Carbon Nanotube Field Effect Transistors: The Next Generation of Interconnects

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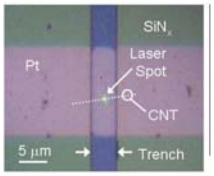
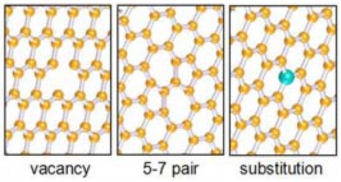
Memristive Behavior in Defected Nanotube Devices[1]

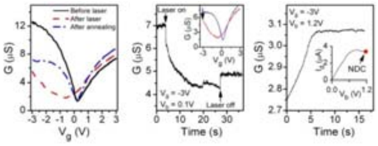
- Suspended Carbon Nanotube field Effect Transistors are fabricated using optical lithography.
- Raman measurements are carried out to characterize the transistor.



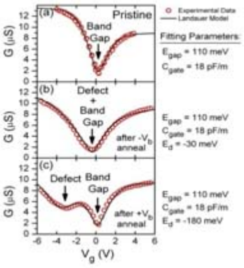
•A defect state can be induced in the pristine nanotube by applying relatively high power 532nm laser.



•By creating a defect in the nanotube, the Gate voltage transfer function changes accordingly. However, annealing the nanotube at high V_{ds} will change the defect state energy.

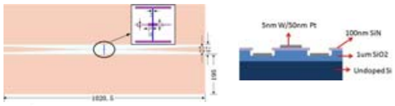


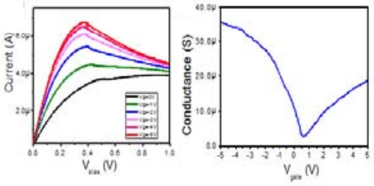
•Changing the direction of the *Vds* annealing will cause a change in the defect state, making the transistor behave like a memresistor.



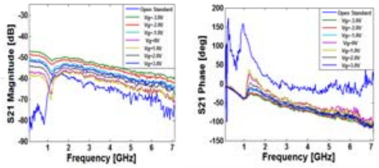
Microwave Electrical Properties of Carbon Nanotube Devices[2]

- It has been theoretically predicted that nanotubes exhibit large kinetic inductance, especially at very high frequencies.
- We aim to measure the inductance of suspended nanotube FETs.
- The figure below shows the device structure along with a typical DC transfer characteristics.

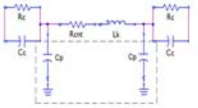


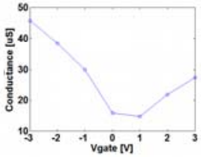


- A vector network analyzer (VNA) is used to measure the scattering parameters of the CNT-FET up to 7.1GHz, in an attempt to extract the circuit model.
- The S21 parameter (magnitude and phase) shows a gate dependence, as shown below



- After de-embedding the circuit parasitics, the extracted high frequency model is shown below on the left, while the conductance at 1GHz is on the right.
- Remarkably, the RF conductance is higher than the DC conductance (above).



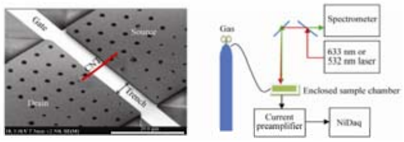


- The table below shows the extracted CNT inductance as a function of gate voltage.

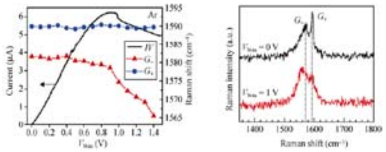
V_{gate} (V)	R_{cnt} (kΩ)	L_k (nH)	C_p (fF)	R_c (kΩ)	C_c (fF)
-3.0	2.43	56.5	7.88	9.72	0.001
-2.0	2.94	64.66	6.63	11.49	0.001
-1.0	3.90	82.68	5.23	14.72	0.001
0	6.41	169.17	2.87	28.39	0.001
1.0	7.05	236.8	2.73	30.34	0.001
2.0	4.52	148.99	3.95	20.62	0.001
3.0	3.94	103.17	4.94	16.34	0.001

Ballistic 1D Conductors: Anomalous Kink Behavior in the $I-V_{ds}$ Curve[3]

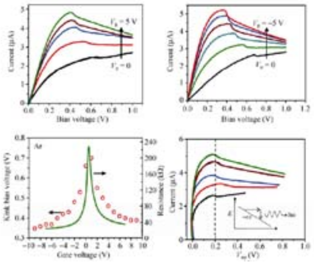
- A sudden drop in the IV_{ds} is observed in suspended carbon nanotube devices. A typical device is shown in the SEM image below where the nanotube is suspended between the source and the drain while a gate electrode is deposited in the middle of the trench.
- A Raman systematic study as a function of bias voltage is carried out to determine the origin of this kink. The experiment schematics is shownon the right figure below.



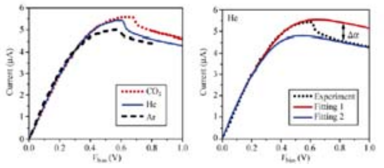
- The figure on the left below shows the Raman *G*-band mode at different bias voltages. Due to joule heating when applying high bias, *G*-band starts to downshift. However, this downshift only starts when the kink occurs in IV_{ds} curve. The figure on the right shows the Raman spectra before and at the kink.



- We also measured the IV_{ds} at different gate voltages. The kink decreases with bias voltage, following the device resistance trend.
- Due to the ballistic nature of carbon nanotubes, and after subtracting the low bias resistance, all the kinks at different gate voltages line up at 0.2*V*, which is the energy of the emission of optical phonons.



- The kink in the IV_{ds} can be modeled as a change in the optical phonon relaxation coefficient, where higher values means higher non-equilibrium optical phonon population.
- We measured IV_{ds} in different gases and found that the kink magnitude, and hence the non-equilibrium phonon population coefficient, follows the following ordering: $\Delta I^{Ar} < \Delta I^{CO_2} < \Delta I^{He}$



- The table below shows the change in current for different samples measured in argon, carbon dioxide, and helium.
- The ordering of the kink magnitude does not follow the atomic mass ordering, nor the thermal conductivity ordering for these gases.

Samples	Type	ΔI^{Ar} (µA)	ΔI^{CO_2} (µA)	ΔI^{He} (µA)
Sample 1 *L*=5µm	M	0.31	N/A	N/A
Sample 2 *L*=2µm	M	0.26	0.48	0.6
Sample 3 *L*=2µm	SC	0.16	0.2	0.26
Sample 4 *L*=2µm	M	0.25	0.55	0.6
Sample 5 *L*=2µm	M	0.25	N/A	N/A
Sample 6 *L*=5µm	SC	N/A	0.2	0.25
Sample 7 *L*=2µm	M	0.23	N/A	N/A

Summary and References

In summary, we have created a nano-memristor by laser inducing a defect in suspended carbon nanotube device. The energy of the defect state can be altered by the high bias annealing direction (forward or reverse). Also, the microwave properties of carbon nanotube field effect transistor have been investigated and it is found that suspended nanotubes have higher RF conductance compared to DC conductance. Finally, we identify the origin of a sudden drop in current "kink" measured in the $I-V_{ds}$ curve. This kink is found to strongly depend on the gate voltage and the type of gas surrounding the suspended nanotube. However, by subtracting the low bias resistance of the nanotube and using the ballistic nature in pristine ultra-clean nanotubes, the kink is found to be the threshold of the optical phonon emission at high bias voltage. Thus, making nanotube devices promising candidates for future electronic interconnects or high frequency transistors.

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