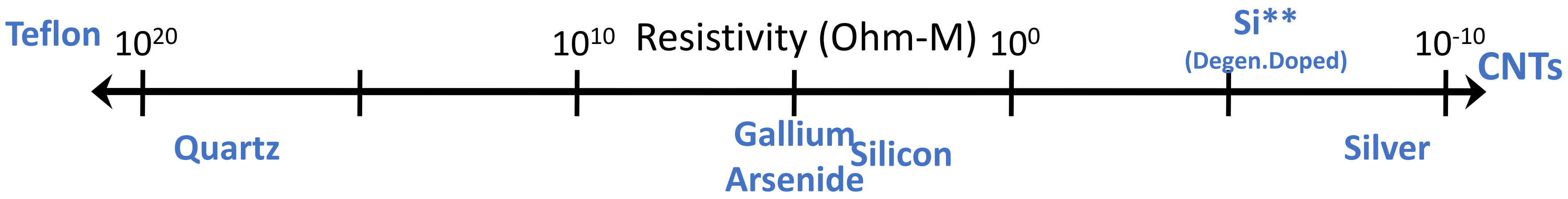
EES2 CNTFET Lightning Talk

J Provine and Steffen McKernan

June 21, 2023

CNTs: “A Switchable Super Metal*”



Sensors

- ➢ **Capable of single molecule chemical sensing**
- ➢ **DNA wrapping for bio-particular sensing**

RF

- ➢ **Highest mobility (>100x doped Si): THz capable**
- ➢ **Intrinsically linear: More data with less spectrum and energy**

Digital

- ➢ **On SiO2, >7x the speed for power of Si CMOS;**

***The size of an atom to the universe is ~37 orders of magnitude. Conduction ranges across ~33 orders. Current semis, even when degenerately doped**, are really crappy conductors. CNTs are better than any metal**

It is hard to understand how different CNTs are: **Current/Area: <u>550,000 x</u> Copper**

Aligned Carbon

Human Hair of Carbon Nanotubes (0.01 cm/0.004")

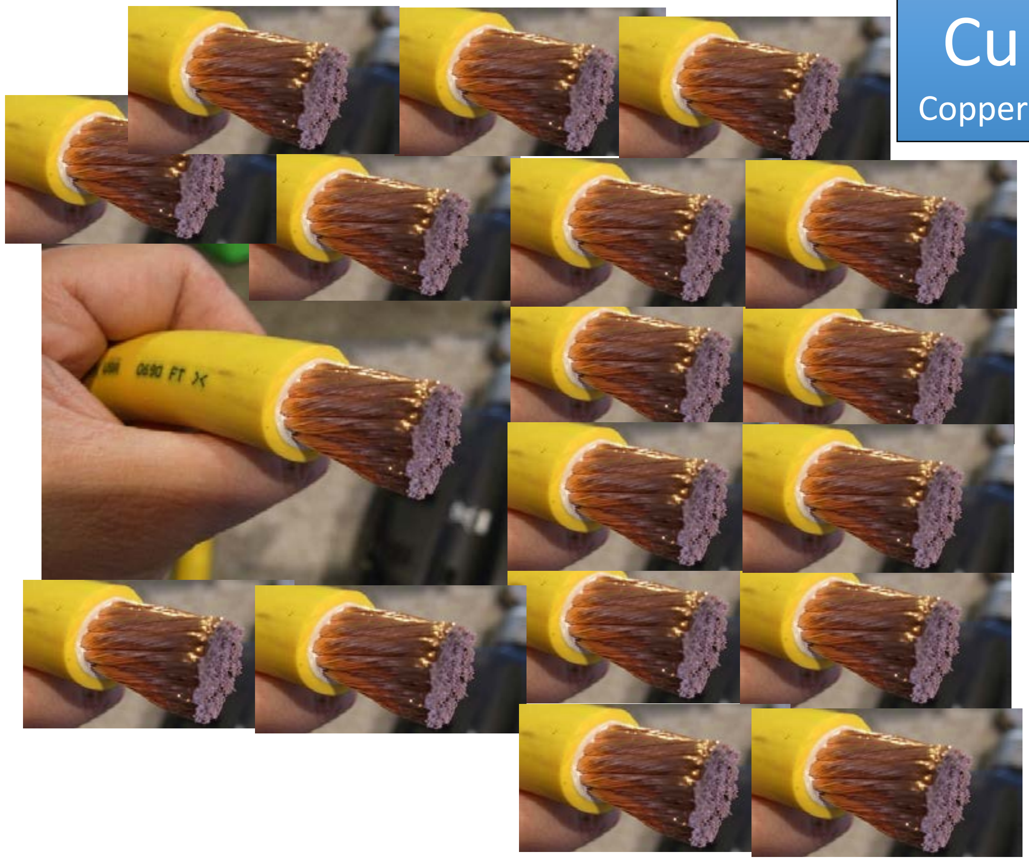
Vs.

18 "000 Gauge" Copper Cables

29
Cu
Copper

6
C
Carbon

Same 4.3KA Current Carrying Capacity



But, New Semis Take Time

Materials Science = Real Science = What We Don't Know

RCA REVIEW

a technical journal

RADIO AND ELECTRONICS
RESEARCH • ENGINEERING

Published quarterly by
RCA LABORATORIES
in cooperation with all subsidiaries and divisions of
RADIO CORPORATION OF AMERICA

VOLUME XXIV DECEMBER 1963 NUMBER 4

CONTENTS

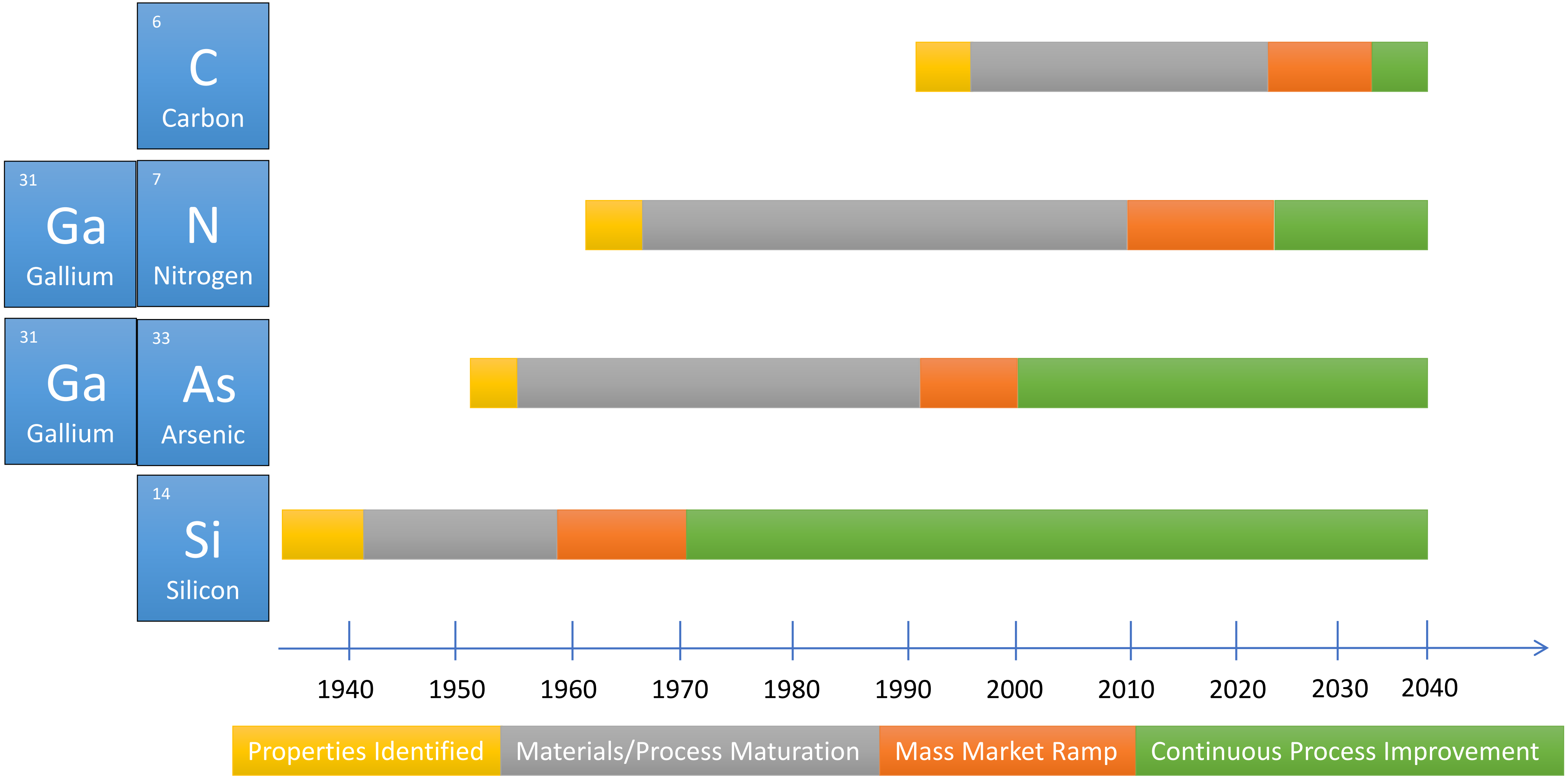
Synthesis and growth of single crystals of gallium nitride R. B. Zetterstrom

Journal of Materials Science **5**, 1102–1104(1970)

The Economist

The TSMC fab's raw material is the most common element in the Earth's crust: silicon. …refined with a purity of 99.999999999%

Carbon: It's Just A Matter Of Time



Electronics Material Science

Good Enough Material

- Si is now 11 9s pure
- GaAs properties: 1950s; Products: 1990s
- GaN properties: 1960s; Products: 2010s
- CNT properties: 1990s; Products: 2020s

CNT Material Requirements

- Clean: Hysteresis << 100mV
- Diameter/bandgap control: 1-2nm; ±0.1nm
- Density: 1/um for sensors; 10/um for RF; 100/um for digital
- Semi:Metallic: 10 for RF; 1000++ for digital

CNT Material Approaches

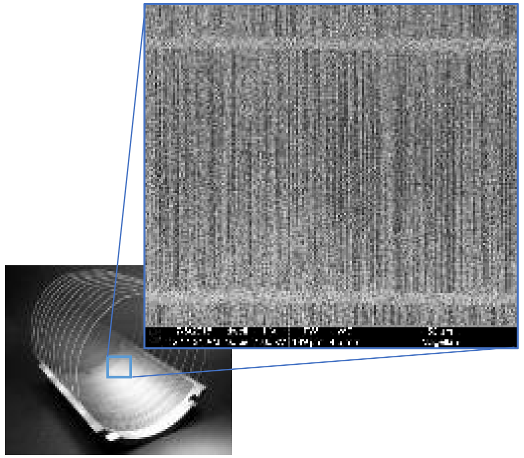
1. Aligned Carbon: CVD Grow and Remove Metallic Tubes
    a. CNT density
    b. Demonstrate high semiconducting:metallic ratio
2. Carbon Tech: Selectively Grow Diameter Controlled Semi CNTs
    a. Demonstrate high semiconducting:metallic ratio
    b. Alignment
3. SixLine*/Nantero*: Solution process and deposit
    a. Lack of order/defects
    b. Short CNTs (~1 μm)
    c. Polymer contamination for ultracentrifuged tubes; Nantero does not use polymers for its memory tech

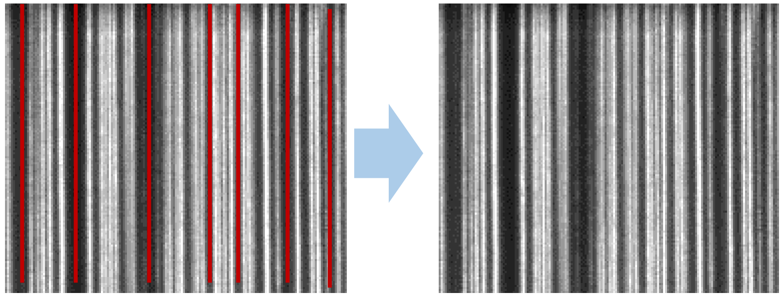
*We did not discuss this with them. Our goal is to promote CNT investment

