Supporting Information

Toward Practical Gas Sensing with Highly Reduced Graphene Oxide: A New Signal Processing Method to Circumvent Run-to-Run and Device-to-Device Variations

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1. Measurement of contact resistance between R-GO and Au electrode

We used four Au contact pads (#1, #2, #3, and #4) which were partially covered and connected by highly reduced graphene oxide (R-GO) to evaluate the contact resistance between R-GO and Au. Figure S1a is an SEM image of the four Au contact pads which were mostly rectangular (about 2×0.8 mm) and separated by ~ 0.2 mm. Each of the pads was partially covered with R-GO; the uncovered area on each contact pad was used for probe connection during electrical measurements. Two terminal I_{ds}-V_{ds} measurements were carried out between pad pairs of 1-2, 2-3, 1-3, 3-4, and 2-4. The I_{ds}-V_{ds} curves in Figure S1b are linear and symmetric, implying most likely Ohmic contact between R-GO and Au. The resistance between a contact pad pair was extracted from the slope of the corresponding I_{ds}-V_{ds} curve. The measured resistance between a contact pad pair could be regarded as the sum of two contact resistances and the resistance of R-GO between these two pads. Thus, the resistance between pads #1 and 2 (R_{12}) can be expressed as

$$R_{12} = R_{C1} + R_{G12} + R_{C2}, \quad \text{(S1)}$$

where R_{C1} and R_{C2} are the contact resistances at pads #1 and 2, respectively, and R_{G12} is the resistance of R-GO between pads # 1 and #2. Similarly, we can have

$$R_{23} = R_{C2} + R_{G23} + R_{C3} \quad \text{(S2)}$$

$$R_{13} = R_{C1} + R_{G13} + R_{C3} \quad \text{(S3)}$$

Note that $R_{G13} = R_{G12}+R_{G23}$ since the R-GO in contact with pad #2 was short-circuited by Au during I_{ds}-V_{ds} measurement for pads # 1 and 3. Hence, combing (S1), (S2), and (S3) yields

$$R_{C2} = (R_{12} + R_{23} - R_{13})/2. \quad \text{(S4)}$$

Likewise, we can have the contact resistance for pad #3 as

$$R_{C3} = (R_{23} + R_{34} - R_{24})/2. \quad \text{(S5)}$$

For the device before NO_2 exposure, we obtained R_{12} = ~ 1,860 kΩ, R_{23} = ~ 626 kΩ, R_{13} = ~ 2,384 kΩ, R_{34} = ~ 598 kΩ, and R_{24} = ~ 1,204 kΩ using I_{ds}-V_{ds} curves (solid ones) in Figure S1b and got R_{C2} ~

50 kΩ and R_{C3} ~ 10 kΩ using equations (S4) and (S5). Therefore, the contact resistance between pads # 2 and 3 is ~ 10% of the total resistance, or $(R_{C2}+R_{C3})/R_{23}$=~ 10%.

In addition, Figure S1c shows that the resistance between a pair of Au contact pads (connected by R-GO) increases quite linearly with the increasing gap distance between Au pads, implying that the measured resistances are dominated by the resistance of R-GO rather than the contact resistance between R-GO and the Au contact pads. Of course, the configuration of the four contact pads is quite different from that of the interdigitated electrodes used for R-GO sensors. Nevertheless, the results of our preliminary measurements suggest that the contact between R-GO and Au played a minor role in the total device resistance. More sophisticated measurements on better designed electrode layouts are needed to further investigate the contact issue between R-GO and metal electrodes.

