

Comparison of Self-Heating and Electrode Heating recoveries in a suspended-CNT CNFET NO₂ Sensor

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Summary:

We compare self-heating (SH) and electrode-heating (EH) recovery of a carbon nanotube FET NO₂ sensor. Both methods sustained reproducible sensing across nine cycles, five cycles with EH and four cycles with SH; the post-reset operating point had comparable cycle-to-cycle spread for both methods, while EH delivered a 1.7–2.2× smaller standard deviation in NO₂ response amplitude.

Keywords: CNFET, NO₂ gas sensor, sensor recovery, self-heating, electrode heating.

Background, Motivation and Objective

Suspended Carbon nanotube field-effect transistor (CNFET) gas sensors detect NO₂ at parts-per-billion concentrations [1], but room-temperature desorption of NO₂ from CNTs is slow [2], so an active reset between measurements is required for continuous operation. Two heating-based reset strategies have been demonstrated: self-heating (SH), in which Joule heating the CNT channel is achieved by a drain-source voltage pulse [3], and electrode heating (EH) [4], in which a heater current flows through split, U-shaped source/drain electrodes that conduct heat into the contact-adjacent CNT region. SH targets the channel mid-section. EH heats the contacts directly. Because NO₂ adsorbs on the CNT and on the metal contacts in unpassivated devices, with both contributions reflected in the transfer characteristic [5], the two heating methods may show different characteristics in heating experiments. In this work, we run two consecutive gas experiments on a single suspended carbon nanotube CNFET, with reversed orders of EH and SH, to test the relative reset performance of the two methods on the same sensor.

Methods

The channel of the CNFET is formed by a single suspended carbon nanotube with split palladium source/drain electrodes (5 nm Cr / 35 nm Pd); the channel length is 1 μm, and the distance between the CNT and the gate electrode is 200 nm (air gap). Transfer characteristics (TCs) were continuously acquired (every ~1.5 s, $V_{DS}=0.2$ V, pulsed V_{GS} sweep, 5 ms on, 1 ms off, from 0 V to +10 V to -10 V back to 0 V) in a gas measurement chamber under constant flow of synthetic dry air and 500 ppb NO₂ exposures. From each TC's backward sweep, +10 V to -10 V, we

extract two parameters: I_{on} as I_s at $V_{GS} = -9$ V and the fixed-current threshold V_{th} represented by $V_{GS} @ I_s=0.01$ μA. The gas measurement protocol consisted of 1 h baseline in dry air, followed by ten consecutive 30 min adsorption steps at 500 ppb NO₂, separated by 10 times 1 s reset pulses each, and a final 1 h dry-air purge (Fig. 1). In Experiment 1, the first adsorption step was not preceded by a reset; the next five were each preceded by an EH-reset ($V_{EH} = 2.5$ V), and the last four by an SH-reset ($V_{DS} = 1.7$ V, $V_{GS} = -10$ V). Experiment 2 was started on the same device 3 minutes later under identical conditions but with the reset order reversed: SH for the first five reset pulses, then EH for the last four.

Results

Representative TCs in dry air, after 30 min NO₂ exposure, and after EH or SH reset are shown in Fig. 2. Both reset methods qualitatively restore the transfer curve. In Experiment 1, the post-reset operating point showed comparable cycle-to-cycle standard deviations (SD) for EH and SH on both readouts I_{on} and V_{th} (Fig. 3a, c; Tab. 1). The mean NO₂ response amplitudes per cycle after reset (Fig. 3b, d) showed a smaller standard deviation for EH than for SH on both readouts: the standard deviation of ΔV_{th} was 1.7× smaller for EH, and that of ΔI_{on} 2.2× smaller. In Experiment 2, with the order reversed, I_{on} degraded monotonically across four SH-reset cycles while V_{th} remained stable, before the device failed abruptly during the fifth cycle (Fig. 1 c-d).

Conclusions

EH-reset and SH-reset gave comparable post-reset operating points but EH-reset delivered a smaller cycle-to-cycle standard deviation in NO₂ response amplitude. In Experiment 2, the

monotonic decline of I_{on} with stable V_{th} , ending in abrupt failure, is consistent with a progressive increase in contact resistance rather than a change in channel electrostatics. This pattern may indicate cumulative electro-thermal stress at the metal-CNT contacts under repeated SH pulses, consistent with the expectation that SH leaves the contact-adjacent CNT region cooler and less effectively recovered than EH. Multi-device experiments are needed to confirm this mechanism.