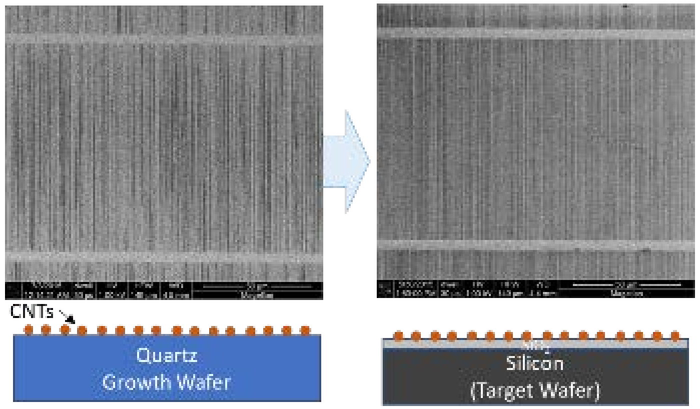
1. Aligned Carbons Unique Technology

Integrates high purity and aligned CNT material onto target wafers

Aligned Carbon







1) Aligned Growth

- Growth of high-density single walled aligned CNTs on quartz or sapphire wafers
- CMOS compatible catalyst stripes with >100 μm long CNTs
- Leverages best known techniques and custom growth systems

2) Purification

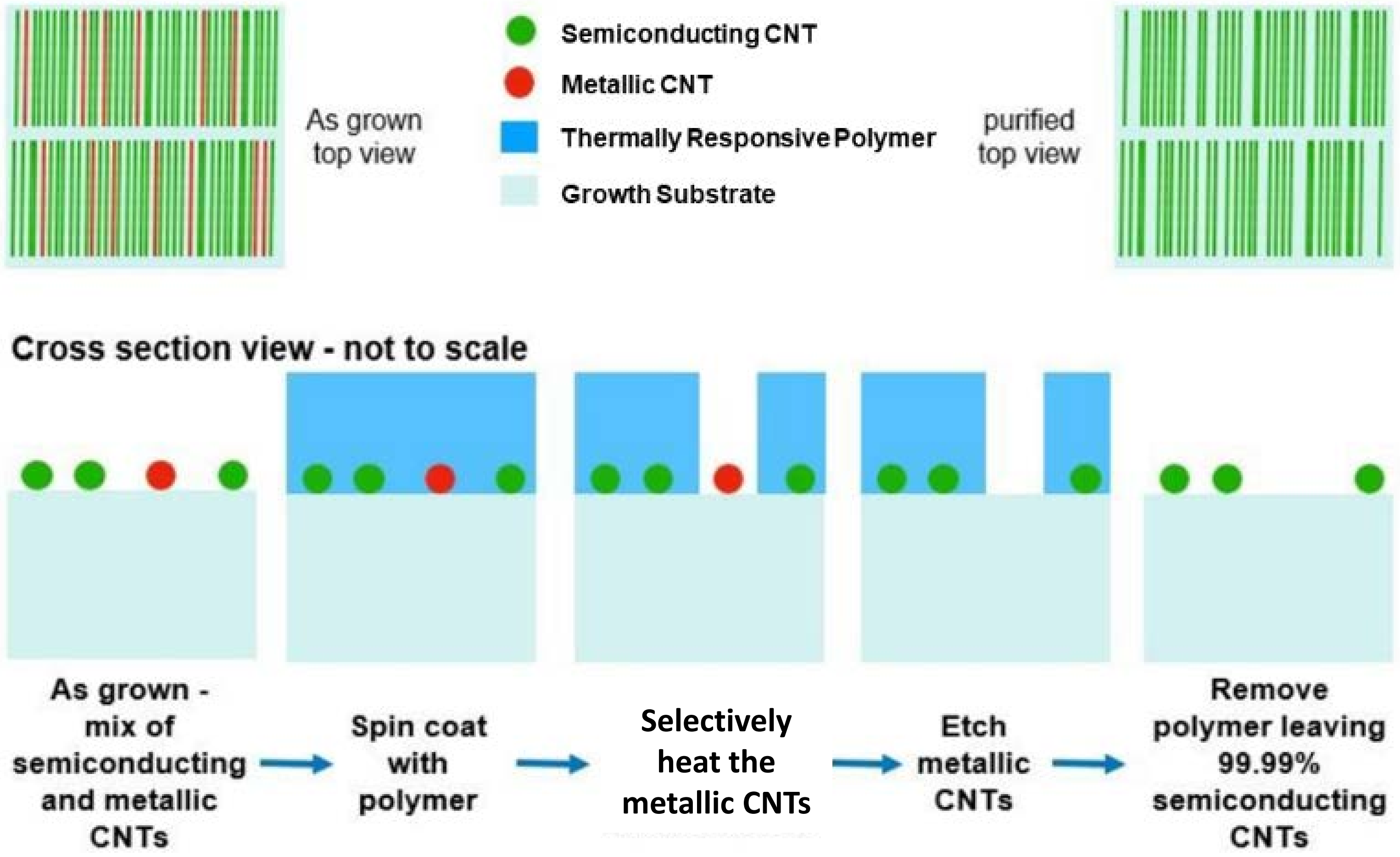
- Key company IP
- In-situ removal of metallic CNTs on the growth wafer (prior to transfer)
- Avoids need to build additional circuitry to induce electrical breakdown on target wafer
- Avoids wet bench processing of target wafer

3) Transfer

- CNTs are embedded in a CMOS compatible sacrificial layer and transferred to target wafer
- Similar process to thin film solar cell transfer
- If needed, multiple transfers can increase density on target wafer

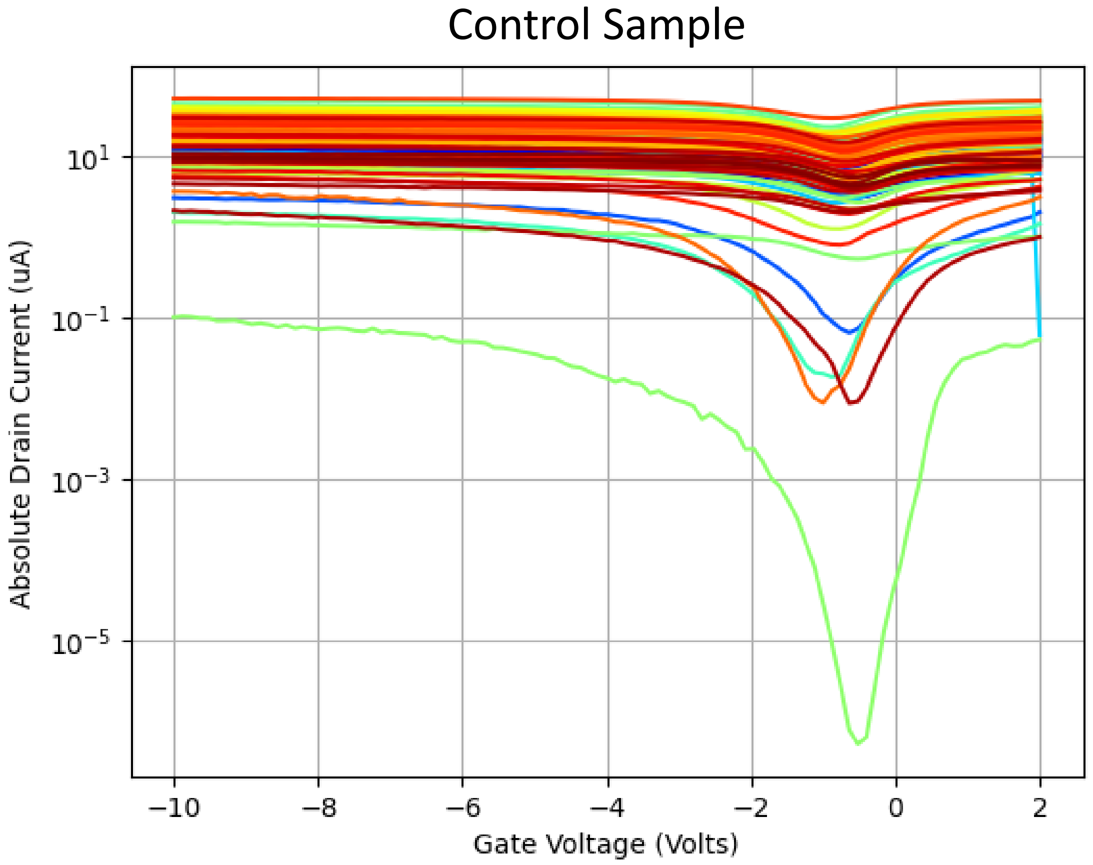
1. Aligned Carbon Purification

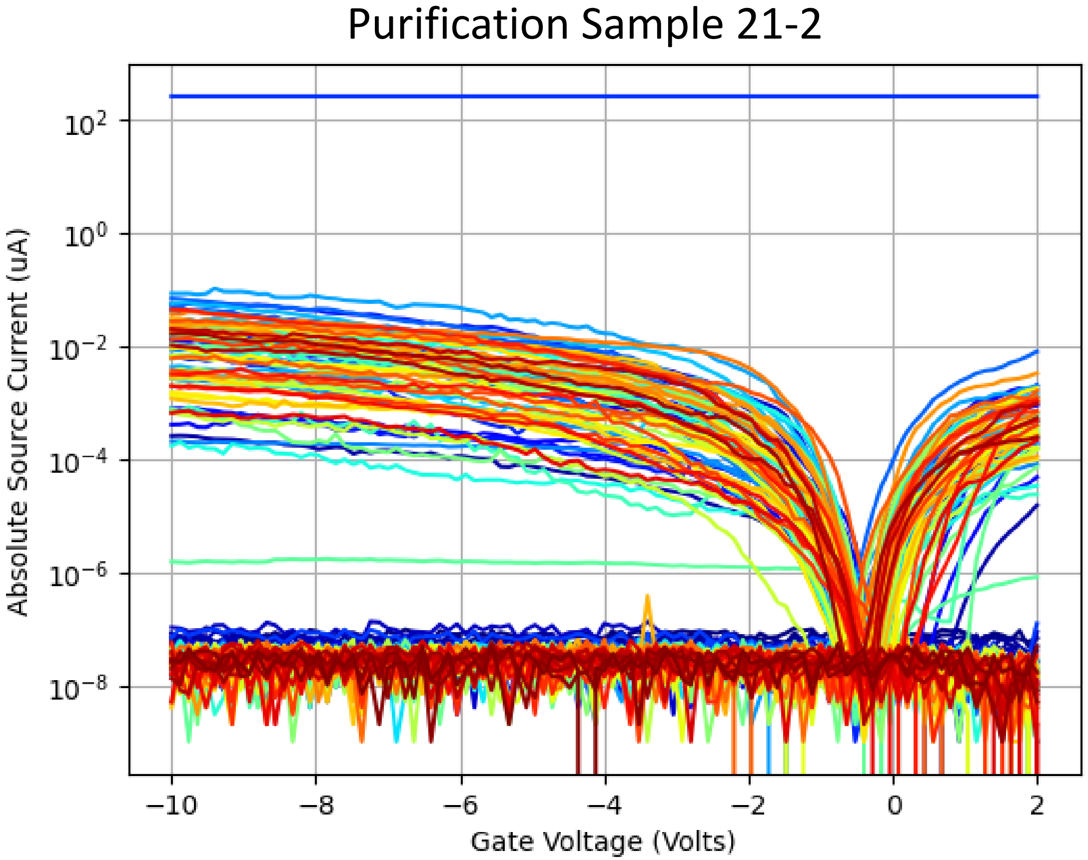
Takes Place on the Growth Wafer



Zero additional mask layers for target wafer

1. Aligned Carbon Progress: Purity

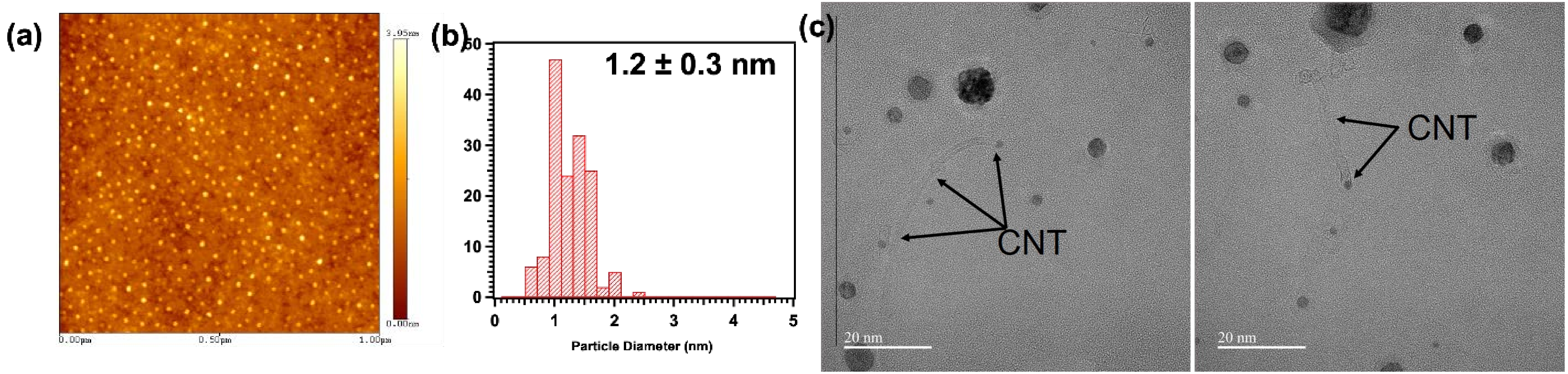




- As grown → ~67% of CNTs semiconducting
- ~2% of CNTFETs are semiconducting

- Post-purification → >99% of CNTs semiconducting
- ~98% of CNTFETs are semiconducting

