Supporting Information

A Calibration Method for Nanowire Biosensors to Suppress Device-to-device Variation

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1. Distribution of Threshold Voltage of In2O3 Nanowire Transistors

Figure S1 shows the distribution of the threshold voltage of In_2O_3 nanowire transistors with an effective channel width of 3600 μm fabricated on a Si substrate with 50 nm SiO_2 dielectric layer. The mean is -0.65 V and the standard deviation is 0.25 V.

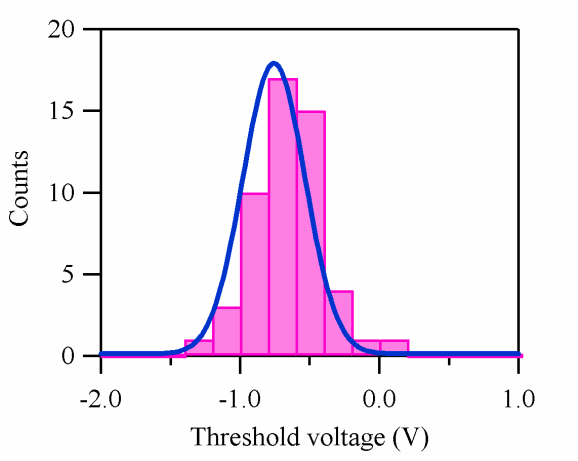


Figure S1. The distribution of the threshold voltage for In_2O_3 nanowire transistors

2. Simulation of Our In_2O_3 Nanowire Transistor Behavior Through Conventional MOSFET Equations

Figure S2 shows the comparison of experimental and simulated data obtained using Eq. 1 on the transistor behavior of our In_2O_3 nanowire transistors. Figure S2a shows the I_{ds}-V_g curve, and S2b shows the I_{ds}-V_{ds} curves under different V_g. The conventional MOSFET equations captures the behavior of our transistor.

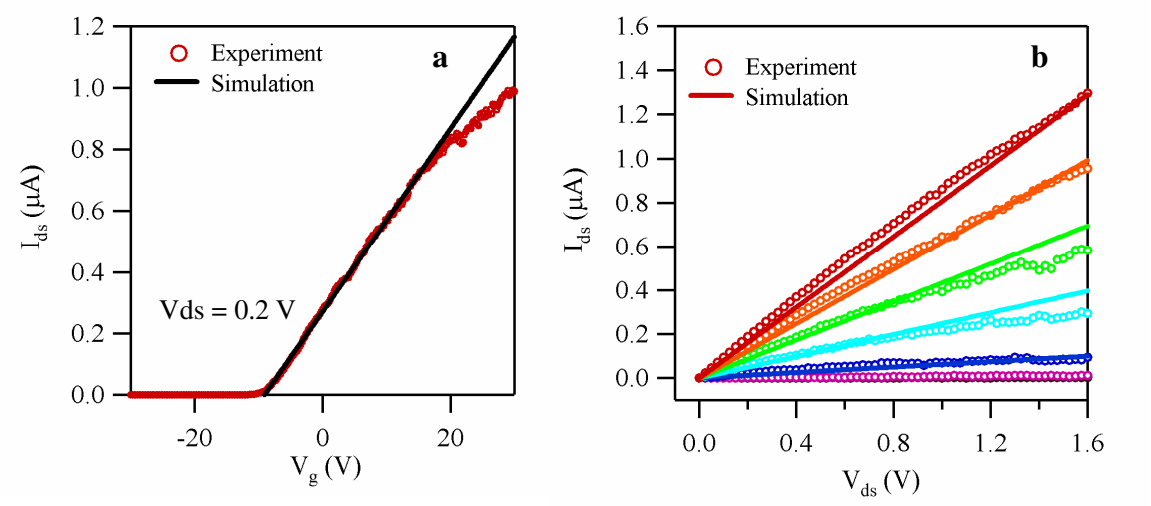


Figure S2. a) I_{ds}-V_g curve of an In_2O_3 nanowire transistor. The red circles represent the experimental result and the black line represents the simulated curve obtained using Eq. 1. b) I_{ds}-V_{ds} curves of the same device (V_{ds} < 0.2 V) under different V_g. The circles represent the experimental results and the solid lines represent the simulated results obtained using Eq. 1.

