An Integrated Logic Circuit Assembled on a Single Carbon Nanotube

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The excellent electrical properties of single-walled carbon nanotubes (SWCNTs) make them the most promising candidate for creating transistors on a scale smaller than can be achieved with silicon. A field-effect transistor (FET), which is the basic component of present computer circuitry, has been demonstrated based on individual SWCNTs (*1*, *2*). An important next step would be the construction of integrated circuits along a single SWCNT. This achievement would demonstrate that SWCNTs can be used as a basis for electronics, similar to the way silicon wafers are currently used. A ring oscillator is the ultimate test for new materials in high-frequency ac applications and for evaluating their compatibility with conventional circuit architectures. Here we demonstrate a complementary metal-oxide semiconductor (CMOS)–type ring oscillator built entirely on one 18-μm-long SWCNT (Fig. 1A).

In a CMOS inverter, both an n-type FET (electron carrier) and a p-type FET (hole carrier) are needed to realize a basic logic function. In order to obtain both p- and n-type FETs on the same SWCNT, we controlled the polarities of the FETs by using metals with different work functions as the gates. We chose Pd as the metal gate for the p-FET and Al for the n-FET. The difference in the work functions of these two metals effectively shifts the SWCNT FET characteristics to form a p/n-FET pair (Fig. 1B). In each logic cycle, ideally only one of the two FETs is active, with only a very small current passing through the inverter; therefore, CMOS logic involves almost no static power dissipation. By arranging five inverters (10 FETs) side by side on one SWCNT, we successfully applied the CMOS architecture onto a single molecule to realize a ring oscillator circuit. An extra inverter stage (two FETs), which eliminates interference between the measurement setup and the oscillator operation, follows the ring oscillator portion to allow for the signal to be read by a spectrum analyzer. The inverter characteristics (Fig. 1C) show that the gain is greater than one. Signal propagation in a ring oscillator requires all five inverters to be stable throughout the oscillation cycles, and its robustness can be judged from the area of the "eye" (Fig. 1C, shaded area).

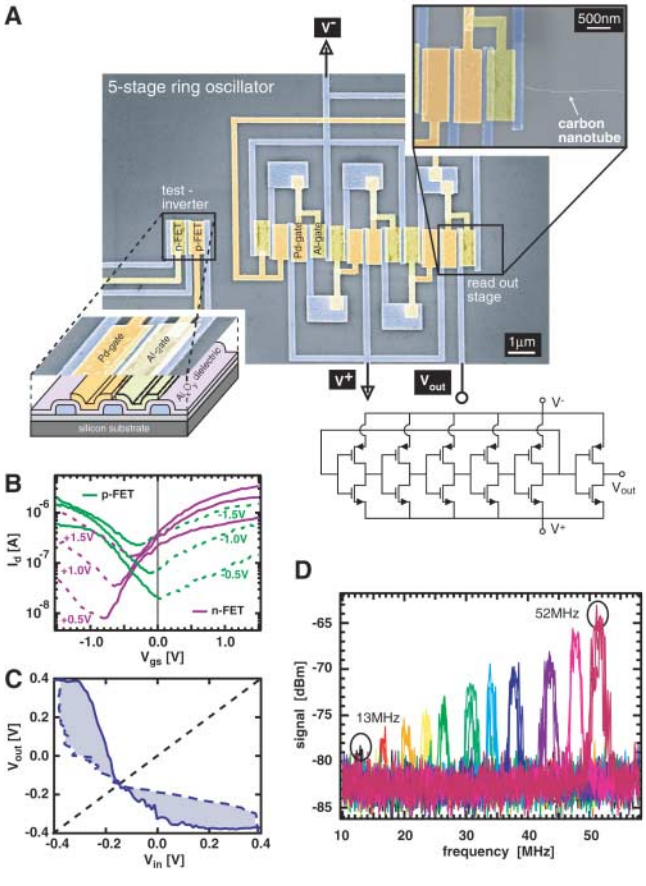

Fig. 1. (**A**) Scanning electron microscope image of a SWCNT ring oscillator consisting of five CMOS inverter stages. A test inverter was added to determine the parameter set for the actual measurement. (**B**) Characteristics for the p-type FET with Pd metal gate and n-type FET with Al gate. (**C**) Inverter characteristics and its mirrored curve. (**D**) Voltage-dependent frequency spectra. From the left to the right, the respective supply voltages are as follows: V_{dd} = 0.5 V and 0.56 V to 0.92 V (in 0.4-V increments).

The output signal of the ring oscillator was measured as a function of the supply voltage (Fig. 1D). A resonance occurs at 13 MHz for supply voltage V_{dd} = 0.5 V. The frequency increases with the voltage and reaches 52 MHz at V_{dd} = 0.92 V, with a corresponding stage-delay time of 1.9 ns. This behavior, which is a result of the increasing drain current I_d in the individual FETs with increasing gate/drain voltage, agrees with the anticipated operation of the ring oscillator. The measured frequencies are limited by the parasitics rather than by the intrinsic nanotube properties (*3*). Compared with previous ring oscillators fabricated on multiple nanotubes with external wiring (*4*, *5*), our ring oscillator shows a five– to six–orders of magnitude greater frequency response. Between V_{dd} = 0.5 V and V_{dd} = 0.92 V, the signal height detected by the spectrum analyzer changed from –79 dB m to –64 dB m, again as a consequence of the I_d–V_{dd} dependence. Because of the impedance mismatch between the output of the ring oscillator (~1 × 10^6 ohm) and the input of the spectrum analyzer (50 ohm), the circuit signal is attenuated by approximately four orders of magnitude, resulting in signal heights of 25 to 140 μV rather than the applied V_{dd}.

The demonstrated intramolecular ring oscillator is a useful tool to characterize the suitability of SWCNTs for ac applications. It enables the detailed study of the performance-limiting aspects in SWCNTs and offers a way to evaluate their potential as a platform for future nanoelectronics applications. The central goal is to ultimately benefit from the expected intrinsic switching speed in SWCNT FETs, which is predicted to allow for terahertz applications.

References and Notes

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