2. Carbon Tech (CTI): Control the Catalyst, Control the CNTs

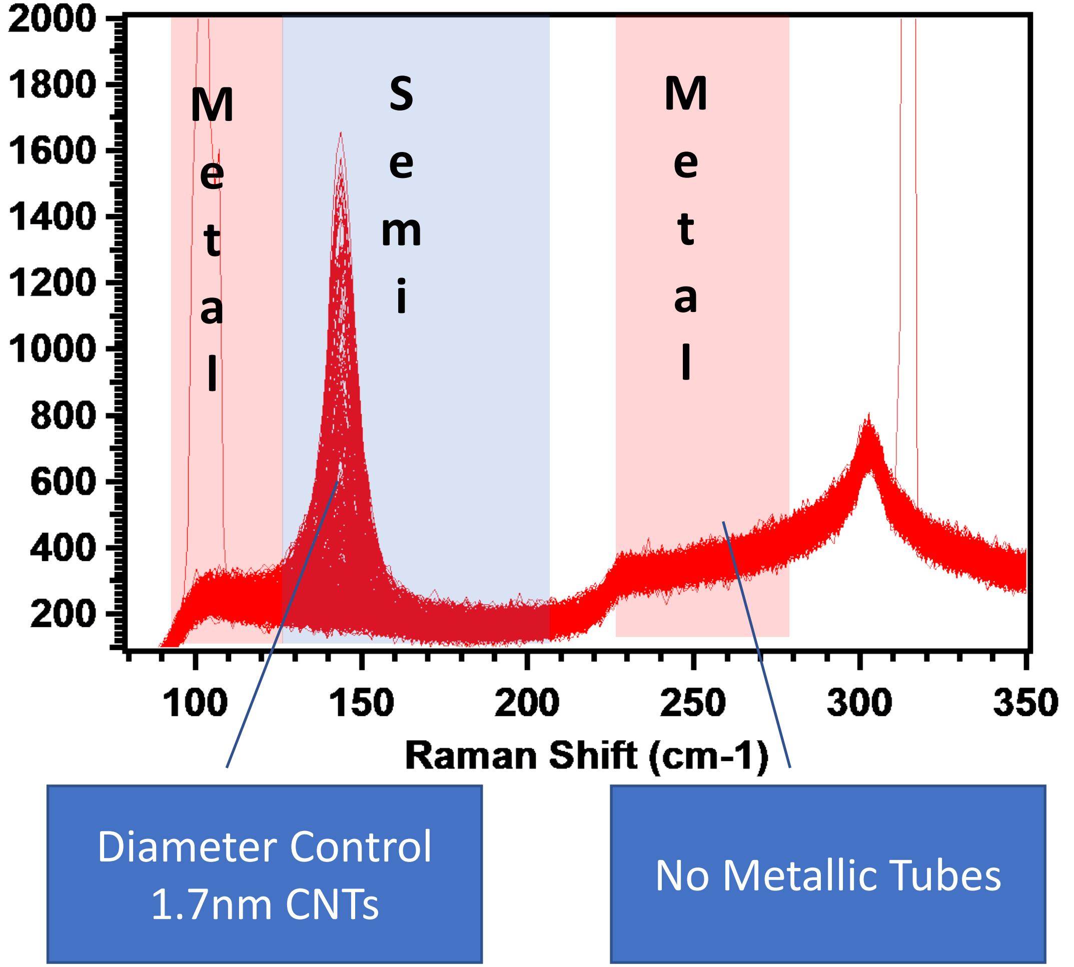


(a) and (b), AFM image and histogram of CTI catalyst sizes (SiO2 substrate roughness is ~0.3nm; (c) 2 TEM images of CNTs growing tangentially from the catalyst

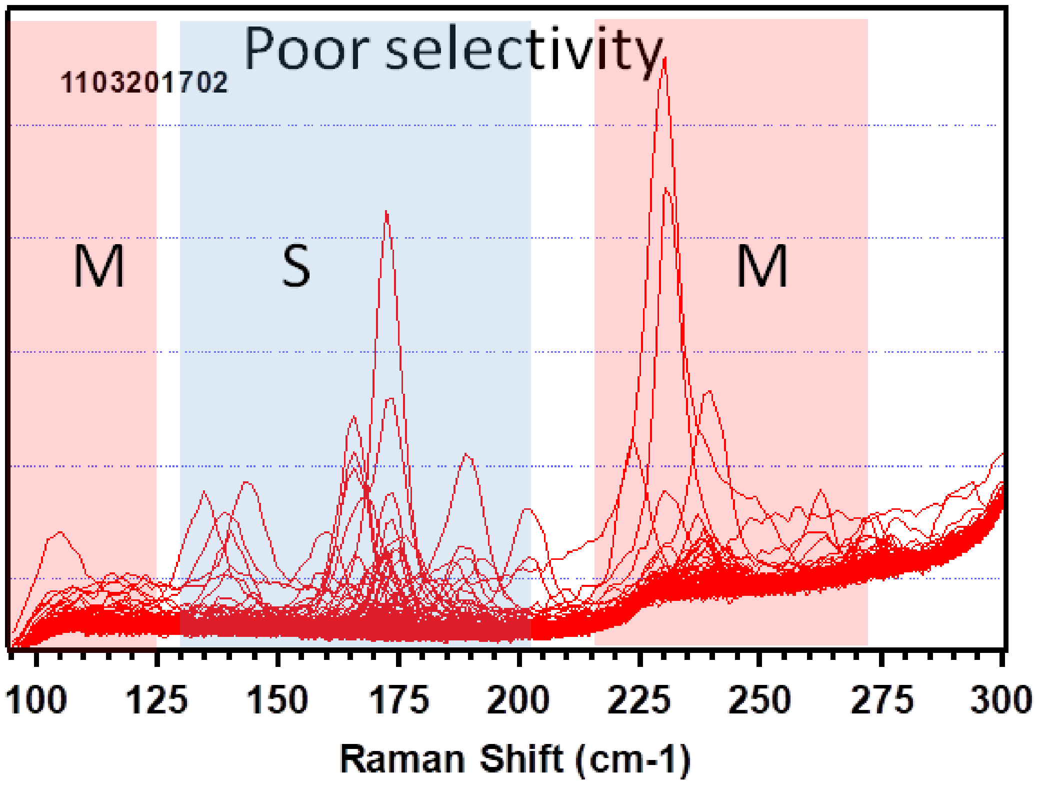
2. Carbon Tech Breakthrough: Direct Grow Semi, Right Diameter CNTs