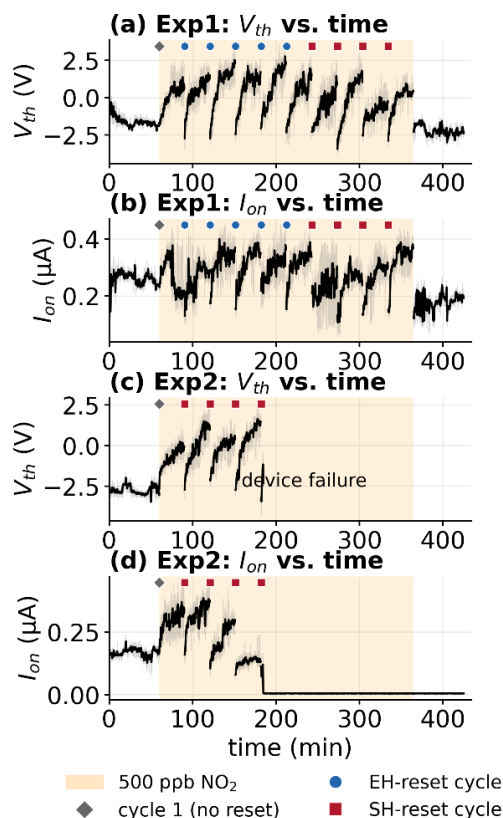


Fig. 1. Sensor signals over both gas experiments. (a, b) Exp1 and (c, d) Exp2 show V_{th} and I_{on} extracted from the backward sweep of every TC. Shaded orange regions mark continuous 500 ppb NO_2 exposure. Colored dots mark the start of each adsorption cycle: gray = cycle 1 (no preceding reset), blue = EH-reset, red = SH-reset. Exp1 sustains nine reset cycles (five EH, four SH); Exp2 fails during the fifth SH cycle.

Tab. 1: Per-cycle metrics for Exp1, mean $\pm$ 1 SD across $n = 5$ EH-reset and $n = 4$ SH-reset cycles.

Metric	EH-reset	SH-reset	SH/EH SD
Post-reset V_{th} (V)	-2.40 ± 0.37	-2.79 ± 0.49	1.3
Post-reset I_{on} (μA)	0.17 ± 0.04	0.15 ± 0.05	1.2
ΔV_{th} (V)	4.30 ± 0.49	3.28 ± 0.83	1.7
ΔI_{on} (μA)	0.18 ± 0.02	0.16 ± 0.04	2.2

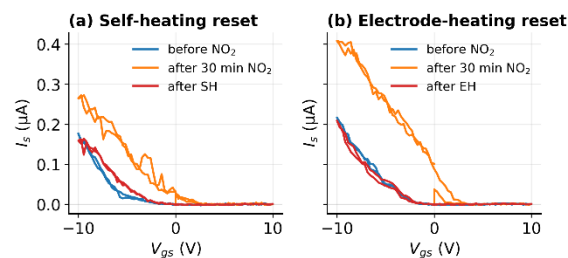


Fig. 2. Representative transfer characteristics (full sweep) before NO_2 exposure (blue), after 30 min at 500 ppb NO_2 (orange), and after a 10x1 s reset pulse (red).

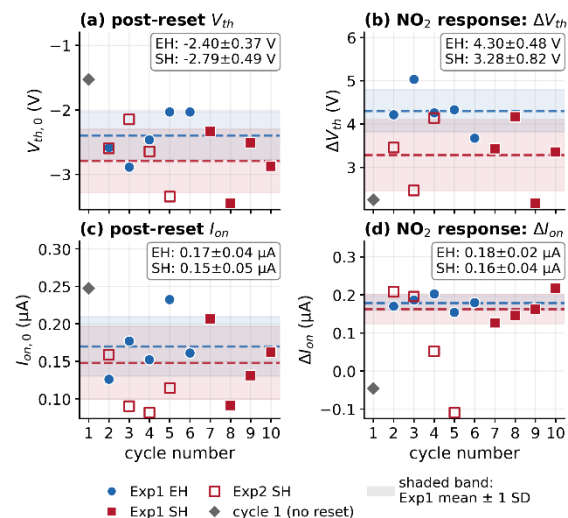


Fig. 3. Per-cycle metrics from each adsorption cycle. (a, c) Post-reset values y_0 (average of the first 5 s of each cycle) for V_{th} and I_{on} . (b, d) NO_2 response amplitudes $\Delta y = y_{\infty} - y_0$, where y_{∞} is the average of the last 10 s of each cycle. Filled markers: Exp1 (circles = EH-reset, squares = SH-reset). Open squares: Exp2. Dashed lines and shaded bands indicate Exp1 mean $\pm$ 1 SD per reset method.

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