3. Measurement of Leakage

To check the leakage current through the buffer for the I_{ds}-V_g measurement in Figure 2, we have measured the conduction using a device with the same source and drain electrodes, but WITHOUT nanowires in the channel under the same condition. Figure S3 shows the plots of I_{ds}-V_g curves WITH (red) and WITHOUT (blue) nanowires in the channel. It can be seen that the leakage current is negligible compared to the current through nanowires.

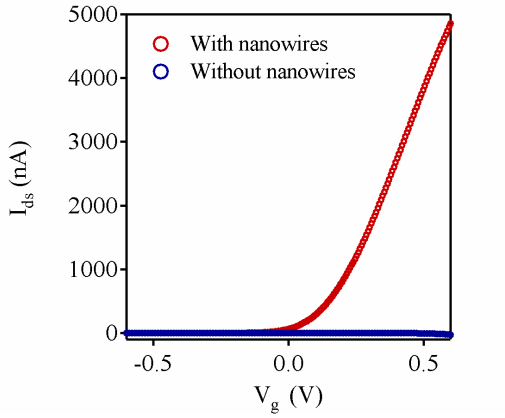


Figure S3. I_{ds}-V_g for devices WITH (red) and WITHOUT (blue) nanowires inside the channel.

4. Change of I_{ds}-V_g Before/After The Exposure to Streptavidin

Figure S4 shows the I_{ds}-V_g curves used in Figure 2a, where the curve after the exposure is shifted by +14 mV. The close match of these two curves indicate that the response was dominated by doping of the channel.

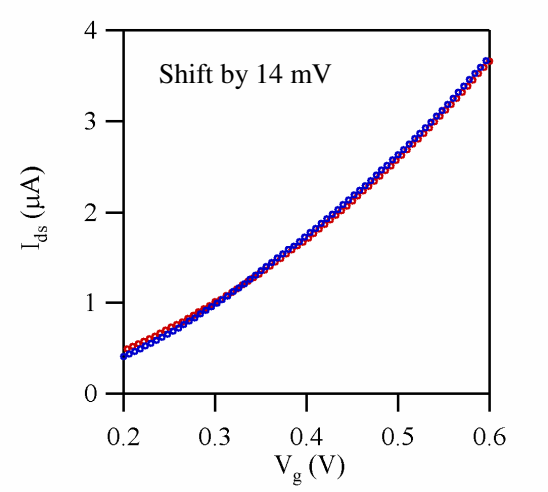


Figure S4. I_{ds}-V_g shown in Figure 2 where the I_{ds}-V_g curve after exposure is shifted by +14 mV.

5. Stability of the I_{ds}-V_g Measurements Using Liquid Gate

To confirm that the liquid gate measurement gives stable readout and that the sensing signal for Figure 2a is real, we repeatedly performed the I_{ds}-V_g measurement using a liquid gate on a device. Figure S5a shows plots of several I_{ds}-V_g measurements before and after the exposure to streptavidin (S-Av), where there are 4 distinct plots before exposure and 2 plots after exposure. It can be seen that the plots overlap with each other before and after exposure, confirming the stability of the measurement and the existence of the signal. We also extracted the on-current (I_{ds} at V_g = 0.6 V), and plotted against time as shown in Figure S5b. Clearly, the on-current was stable, and did not change upon addition of further PBS. When streptavidin was introduced in the buffer, the signal decreased significantly.