Breakthrough: ✓ Semiconducting CNTs✓ Diameter Controlled @ 1.7nm

Raman: Clean Semiconducting CNTs w/ Diameter Control



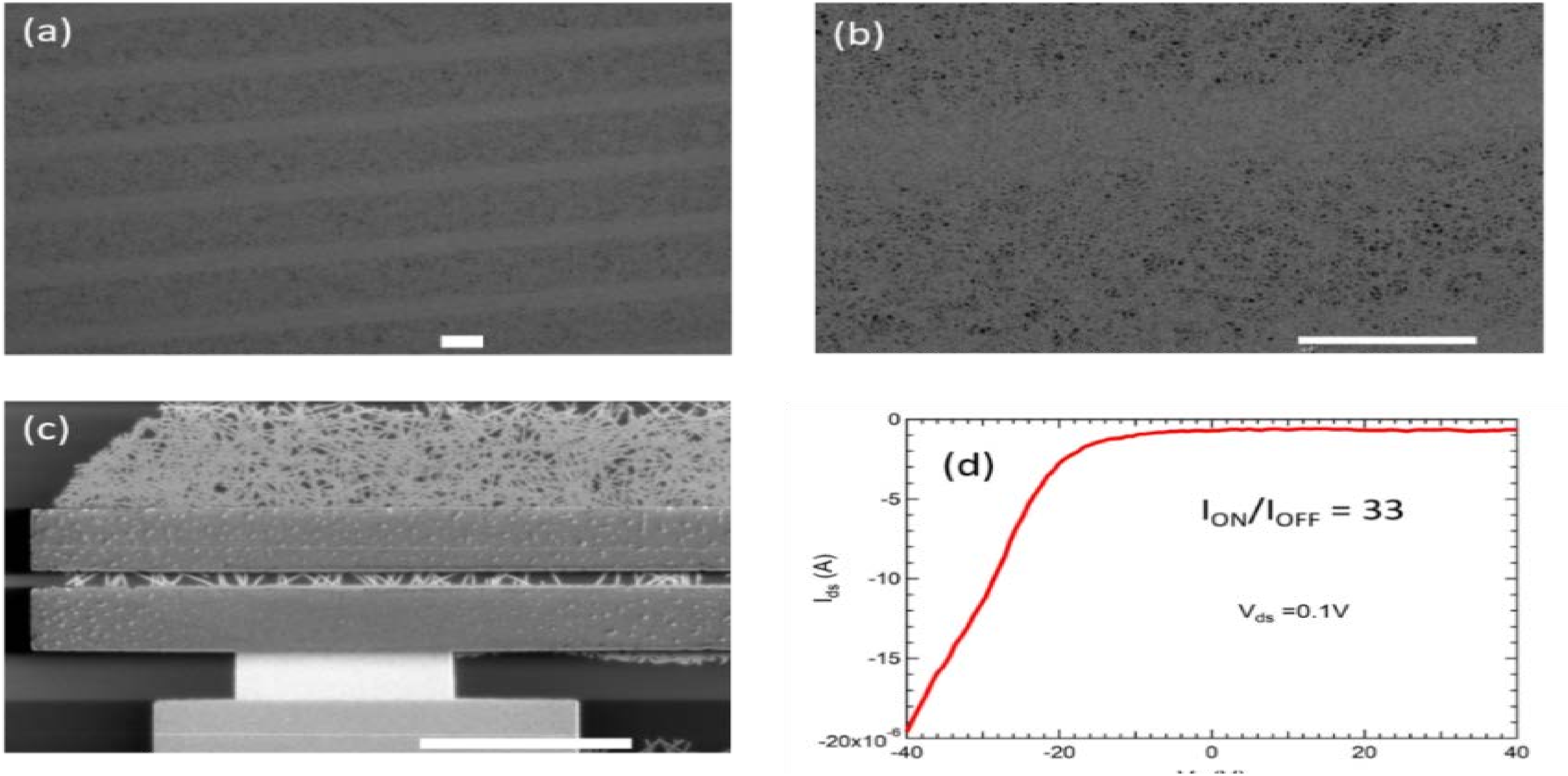
Vs. No Selectivity



2. Carbon Tech CVD: CNT Density >20/micron; On/Off >30

✓ > 10 CNTs/uM

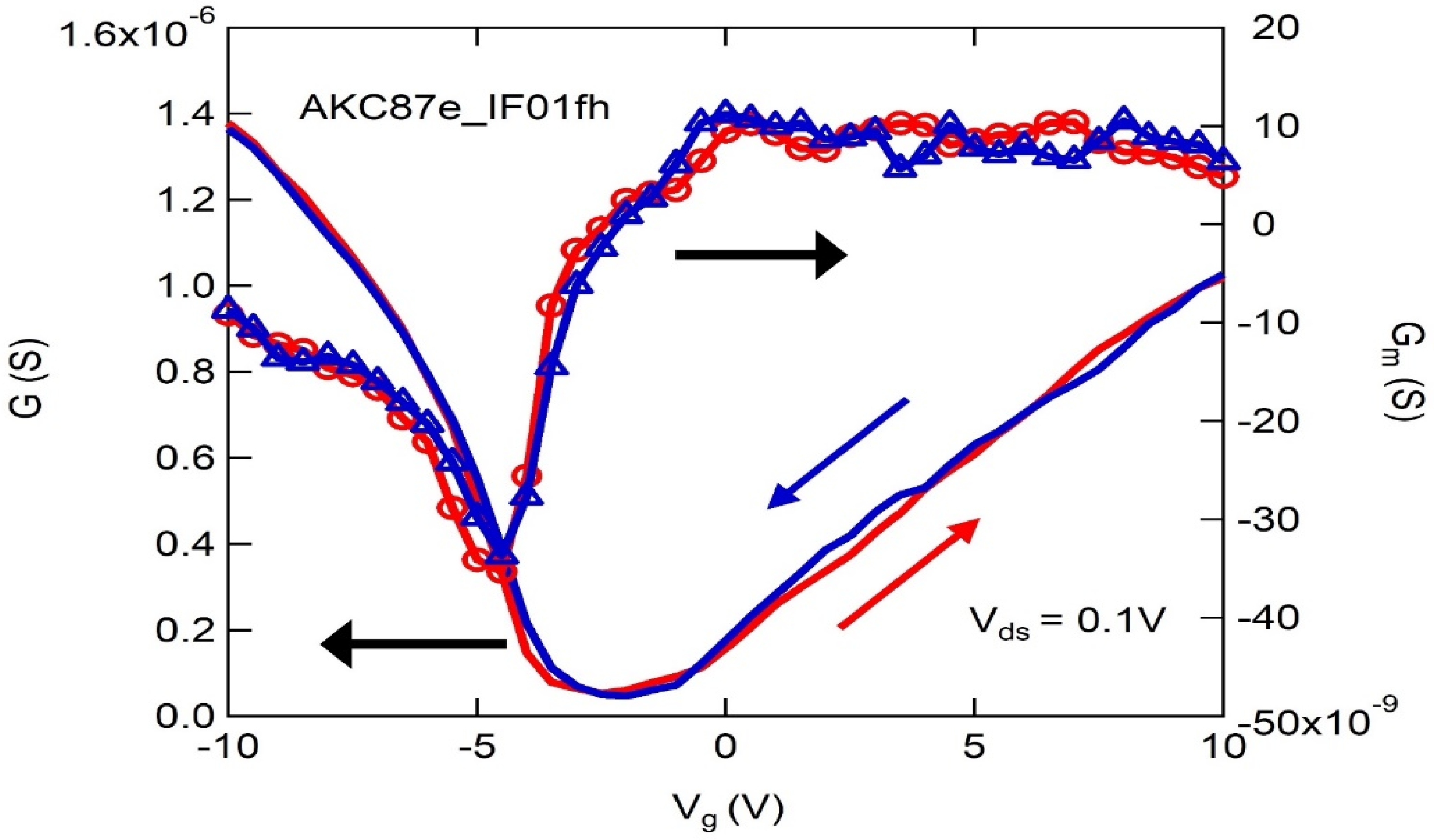
✓ Semi:Metallic > 10:1



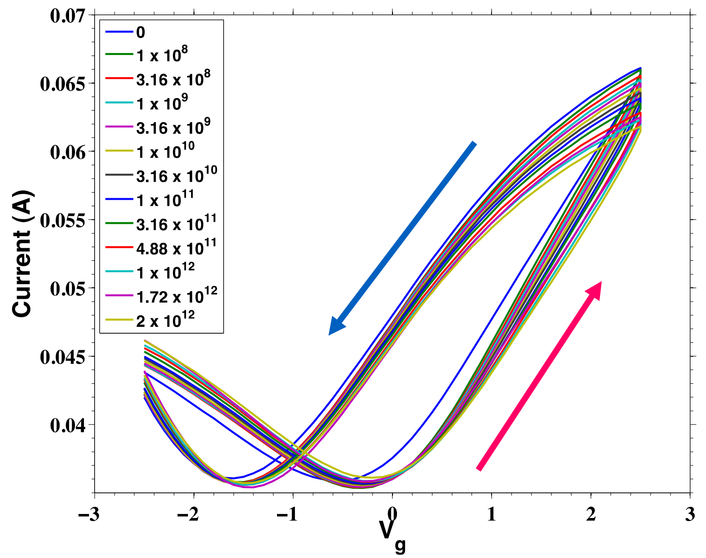
(a) and (b), SEM images of CNTs grown from CVD method showing density of more than 20 CNTs/μm; (c) SEM image of a CNT device with SD metal contact; (d) Id -Vg curve of the device shown in (c). Scale bars for all SEM images are 5μm

2. CTI Clean: Process Breakthrough No Hysteresis

Clean: No hysteresis; DC Linear



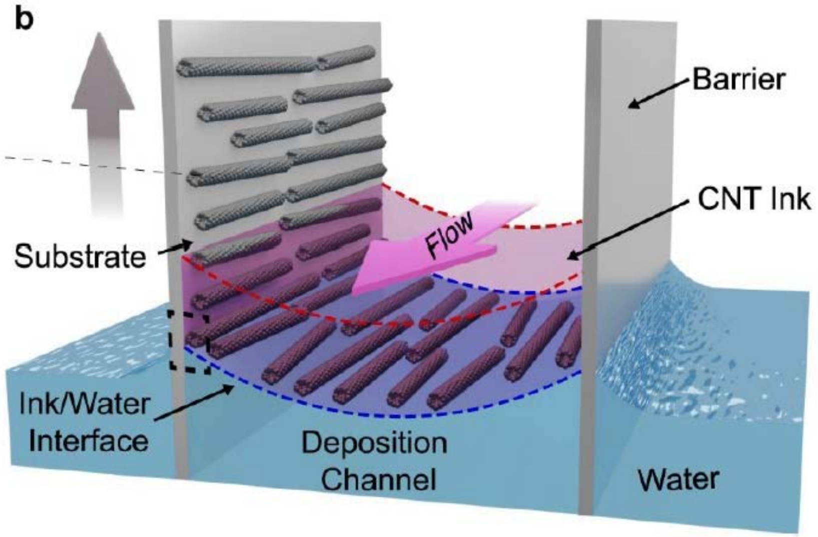
Not Clean*: Hysteresis



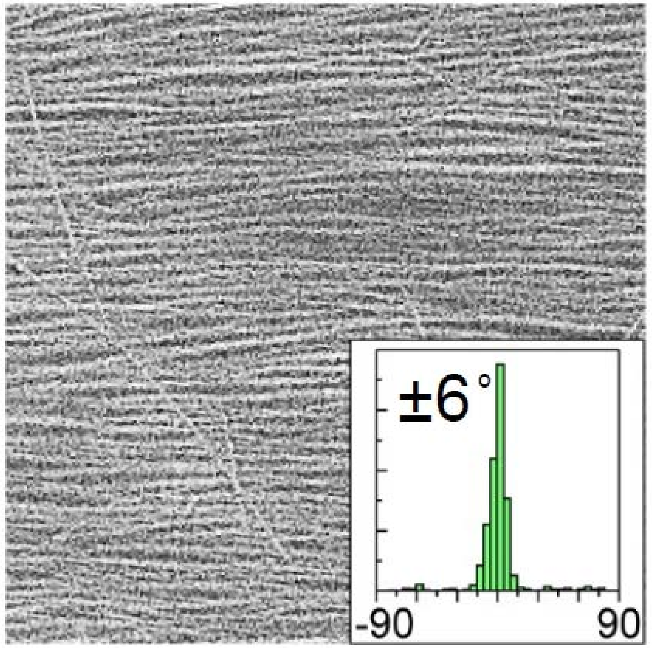
*But, rad hard! Exposure data from work with the Aerospace Corp

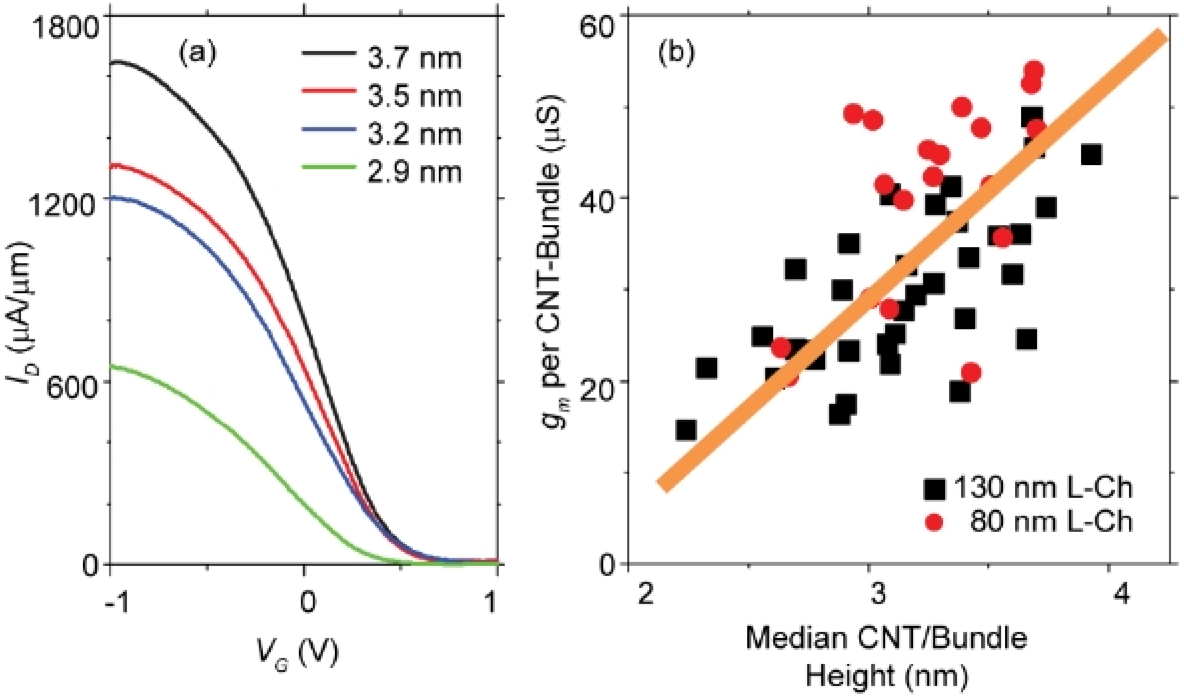
3. Sol'n Process Invented in the US: Wisconsin/SixLine New Effort

- Add order to solution purified CNTs
- Tangential Flow Interfacial Self-Assembly (TaFISA)



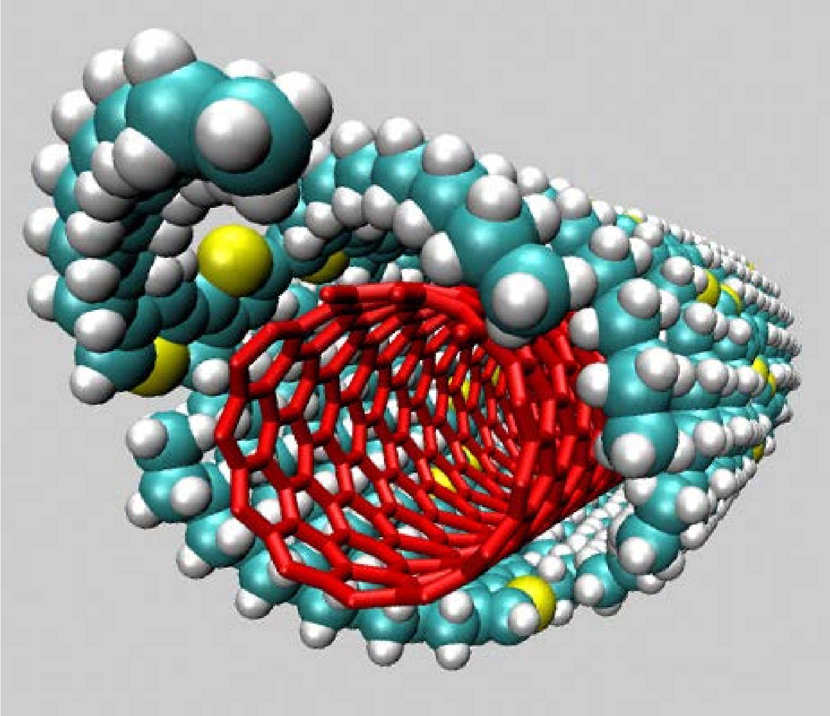
APL (2014); ACS Nano (2014); Science Advances (2016); JAP (2017); JAP (2020); Science Advances (2021).





