Supporting information

for

Gate Bias Stress Instability and Hysteresis Characteristics of InAs Nanowire Field-Effect Transistors

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1. Statistical data of the mobility

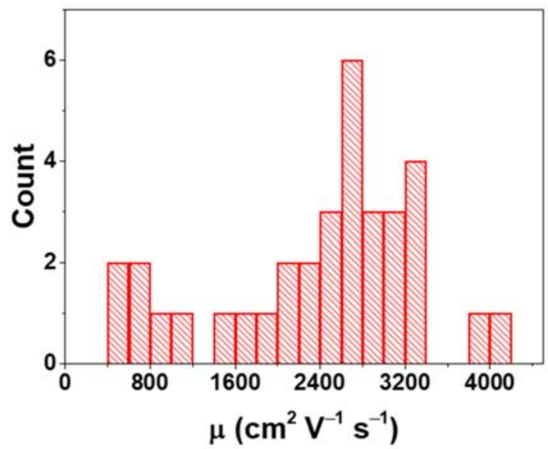

Figure S1. Statistical data of the mobility.

2. Gate voltage bias stress effect of other devices

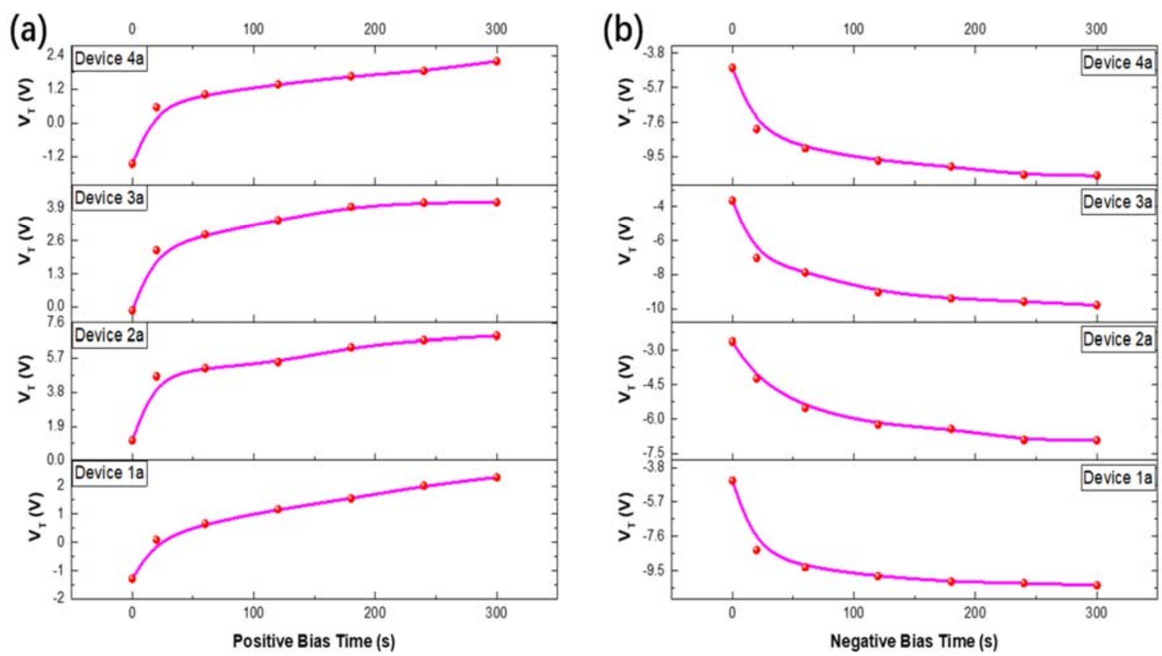

Figure S2. Gate voltage bias stress effect from different devices. (a) Positive voltage bias effect. (b) Negative voltage bias effect.

