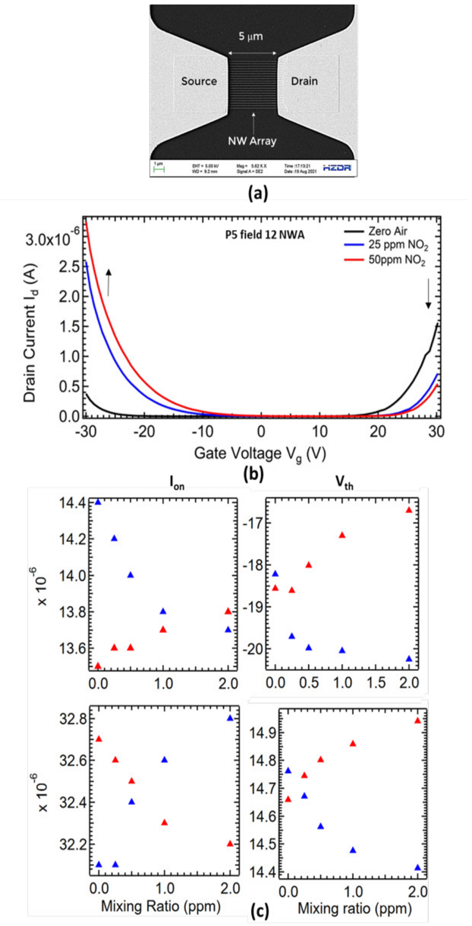

Figure 1. (a) SEM top view image of the Si-JNT devices. (b) Transfer characteristics of Si-JNT upon NO_2 exposure. (c) Effect of gas interaction on different parameters of ambipolar Si-JNTs for NO_2 (red) and NH_3 (blue). Top and bottom row represent device parameters for p and n-type conduction respectively.

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The threshold voltage in hole-channel conduction (hole accumulation) shifts to the positive side (decreases) whereas it shifts to the negative direction[7] (increases) in electron-channel conduction upon NO_2 exposures for all the studied Si-JNT devices. Both[8] observations are due to the electron-trapping effect from NO_2[19]. The NO_2 exposure also generates the largest influence on hole mobility in Si-JNTs with native oxide layer.

To demonstrate the sensing performance of the ambipolar Si-JNTs, we tested and compared the interaction of Si-JNTs towards four gases, NO_2, NH_3, CH_4, and SO_2 at a low concentration regime (0.25-2 ppm). Fig. 1c shows the change in two representative JNT parameters (I_{on} and threshold voltage V_{th}) upon exposure to different mixing ratios of NO_2. For the strong oxidative gas NO_2 steady linear increase of on-current on hole-conducting channel (p-type) and decrease in I_{on} on the electron-conducting channel (n-type) was clearly observed (Fig. 1c) at low concentrations. Similarly, the threshold voltage and mobility show change to that of high mixing ratio of NO_2. For p-type transport a more prominent change in V_{th} is observed than change for n-type transport.

In contrast to NO_2, the reductive gas NH_3 causes an inverse response in Si-JNT electrical characteristics, whereas other gases such as SO_2 and CH_4 show significantly low response for each JNT parameters. Under the same conditions, the unipolar devices will only present one type of response. To clearly demonstrate the responsivity of the multiple parameters, a pattern graphic based on the absolute current change value, threshold voltage and carrier mobility for ambipolar devices were extracted for different combination of 4 interfering gases (NO_2, NH_3, SO_2 and CH_4). The significant different response for each JNT parameters easily distinguishes the target analyte, NO2.

In summary, different Si-JNT characteristics including I_{on}, V_{th} and μ have demonstrated dynamic change on both the p- and n- transport channel of the ambipolar JNT towards very low NO_2 concentration, resulting in gate-tunable gas sensing behaviors.

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