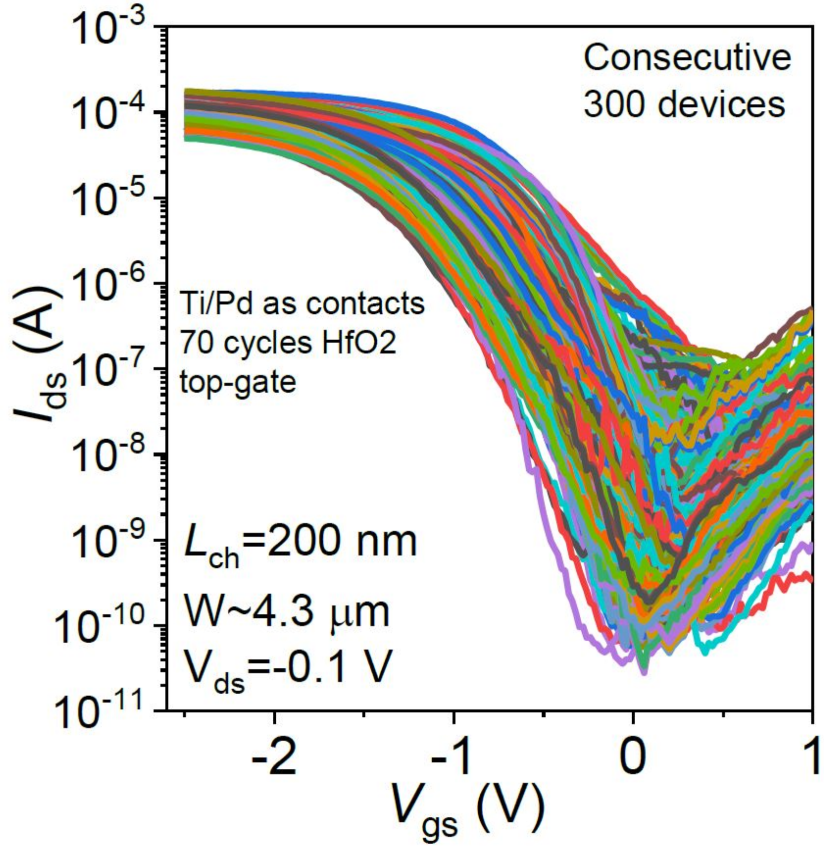
3. Solution Processed CNTs: China Leading

Hysteresis + Wide Performance Distribution



Cartoon cross-section of polymer-coated (blue) carbon nanotube (red) required for solution processing. **Will you ever get the O2 off without "rusting" a CNT?**

Tsuyohiko Fujigaya and Naotoshi Nakashima 2015 *Sci. Technol. Adv. Mater.* **16** 024802



Distribution of 300 state of the art solution processed CNTFETs

Liu et al., Science 368, 850–856 (2020)

OPINION
GUEST ESSAY

How China Is Fighting the Chip War With America

Oct. 27, 2022

A member of security staff inside the Great Hall of the People in Beijing on Sunday. Noel Celis/Agence France-Presse, via Getty Images

The NY Times Gets It:
“Chip materials like silicon may be swapped for new-generation [materials].”

CARBON TECHNOLOGY INC

3. Best Recent Publications are out of China: CNTs are >7x Better for Digital/RF; 15x more Rad Hard

Science

Aligned, high-density semiconducting carbon nanotube arrays for high-performance electronics

Lijun Liu[1*], Jie Han[1*], Lin Xu[1], Jianshuo Zhou[1], Chenyi Zhao[1], Sujuan Ding[2,3], Huiwen Shi[1], Mengmeng Xiao[1], Li Ding[1], Ze Ma[1], Chuanhong Jin[2,3], Zhiyong Zhang[1,2,4]†, Lian-Mao Peng[1,2,4]†

Single-walled carbon nanotubes (CNTs) may enable the fabrication of integrated circuits smaller than 10 nanometers, but this would require scalable production of dense and electronically pure semiconducting nanotube arrays on wafers. We developed a multiple dispersion and sorting process that resulted in extremely high semiconducting purity and a dimension-limited self-alignment (DLSA) procedure for preparing well-aligned CNT arrays (within alignment of 9 degrees) with a tunable density of 100 to 200 CNTs per micrometer on a 10-centimeter silicon wafer. Top-gate field-effect transistors (FETs) fabricated on the CNT array show better performance than that of commercial silicon metal oxide–semiconductor FETs with similar gate length, in particular an on-state current of 1.3 milliamperes per micrometer and a recorded transconductance of 0.9 millisiemens per micrometer for a power supply of 1 volt, while maintaining a low room-temperature subthreshold swing of <90 millivolts per decade using an ionic-liquid gate. Batch-fabricated top-gate five-stage ring oscillators exhibited a highest maximum oscillating frequency of >8 gigahertz.

Liu et al., Science 368, 850–856 (2020) 22 May 2020

ACS APPLIED MATERIALS & INTERFACES

www.acsami.org Research Article

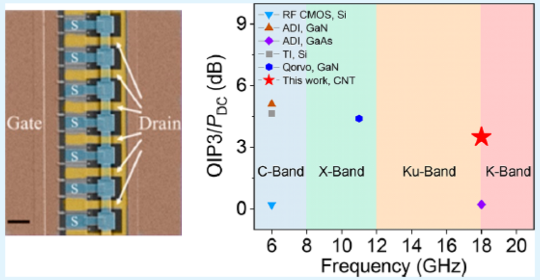
Carbon Nanotube Based Radio Frequency Transistors for K-Band Amplifiers

Jianshuo Zhou, Lijun Liu, Huiwen Shi, Maguang Zhu, Xiaohan Cheng, Li Ren, Li Ding,* Lian-Mao Peng, and Zhiyong Zhang*

Cite This: https://doi.org/10.1021/acsami.1c07782 Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information

ABSTRACT: Owing to the combination of high carrier mobility and saturation velocity, low intrinsic capacitance, and excellent stability, the carbon nanotube (CNT) has been considered as a perfect semiconductor to construct radio frequency (RF) field-effect transistors (FETs) and circuits with an ultrahigh frequency band. However, the reported CNT RF FETs usually exhibited poor real performance indicated by the as-measured maximum oscillation frequency (f_{max}), and then the amplifiers, which are the most important and fundamental RF circuits, suffered from a low power gain and a low frequency band. In this work, we build RF transistors on solution-derived randomly orientated CNT films with improved quality and uniformity. The randomly orientated



nature electronics ARTICLES

https://doi.org/10.1038/s41928-020-0465-1

Check for updates

Radiation-hardened and repairable integrated circuits based on carbon nanotube transistors with ion gel gates

Maguang Zhu[1,2,7], Hongshan Xiao[1,3,4,7], Gangping Yan[5], Pengkun Sun[1], Jianhua Jiang[5], Zheng Cui[3], Jianwen Zhao[3]✉, Zhiyong Zhang[1,6]✉ and Lian-Mao Peng[1,2,6]✉

Electronics devices that operate in outer space and nuclear reactors require radiation-hardened transistors. However, high-energy radiation can damage the channel, gate oxide and substrate of a field-effect transistor (FET), and redesigning all vulnerable parts to make them more resistant to total ionizing dose irradiation has proved challenging. Here, we report a radiation-hardened FET that uses semiconducting carbon nanotubes as the channel material, an ion gel as the gate and polyimide as the substrate. The FETs exhibit a radiation tolerance of up to 15 Mrad at a dose rate of 66.7 rad s^{-1}, which is notably higher than the tolerance of silicon-based transistors (1 Mrad). The devices can also be used to make complementary metal-

3. And out of China on 3/31/2023

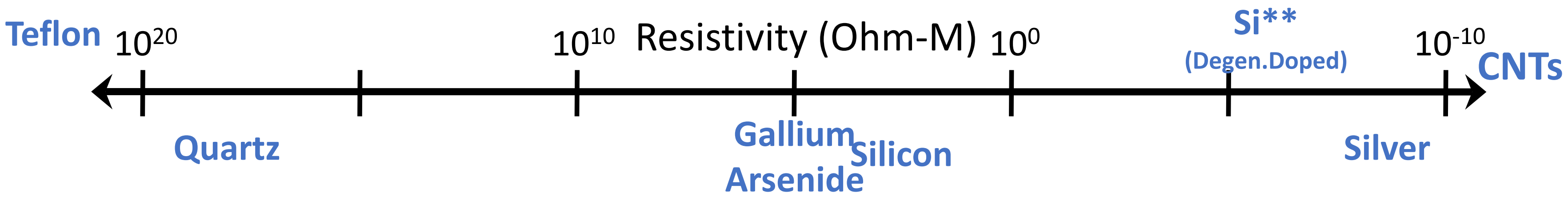
Research Square

Preprints are preliminary reports that have not undergone peer review. They should not be considered conclusive, used to inform clinical practice, or referenced by the media as validated information.

Terahertz metal-oxide-semiconductor transistors based on aligned carbon nanotube arrays

Zhiyong Zhang (zyzhang@pku.edu.cn)
Peking University https://orcid.org/0000-0003-1622-3447
Jianshuo Zhou
Peking University
Li Ding
Peking University https://orcid.org/0000-0003-4310-9957
Lin Xu
Peking University https://orcid.org/0000-0003-1781-1638
Xiaohan Cheng
Peking University

Back to Why CNTs: "A Switchable Super Metal*"



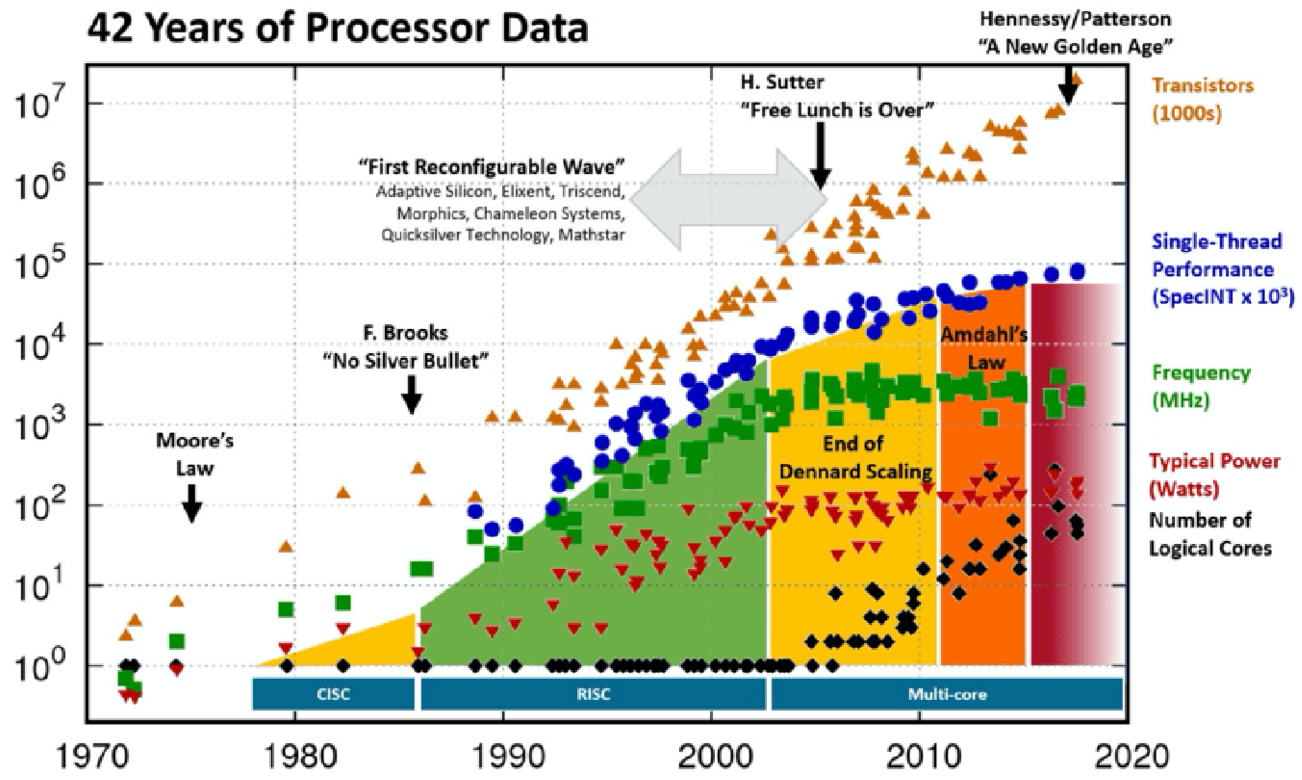
Sensors
- Capable of single molecule chemical sensing
- DNA wrapping for bio-particular sensing

RF
- Highest mobility (>100x doped Si): THz capable
- Intrinsically linear: More data with less spectrum and energy

Digital
- On SiO2, >7x the speed for power of Si CMOS;

*The size of an atom to the universe is ~37 orders of magnitude. Conduction ranges across ~33 orders.
Current semis, even when degenerately doped**, are really crappy conductors. CNTs are better than any metal

The Si Party is ~Over



Dennard's Law: Power = αCFV^2

α—switching % C—Capacitance

F—Frequency V—Voltage

Digital Metric: switches/(s x J x area)

- Si <~5 GHz—Dennard scaling ended 20 years ago
- We now mfg dark and brown Si—can't get rid of the heat
- Moore's cost reduction law is coming to an end ("2nm" transistors are 40nm on a side)

WHAT TO DO?