3. Hysteresis effect

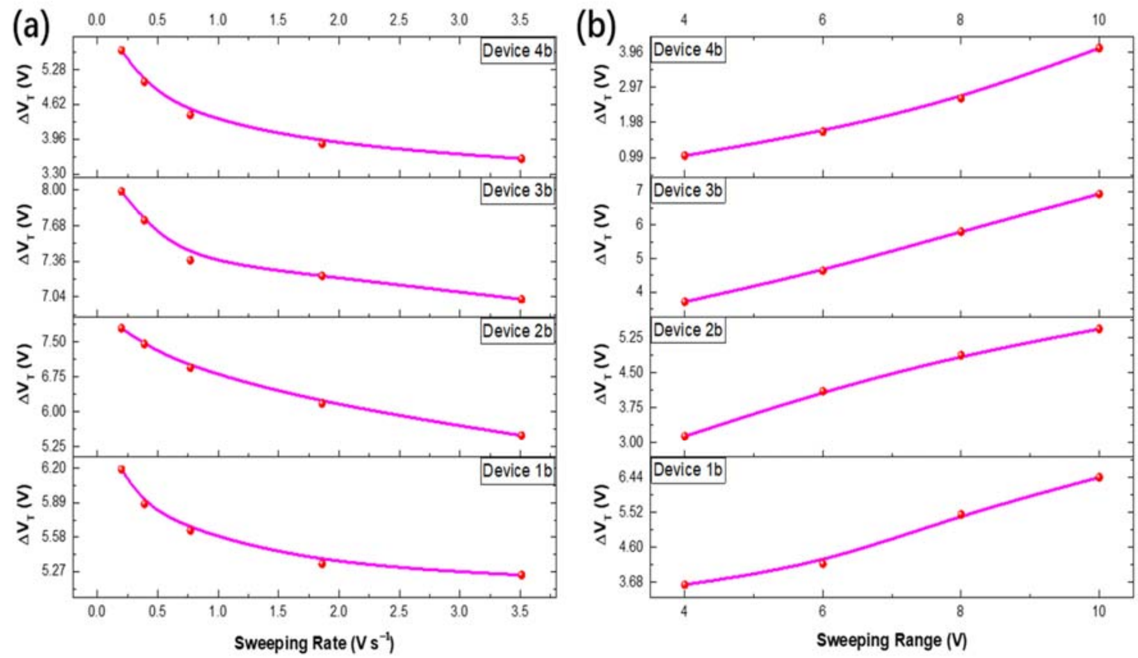

Figure S3. Threshold voltage difference of transfer curves with the hysteresis effect from difference devices. (a) Sweeping rate. (b) Sweeping range.

4. Determination of the output current

The output current (I_{ds}) of the nanowire device can be expressed as:

$$I_{ds} = nqAv = nqA\mu E = nqA\mu V_{ds} / L = qA\frac{V_{ds}}{L}n\mu \tag{1}$$

where n is the free electron density, q is the charge of an electron, A is the cross-section area of the nanowire, μ is the carrier mobility, E is the electrical field, V_{ds} is drain-source voltage, and L is the channel length. Here, only n and μ are unknown, where both of them would change with the gate voltage (V_{gs}).

Determination of the electron density

The electron density (n) is related with both gate voltage sweeping and charge trapping. Thus, the change of n with respect with time (t) can be expressed as:

$$\frac{\partial n}{\partial t} = a\gamma v_s - \frac{n}{\tau} \tag{2}$$

where α is a coefficient depending on the sweeping direction, τ is the lifetime of electrons that can be captured by traps, $\gamma = 4C_{ox}/\pi d^2 Lq$, C_{ox} is the gate capacitance, and d is the diameter of the nanowire. The introduction of α is due to charge trapping. The trapped charges can be acted as extra gate charges, leading to the reduction of gate control ability in the forward sweeping and the enhancement of gate control ability in the backward sweeping. The α value is also related with the gate sweeping rate. Its value can be manipulated in order to get the modeled results being consistent with the experimental results. Furthermore, both α and τ are a function of V_{gs} due to the gradually filling of the traps. For simplicity, only their average values are used. The average carrier lifetime can be extracted from the time dependent current curve (**Figure S4**), which is determined to be ~318 s, indicating the slow charge trapping process. Based on equation (2), the electron density during the forward and backward sweepings can be obtained:

Forward (the threshold voltage of V_T is set to be 0 V for simplicity):

$$n = \alpha\gamma v_s \tau (1 - e^{-\frac{t}{\tau}}) \tag{3a}$$

Backward:

$$n = a\gamma v_s \tau + \left(n_m - a\gamma v_s \tau\right) e^{-\frac{t}{\tau}} \tag{3b}$$

where n_m is the electron density at the maximum gate voltage of V_{gs_m}. Equation (3b) is valid only for $n > 0$. The "backward" threshold voltage of V_T can be determined by letting $n = 0$. It should be noticed that the α and τ are different for the forward and backward sweepings. Due to the slow trapping process, the same value of τ is used for the forward and backward sweepings.

Mobility model

For the carrier mobility (μ), it shows a peak value for the nanowire devices. However, there is not any accurate analytic equation that can be used to model the changes of mobility with gate voltage. For simplicity, an empirical model is used to model the change of mobility as a function of gate voltage:

$$\mu = \begin{cases} k_1 V_{gs}, & V_{gs} < V_0 \\ \mu_0 - k_2 (V_{gs} - V_m)^2, & V_0 < V_{gs} < V_1 \\ \mu_1 \exp(-\frac{V_{gs} - V_1}{V_a}), & V_1 < V_{gs} \end{cases} \tag{4}$$

To be specific, the mobility is divided into three segments: the μ changes linearly with V_{gs} in the first one; a quadratic function is used to model the peak of the mobility in the second segment; an exponential decay function is used to describe the decay after the peak in the third segment. To determine the values of the coefficients in equation (4), the continuity condition and the continuity condition of the first derivative at the joint points are considered. Thus, four equations can be obtained:

$$k_2 = \frac{\mu_0 - k_1 V_0}{(V_0 - V_m)^2} \tag{5a}$$

$$k_2 = \frac{\mu_0 - \mu_1}{(V_1 - V_{\mathrm{m}})^2} \tag{5b}$$

$$k_1 = 2k_2(V_{\mathrm{m}} - V_0) \tag{5c}$$

$$k_2 = \frac{\mu_1}{2(V_1 - V_{\mathrm{m}})V_{\mathrm{a}}} \tag{5d}$$

In the simulation, V_0, V_1, V_{m}, k_2 are set as 4 V, 7 V, 6.3 V, 2.4×10^{-3} $\mathrm{m^2\ V^{-2}\ s^{-1}}$, respectively, for the forward sweeping. The other parameters can be obtained using equations (5a) – (5d).

For the backward sweeping, the mobility cannot change when only changing the sweeping direction at the maximum gate voltage. In this regard, $\mu(V_{\mathrm{gs\_m}})$ for the forward and backward sweepings should be the same. For simplicity, the threshold voltage of V_{T} for the backward sweeping is determined first from the "backward" electron density. Then, the mobility function is shifted to the right side for the V_{T} shift. After that, the mobility function multiplies a value to make that the $\mu(V_{\mathrm{gs\_m}})$ equals to the "forward" one (**Figure S5**). In fact, the electron transport can be affected by the trapped electrons, leading to the reduced mobility during the backward sweeping. Thus, our method for "backward" sweeping mobility is reasonable, and its validity is confirmed as the simulated curves are consistent with experiment results as shown in the main text.

With n and μ, the I_{ds} (V_{gs}) can be reproduced by using equation (1).

