Toward Separated Carbon Nanotube Based Large Scale Thin-Film CMOS Integrated Circuits

Jialu Zhang†, Chuan Wang†, Yue Fu, and Chongwu Zhou

Dept. of Electrical Engineering, University of Southern California, jialuzha@usc.edu

† These authors contributed equally to this work

Introduction

Flexible transparent thin-film transistors are important for applications such as flat-panel displays, e-papers and radio-frequency identification tags. However, the challenge is to find the right channel materials.

Materials	Advantages	Challenges
α-Si TFTs	- High Reliability - Presently used in LCDs	(a) High temperature processing; (b) Low mobility (μ ≤ 1 cm²/V·sec)
Poly-Si TFTs	- High mobilities (~ 150 cm²/V·sec) - Presently used in AMOLEDs	(c) High temperature processing; not suitable for plastic substrates
OTFTs	- Low temperature processing: - can use on plastic substrates	(d) Low mobilities (μ ≤ 1 cm²/V·sec) (e) Moisture sensitivity

Carbon nanotubes: Significantly higher mobility, compatible with transparent flexible electronics, low temperature processing: low cost.

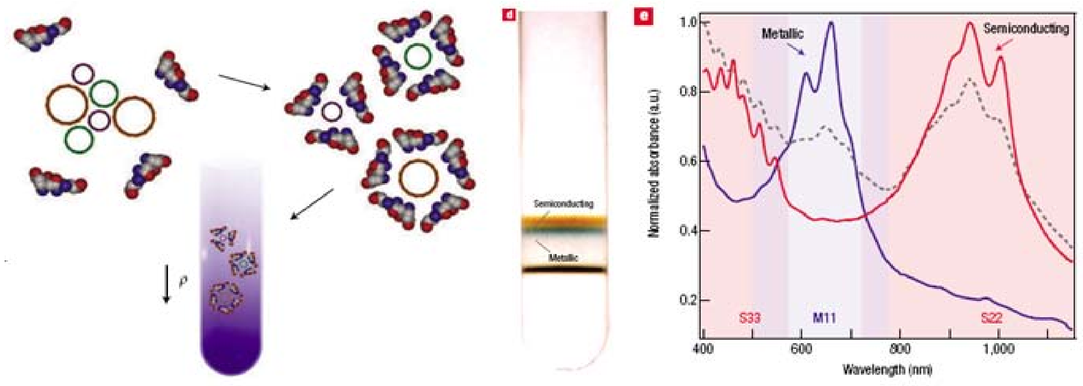
Challenges: 1.Coexistance of metallic and semiconducting nanotubes.

2. Carbon nanotubes are usually p-type doped in ambient air.

Experimental

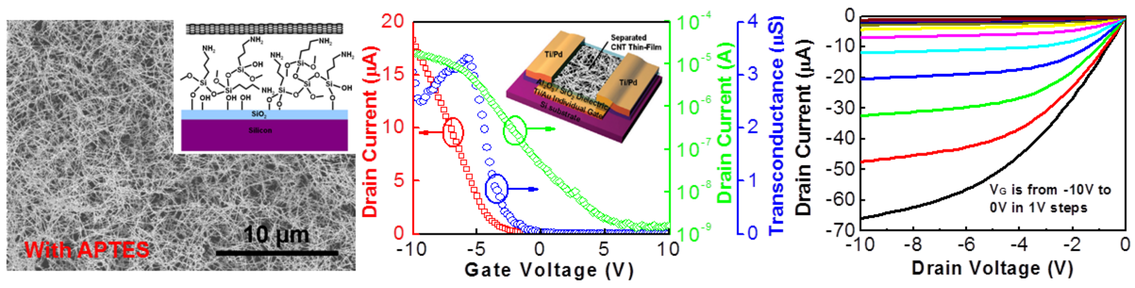
Separation of metallic and semiconducting nanotubes:

Density gradient ultracentrifugation method



M. Arnold, M. Hersam et al., ***Nature Nanotechnol.***, Vol. 1, 60, **2006**

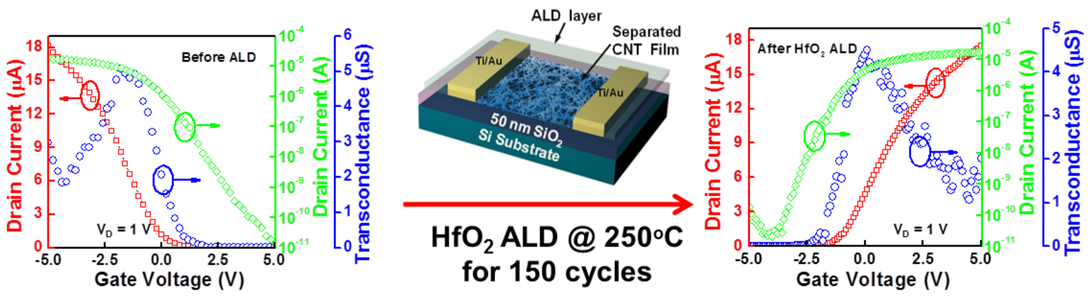
p-Type thin-film transistors:



- 95% semiconducting nanotube solution
- On/off ratio: ~ ***10000***, peak transconductance: 3.5 μS
- Highest mobility of ***67*** cm²/V·sec

n-Type thin-film transistors:

By passivate the p-type SN-TFTs with high-κ oxide layer using atomic layer deposition (ALD), the transistors are converted to n-type

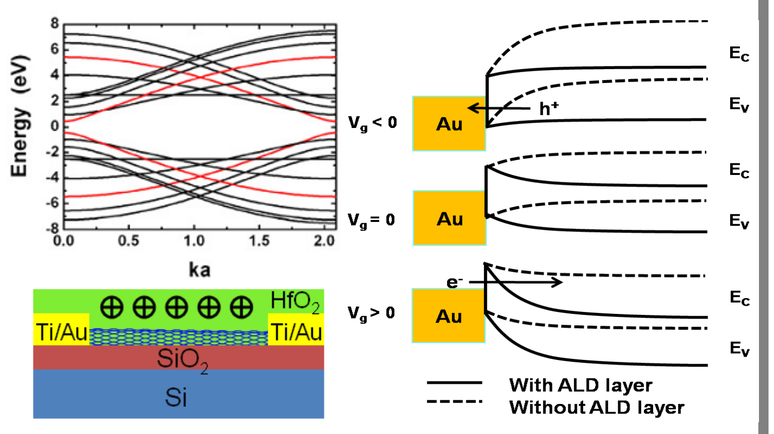


	On-current	transconductance	On/off ratio	Device mobility
Before ALD	18.1 μA	5.06 μS	1.616×10^6	5 $cm^2V^{-1}s^{-1}$
After ALD	17.4 μA	4.59 μS	1.34×10^6	3 $cm^2V^{-1}s^{-1}$

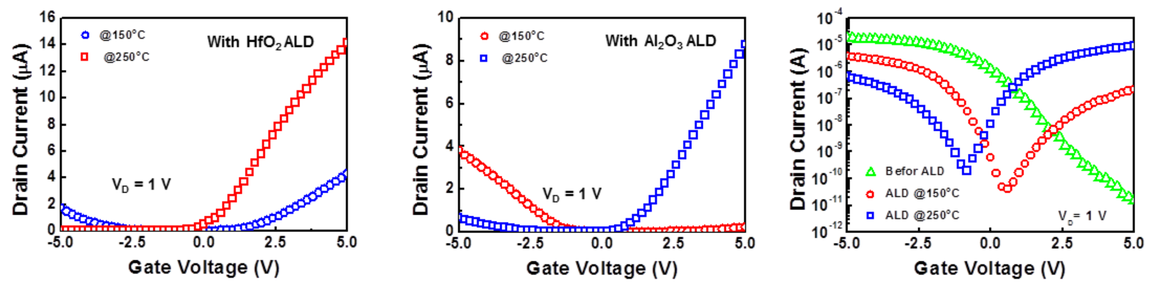
In-depth study of n-type SNTFTs

Mechanism of the Carrier conversion:

- Symmetric E-k relationship for holes and electrons
- The baking process in the vacuum chamber during ALD drives away O_2
- Positive fixed charge in the high-κ oxide layer introduced due to the deficiency of oxygen atoms will tune the energy band



ALD temperature dependence:

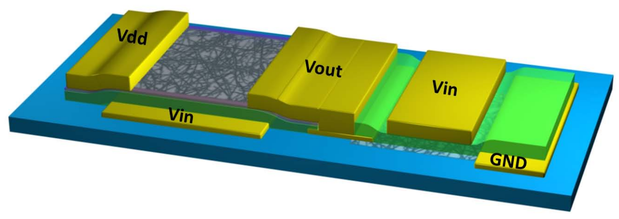


@250 °C (compared with 150°C)

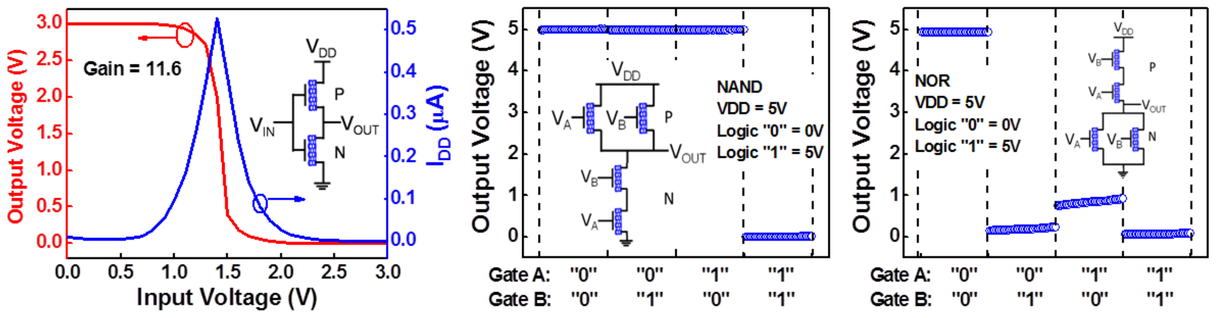
- H_2O vaporizes **faster** and is pumped away immediately
- **Less oxygen atoms** available during the formation of high-κ oxide layer.
- **More positive charge** is accumulated and the nanotube energy band will be **bent down** even further.

Applications

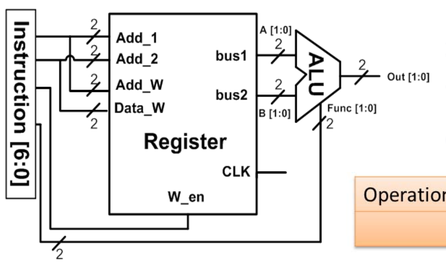
CMOS integrated logic gates:



We use back-gated structure for p-type SN-TFTs and top-gated structure for n-type SN-TFTs and integrate them together for CMOS circuits



2-bit CMOS CPU (ongoing):

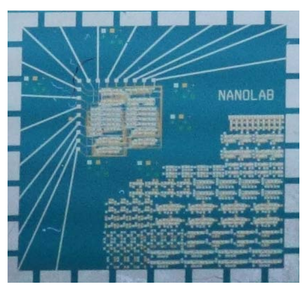


2-bit single cycle (non-pipelining) CPU;

7 bit instruction:

Oper [2:0] Add1 [1:0] Add2 [1:0]

Operations	AND	OR	NOT	ADD	Write
	000	001	010	011	100



Conclusion

We have developed a platform for high performance n-type and p-type separated nanotube TFTs with high yield. Devices exhibit significantly better performance compared with state-of-the-art amorphous silicon and organic TFTs. Our work represents significant advance toward the challenging tasks such as nanotube separation, assembly, air-stable n-type device fabrication and can provide guidance to future research on SN-TFT based large scale CMOS integrate circuits.

Chuan Wang†, Jialu Zhang†, Chongwu Zhou, et al., *Nano Letters*, Vol. 9, pp. 4285-4291, (2009)

Chuan Wang†, Jialu Zhang†, Chongwu Zhou, et al., *ACS Nano*, Vol. 4, pp. 7123-7132, (2010)

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