- Reduce resistance
- Reduce capacitance
- Increase electron mobility
- Increase thermal conductivity

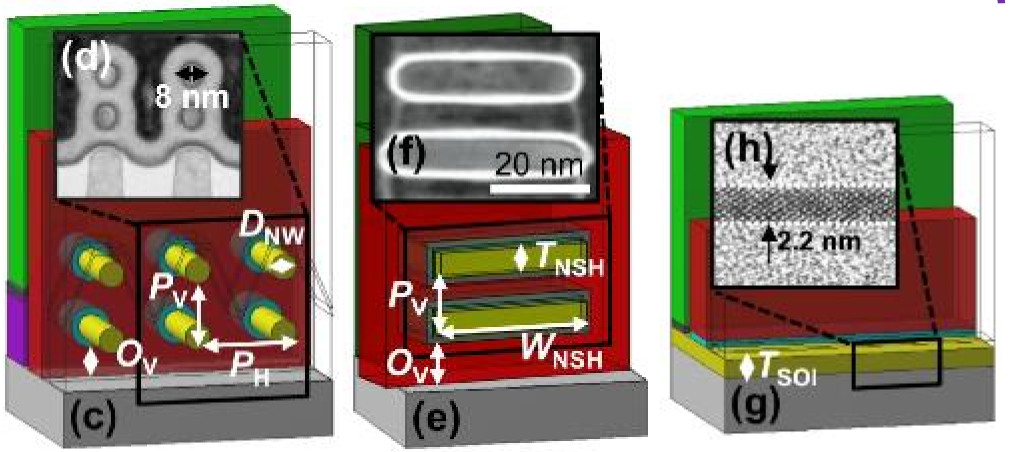
HOW?

- Stop Pounding Sand. Carbon will give us 10-1000x

Hennessy and Patterson, https://www.karlrupp.net/2018/02/42-years-of-microprocessor-trend-data/

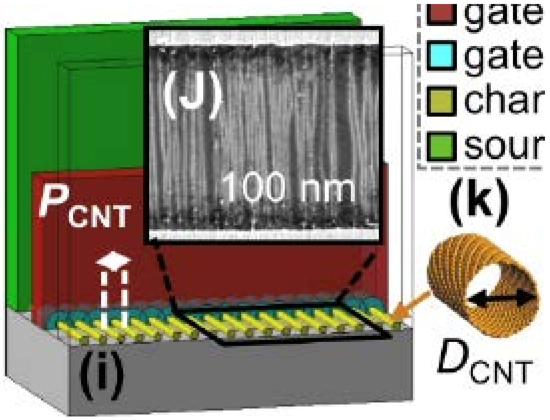
From EES2 we know that Si is not enough

2X Improvement (Not Enough)



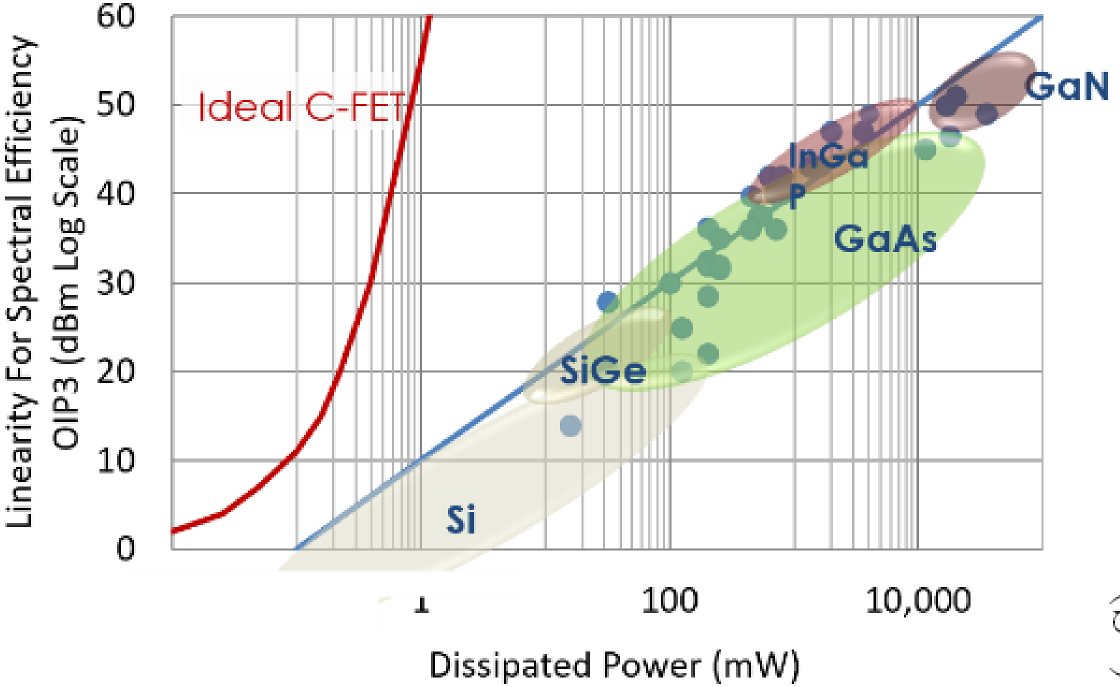
NanoWire **Nanosheet** **Ex Thin SOI**

9X Improvement on Si with current metals
>>9x on with substrates and metals

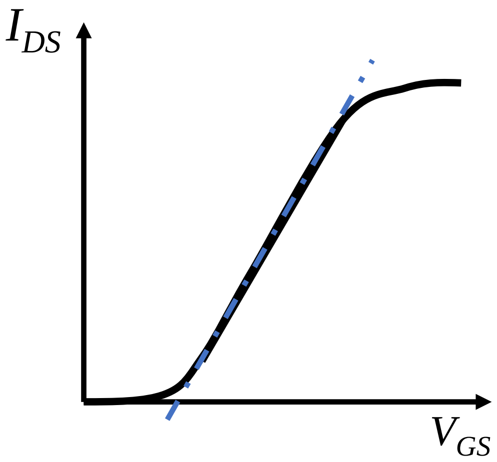


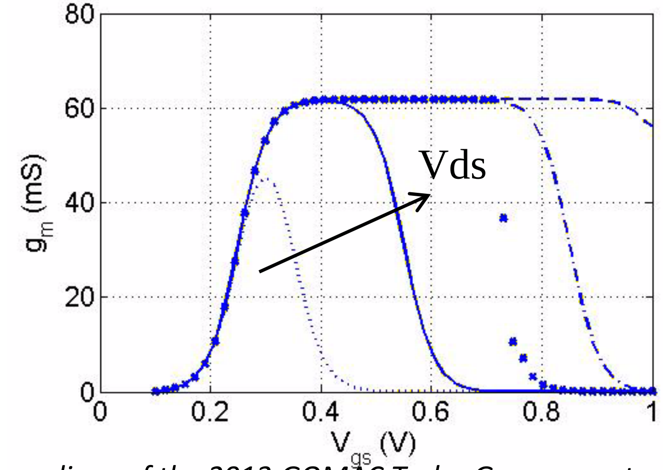
Carbon Nanotubes ("CNTs")

Intrinsically Linear CNTFETs: Dramatically Reduce Comms Power Use

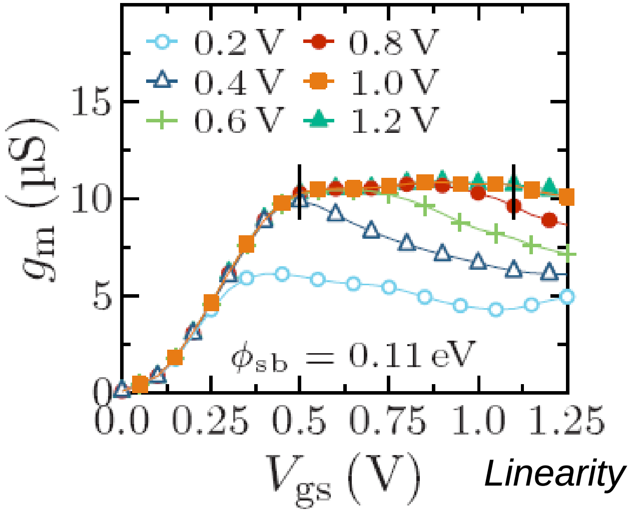


J. Baumgardner, et al, Appl. Phys Lett. **91**, 052107 (2007)

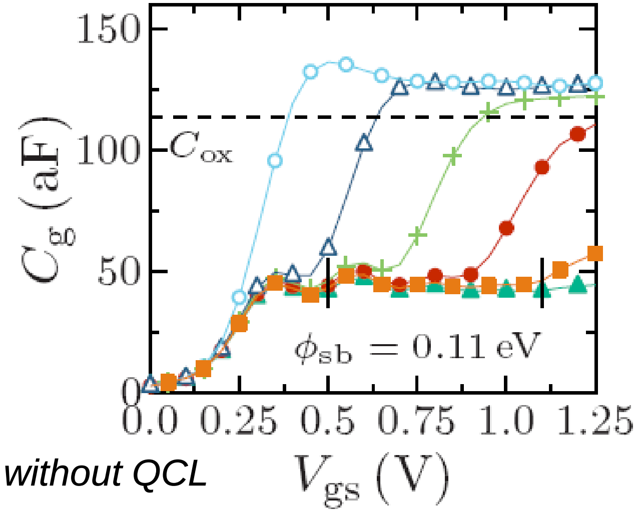




M. Schroter, M. Haferlach, D. Wang, Proceedings of the 2013 GOMAC Tech - Government Microcircuit Applications and Critical Technology Conference, (2013)

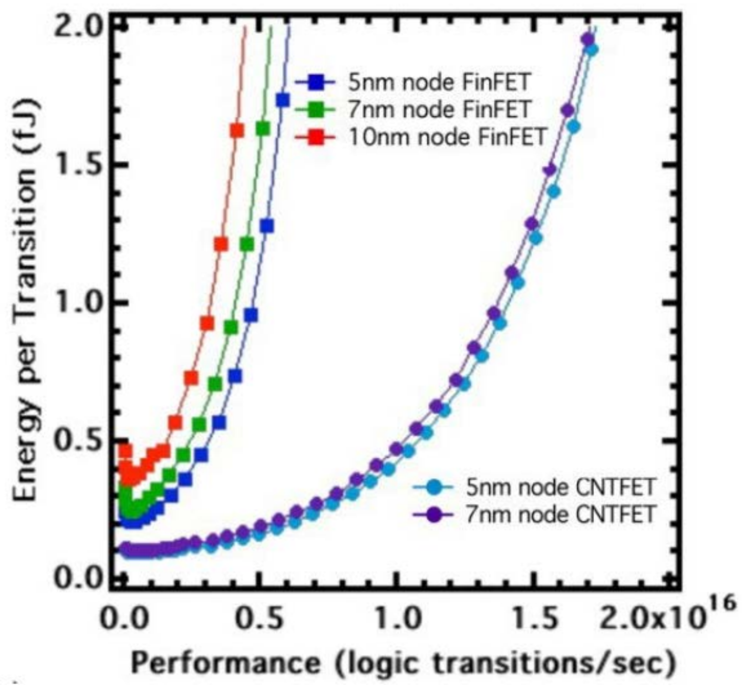


Linearity without QCL



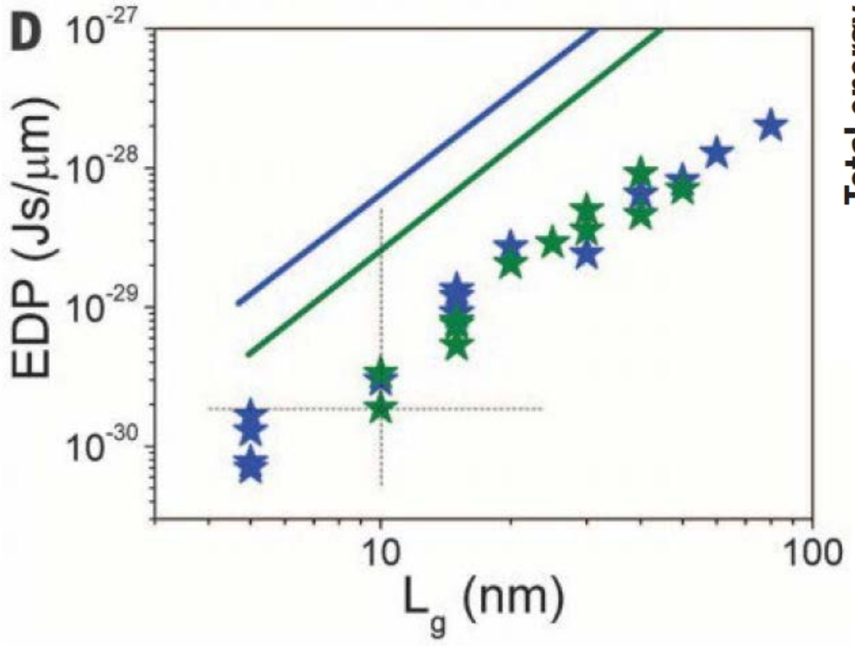
S. Mothes, M. Claus and M. Schröter, IEEE Transactions on Nanotechnology, **14**, 372 (2015)

CNTFETs for Digital (from a sub monolayer of carbon)