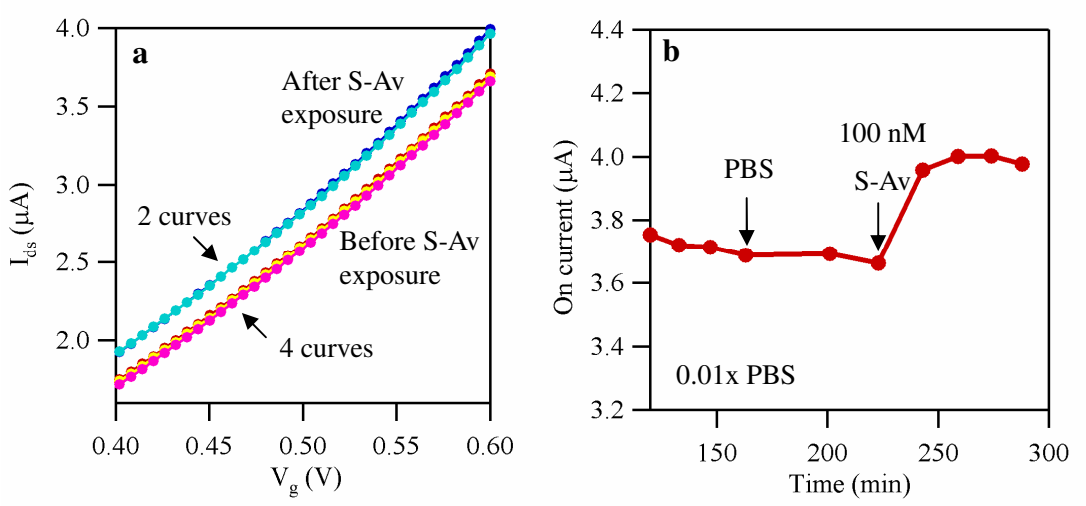
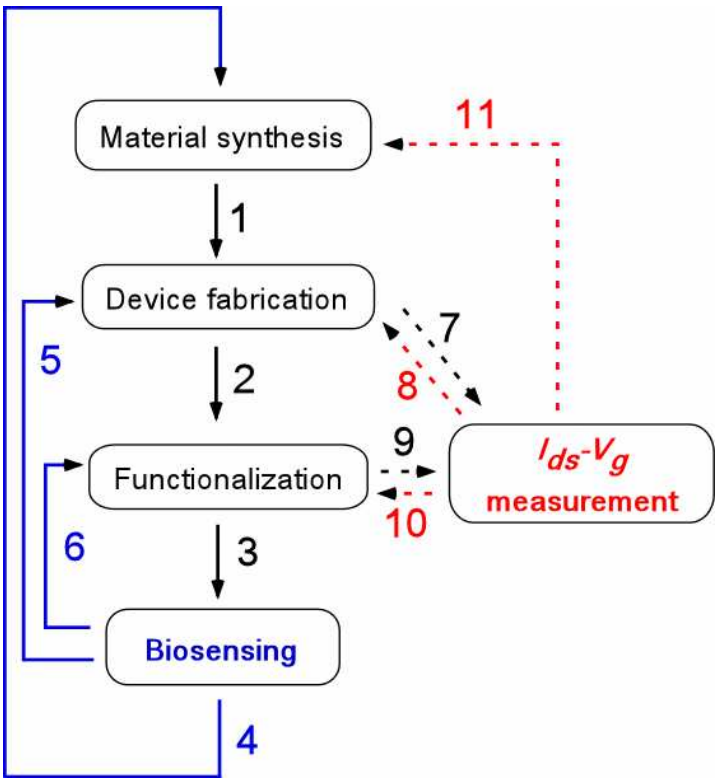


Figure S5. a) Plots of multiple I_{ds}-V_g curves before and after exposure to streptavidin. There are plots for 4 measurements before exposure (pink, orange, yellow, and red) and 2 measurements after exposure (blue and light blue). b) Plot of on current versus time.

6. New Feedback Loop for Designing New Nanobiosensors

From the perspective of developing nanobiosensors, at any stage of the development including material choice/synthesis, device design, processing, and optimization, until now there are not many ways to evaluate/tune the parameters with an instant feedback. Conventionally, new biosensors have often been evaluated as FETs mostly owing to the mature methodology/technology and understanding about transistors. It has also been assumed that a good transistor is a good biosensor. However, the definition of a good transistor as a biosensor, or in other words, the metrics to evaluate a transistor as a biosensor, were never clearly described. A deep understanding of the relationship between transistor metrics and biosensor metrics galvanize this field of research since it allows us to design new nanobiosensors based on transistors, where well-established methodologies for the development already exist.