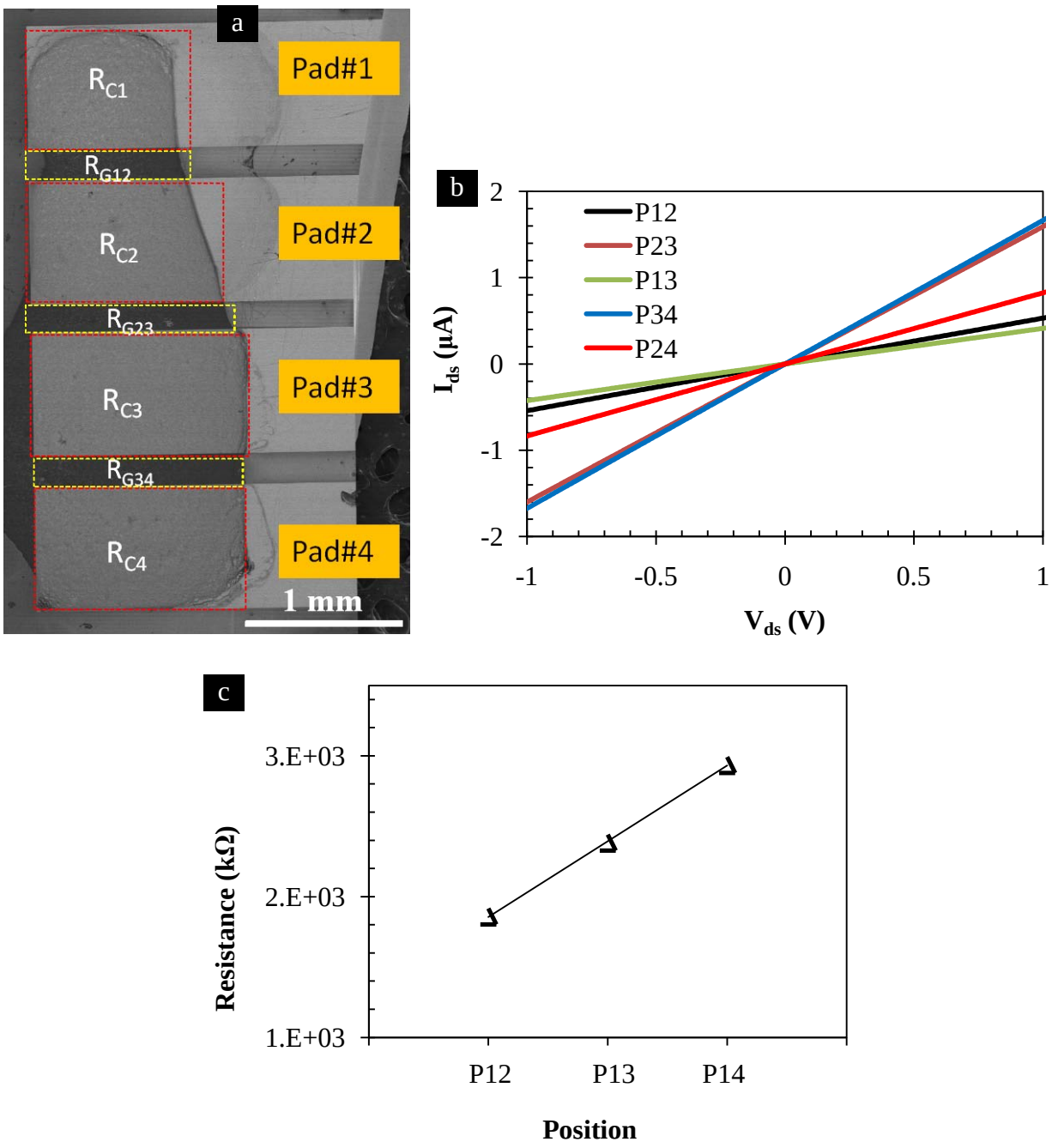

Figure S1. (a) SEM image of four Au contact pads partially covered with R-GO. (b) I_{ds}-V_{ds} curves between contact pads # 1, 2, 3, and 4. (c) The resistance between a pair of Au contact pads increases quite linearly with the increasing gap distance between Au pads.

2. Calibration of an SWCNT sensor for NO_2 sensing with (R_a-R_g) vs. R_a

A CNT gas sensor was fabricated by depositing a few drops of an aqueous suspension containing well-dispersed single-walled CNTs (SWCNTs) (NanoIntegris Inc.)[1] onto Au interdigitated electrodes. Figure S2a is an SEM image that shows SWCNTs bridging Au fingers. The transport characteristics (I_{ds}-V_g) of the SWCNT device in air are typical of a p-type semiconductor, as shown in Figure S2b.

Five cycles were carried out using the SWCNT sensor for 100ppm NO_2 sensing. Each cycle consisted of 5 min air blow (2lpm), 5 min 100ppm NO_2 exposure (2lpm), and 10 min air blow (2lpm) for device recovery. A constant, low dc drain-source current of 100 nA was maintained during the test while monitoring the drain-source voltage (V_{ds}). Figure S2c is the dynamic response (V_{ds} vs. time) of the SWCNT device for 100ppm NO_2 sensing (five runs), which clearly demonstrates the drift and decline of the sensing signal sequentially. We further compared in Figure S2d the responses of the SWCNT sensor using R_a/R_g vs. time curves, which indicates the obvious decreasing of the sensing signal from one run to the next due to incomplete recovery. We then plotted the (R_a-R_g) vs. R_a data in Figure S2e and found a very linear correlation between (R_a-R_g) and Ra, implying that the method we proposed could be effective for overcoming the run-to-run deviation of CNT gas sensors as well.