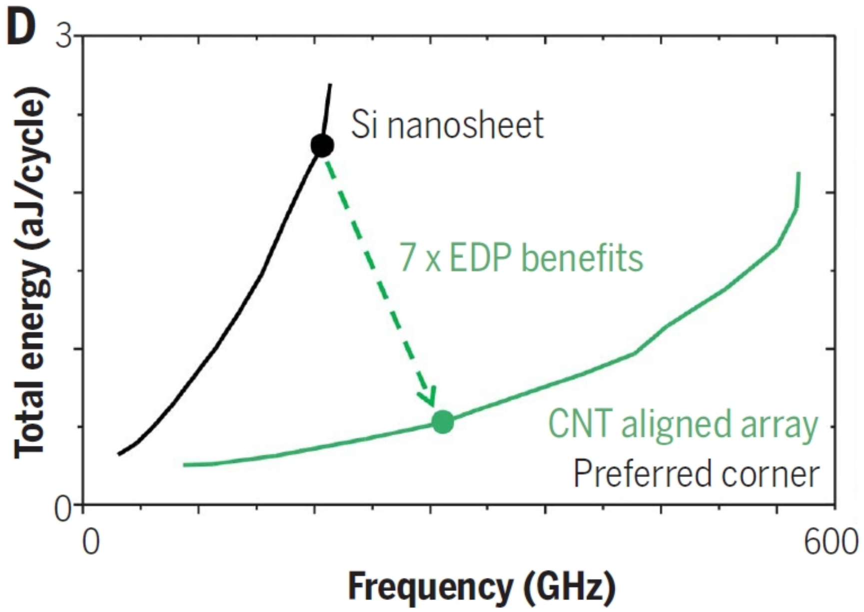
Tulevski, et al (IBM) 2014 – 5x better than 7nm FinFET

2.5x better than 3nm GAA



Qui, et al (Peking) 2017 – 10x better than 5nm FinFET

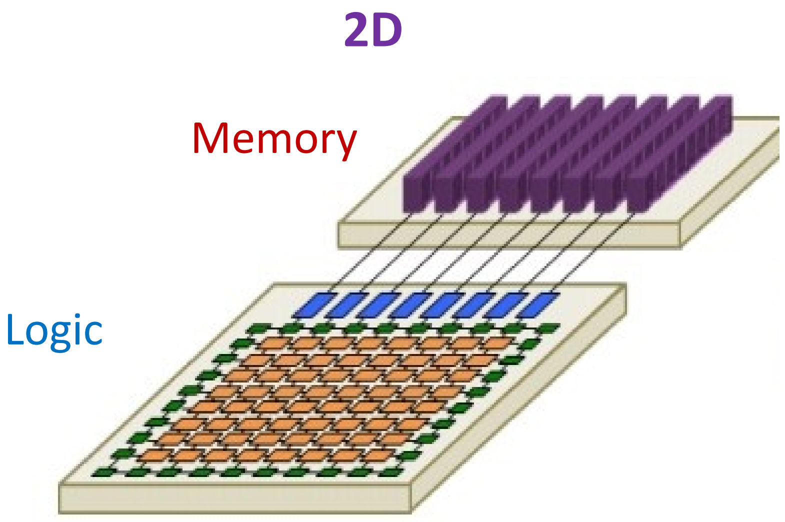
4x better than 3nm GAA

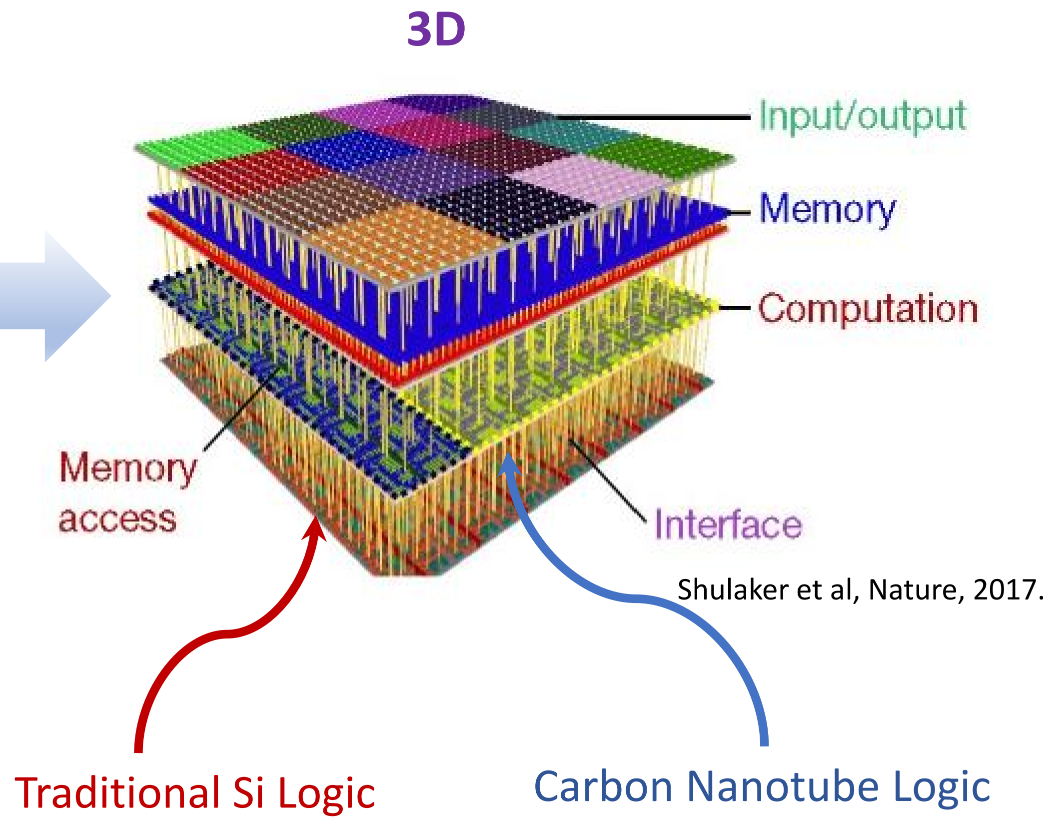


Franklin, Hersham, Wong 2022

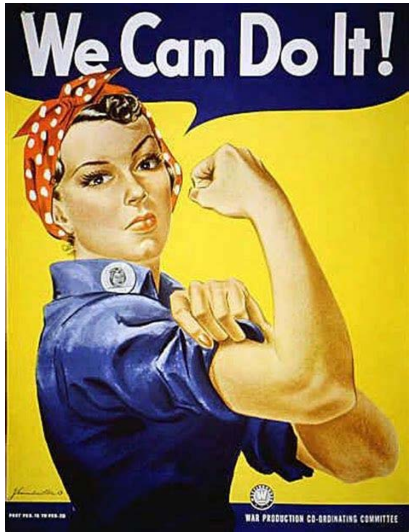
7x better than 2nm GAA

Digital CNTFETs on Si Can Deliver EES2's Goal





Shulaker et al, Nature, 2017.



CNTs + Si: 1000x Performance Improvement
More Carbon + Algos & Circuits: We Will Beat 1000x

Invest in CNT Material

1. Aligned Carbon: CVD Grow and Remove Metallic Tubes
    1. CNT density
    2. Demonstrate high semiconducting:metallic ratio
2. Carbon Tech: Selectively Grow Diameter Controlled Semi CNTs
    1. Demonstrate high semiconducting:metallic ratio
    2. Alignment
3. SixLine/Nantero*: Solution process and deposit
    1. Lack of order/defects
    2. Short CNTs (~1 µm)
    3. Polymer contamination (for ultracentrifuged tubes)

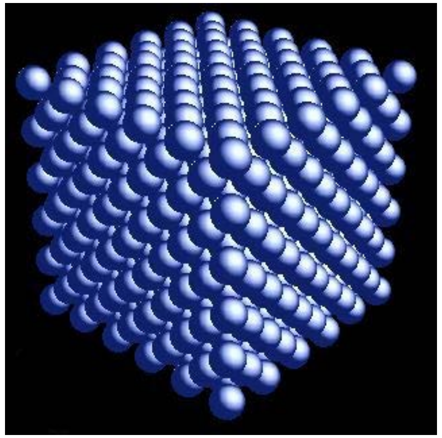
*We did not discuss this with them. Our goal is to promote CNT investment

Backup or extra charts

CNTs are Fundamentally Different

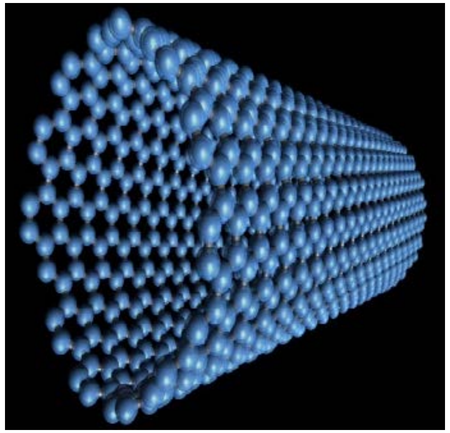
They're Hollow: Current/Atom: <u>2.6 million</u> x Copper