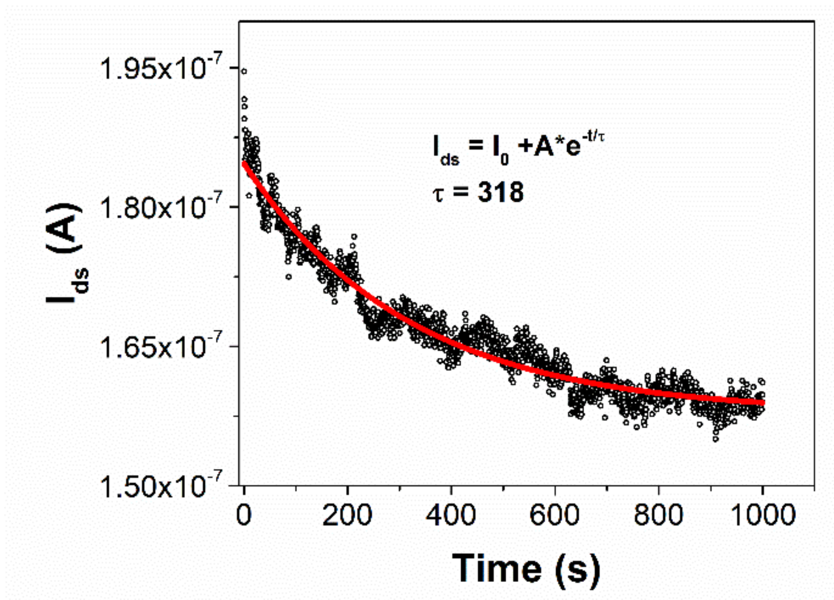

Figure S4. Time dependent current (I_{ds}). V_{gs} = 10 V, V_{ds} = 20 mV.

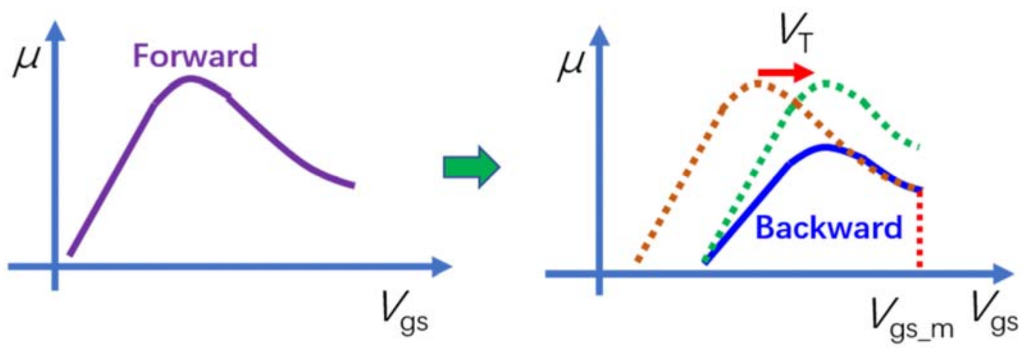

Figure S5. Schematic for the "backward" sweeping mobility determined from the "forward" sweeping mobility.

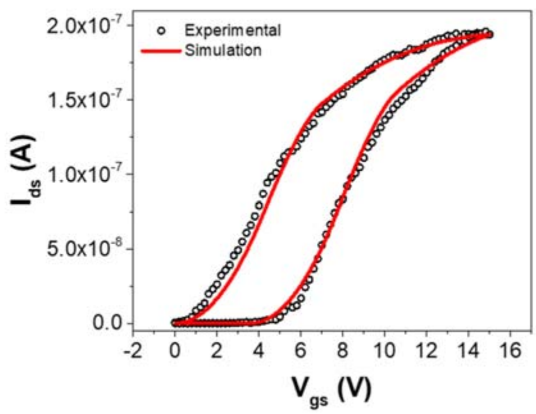

Figure S6. Comparison between experimental and simulation results. The experimental transfer curve shifts towards the positive direction for 5 V in order to meet with the simulation result.