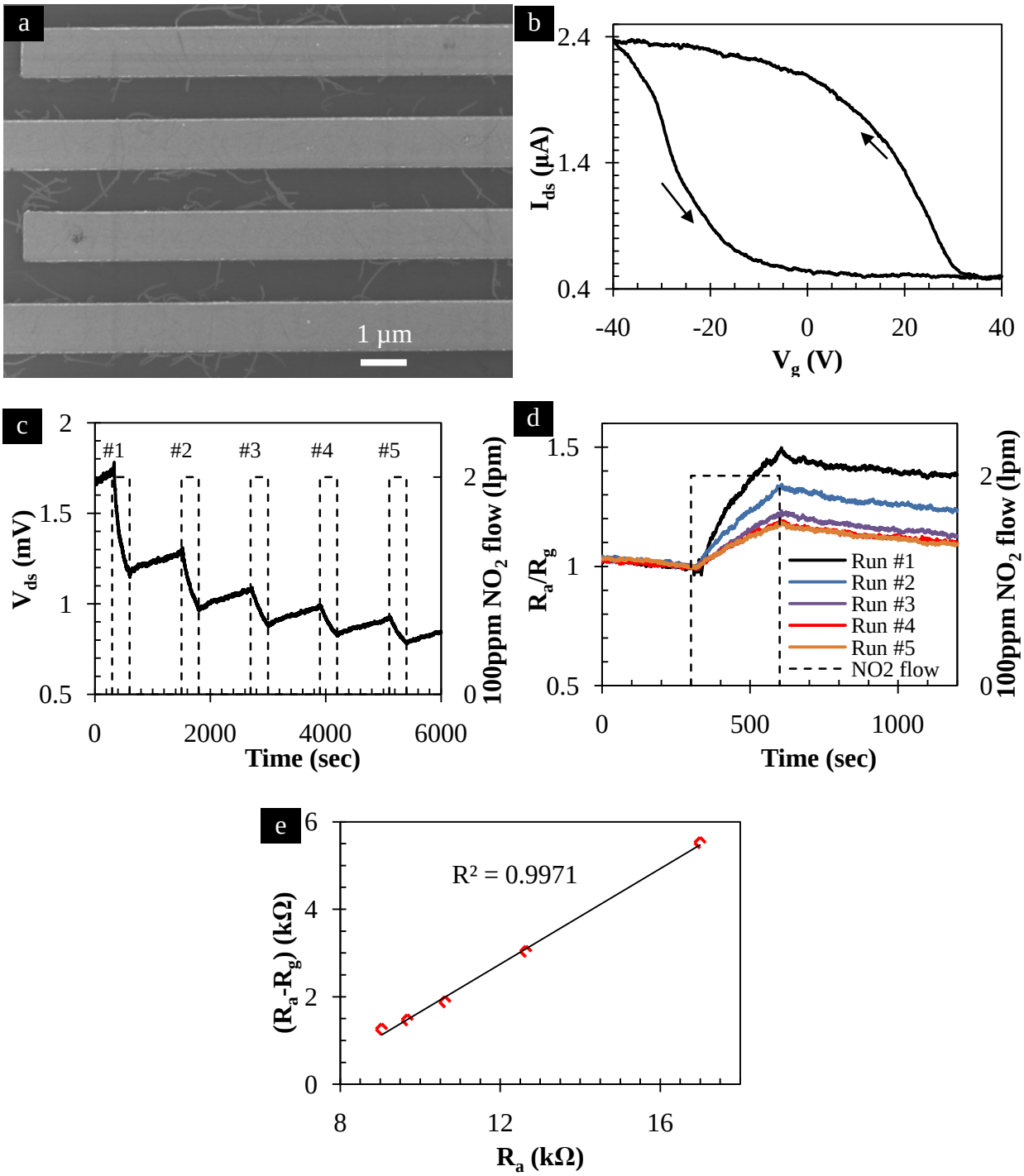

Figure S2. (a) SEM image of SWCNTs bridging Au fingers of an interdigitated electrode. (b) The transport characteristics (I_{ds}-V_g) of the SWCNT device in air, indicating p-type semiconducting behavior. (c) The dynamic response (V_{ds} vs. time) of the SWCNT device for 100ppm NO_2 sensing (five runs). The R_a/R_g vs. time curves (d) and the (R_a-R_g) vs. R_a plot (e) for the five sensing runs shown in (c).

REFERENCES

1. Arnold, M. S.; Green, A. A.; Hulvat, J. F.; Stupp, S. I.; Hersam, M. C. Sorting Carbon Nanotubes by Electronic Structure Using Density Differentiation. *Nat. Nanotechnol.* **2006,** *1*, 60-65.