In the main text we have shown that there is a correlation between the absolute response of the device and the value of dI_{ds}/dV_g (Figure 3). This correlation can be a guideline to quickly evaluate the sensor performance of a transistor and design better sensor. As a result, we propose a new feedback loop to design better biosensors with shorter feedback time. Scheme 1 shows the old/conventional (blue) and the newly proposed (red) feedback loops to design better biosensors. Traditionally, to evaluate biosensor performance, the following four steps must be conducted: 1) nanomaterials synthesis, 2) device fabrication, 3) functionalization, and 4) biosensing. This loop would be closed only when the last step (biosensing) is executed. On the other hand, by adding the step where I_{ds}-V_g of the devices (named I_{ds}-V_g measurement in Scheme 1) are measured, more efficient feedback can be obtained, such as loops 7-8, 9-10, and 1-7-11. The I_{ds}-V_g measurement can be done at the early stage of the experiment, and would allow us to determine whether the transistor would function as high-performance biosensors even without performing the biosensing experiments.



Scheme 1. Old (Blue) and proposed (Red) feedback loops for designing better biosensors.

7. Tuning of the Magnitude of Absolute Responses by Gate Voltage

The correlation we found indicates that it is possibile to tune the magnitude of the response of a biosensor by applying an appropriate gate voltage. Figure S5a shows the plot of dI_{ds}/dV_g versus V_g of a device (left axis); showing that dI_{ds}/dV_g is modulated by the gate voltage and has the highest value at V_g = 0.6 V. The magnitude of absolute response also changes depending on the gate voltage as shown in Figure S6a (right axis), and has the maximum at V_g = 0.6 V. To find the correlation, we plot the absolute response versus dI_{ds}/dV_g for the device, and the plot is shown in Figure S6b. There is a strong correlation between these two values, confirming that the magnitude of response can be tuned by choosing an appropriate V_g.

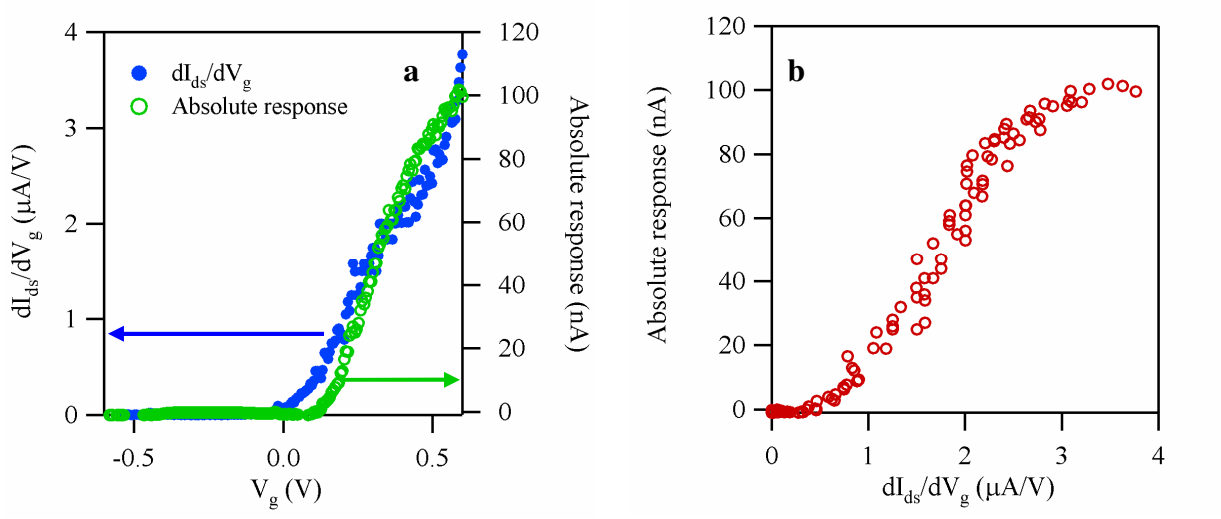


Figure S6. a) Plots of dI_{ds}/dV_g (light blue) and absolute response (green) versus V_g, respectively. b) Plots of absolute response versus dI_{ds}/dV_g.