2×10^{-13} Amps/atom

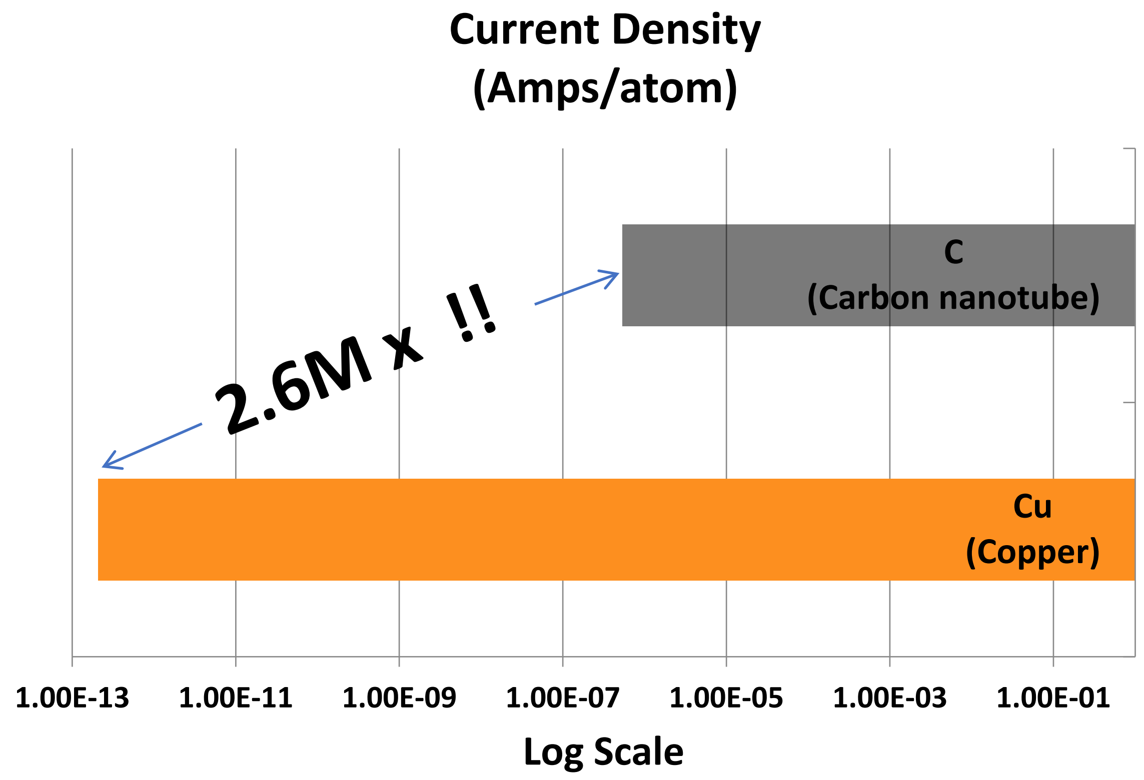


29
Cu
Copper

5×10^{-7} Amps/atom

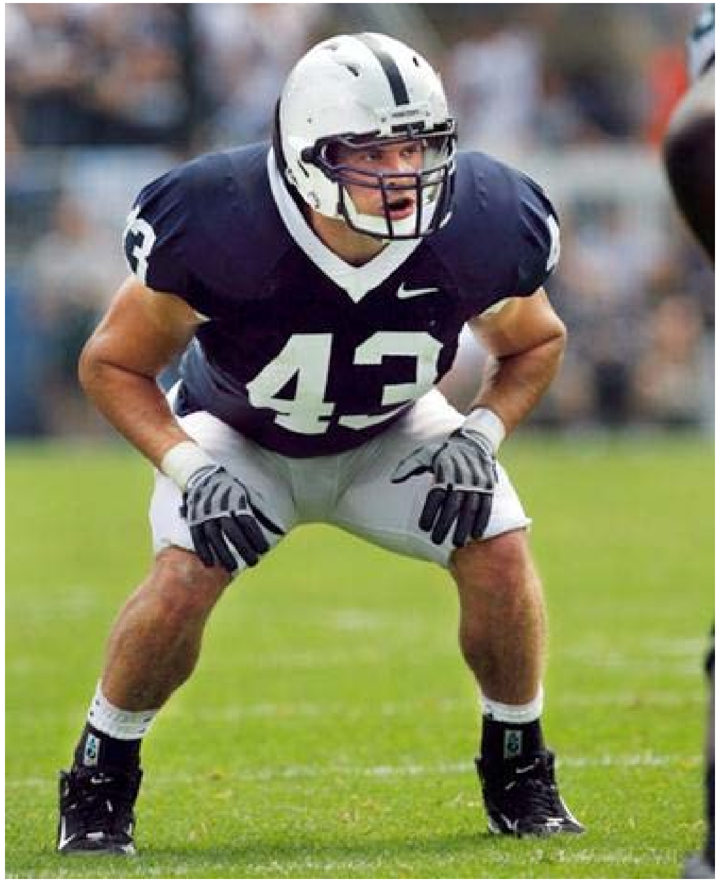


6
C
Carbon



Carbon is Light: Current/mass: <u>14 million x</u> Copper

250lbs of Copper

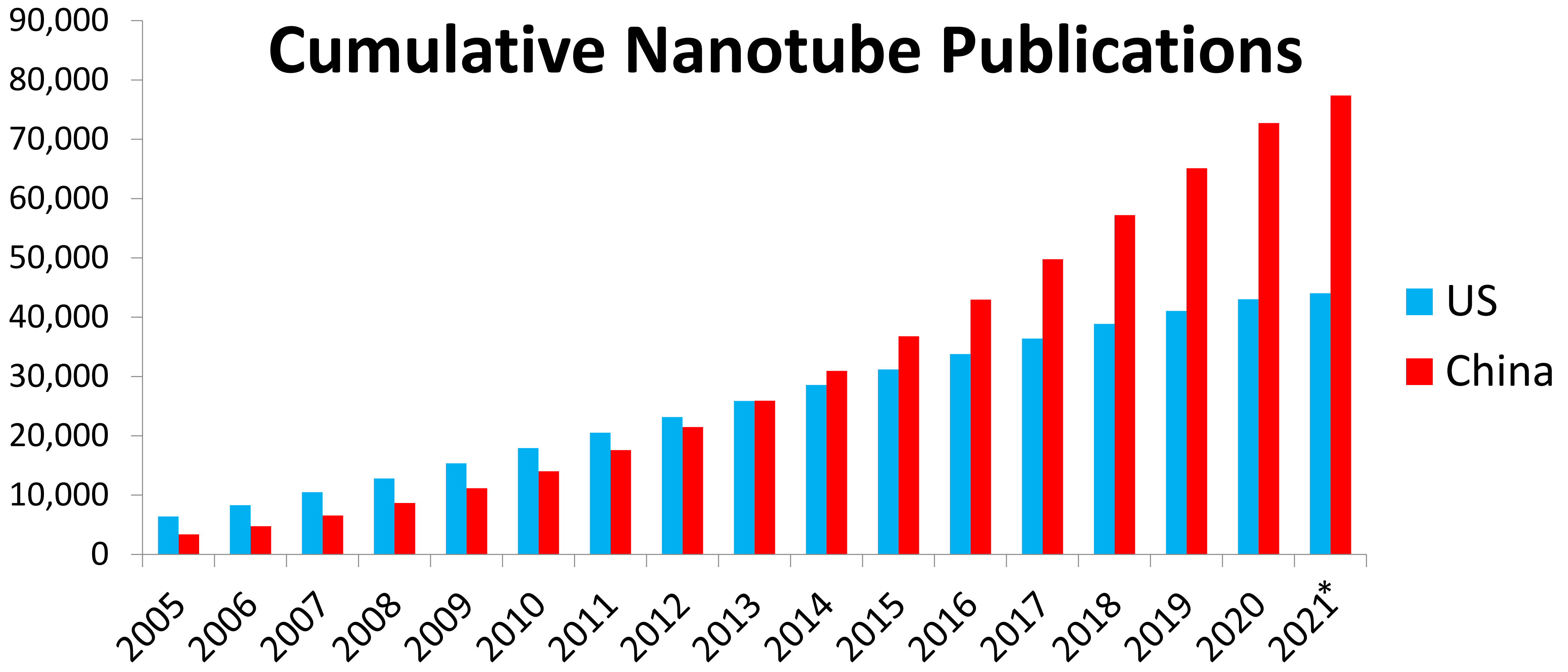


0.0003 ounces of Carbon Nanotube

Same Current Carrying Capacity

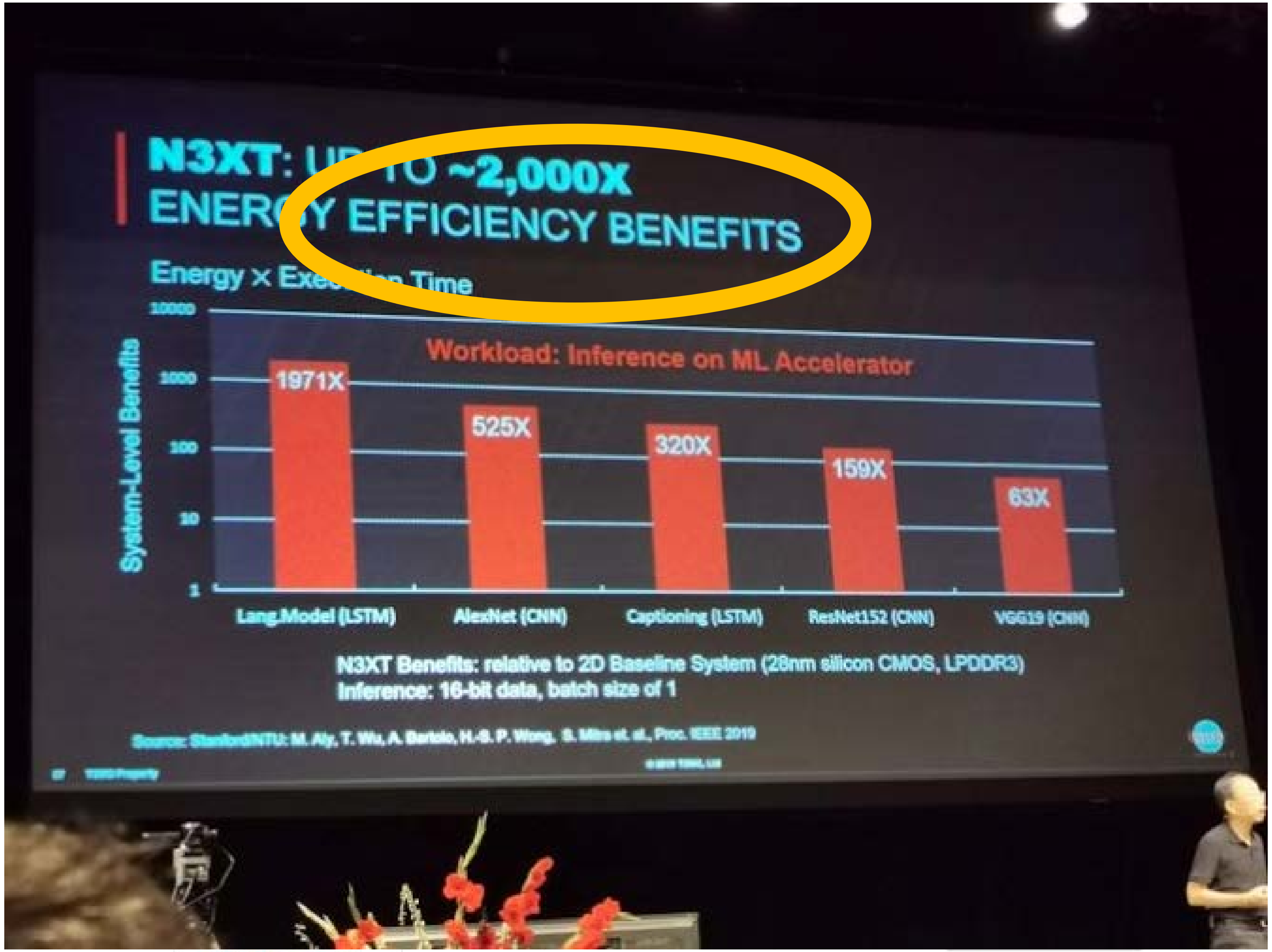
For Si, you would need a ~stadium of material to carry as much current

The Chinese Communist Party is Now Investing a Lot More in CNTs than the US



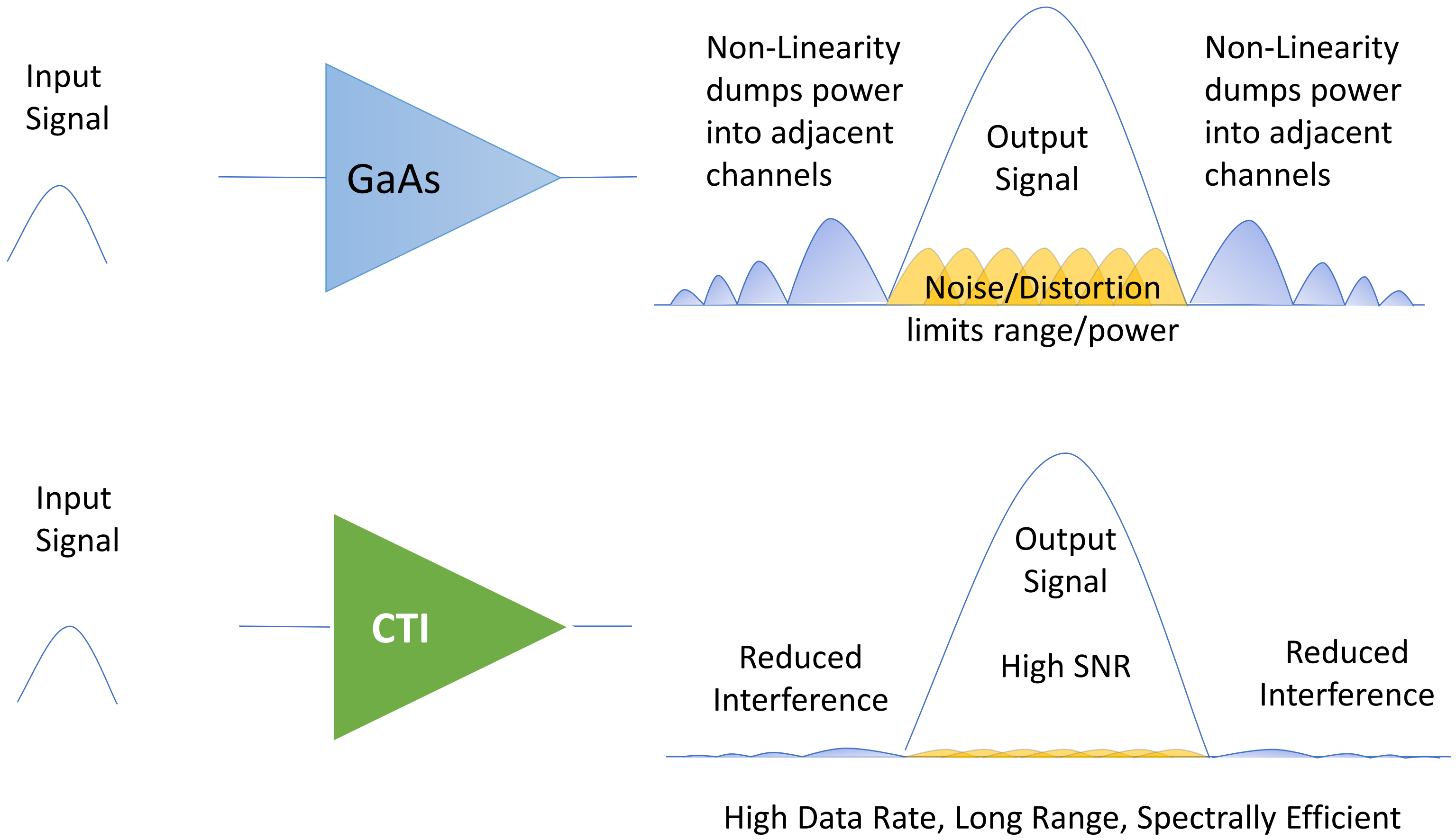
* Through 9/14/2021
Source: Webofscience.com

TSMC: Confirming that 1000x at the Chip Level



Comms Needs Linearity

Non-linearity Destroys Data Dense Modulation and Pollutes Adjacent Bands



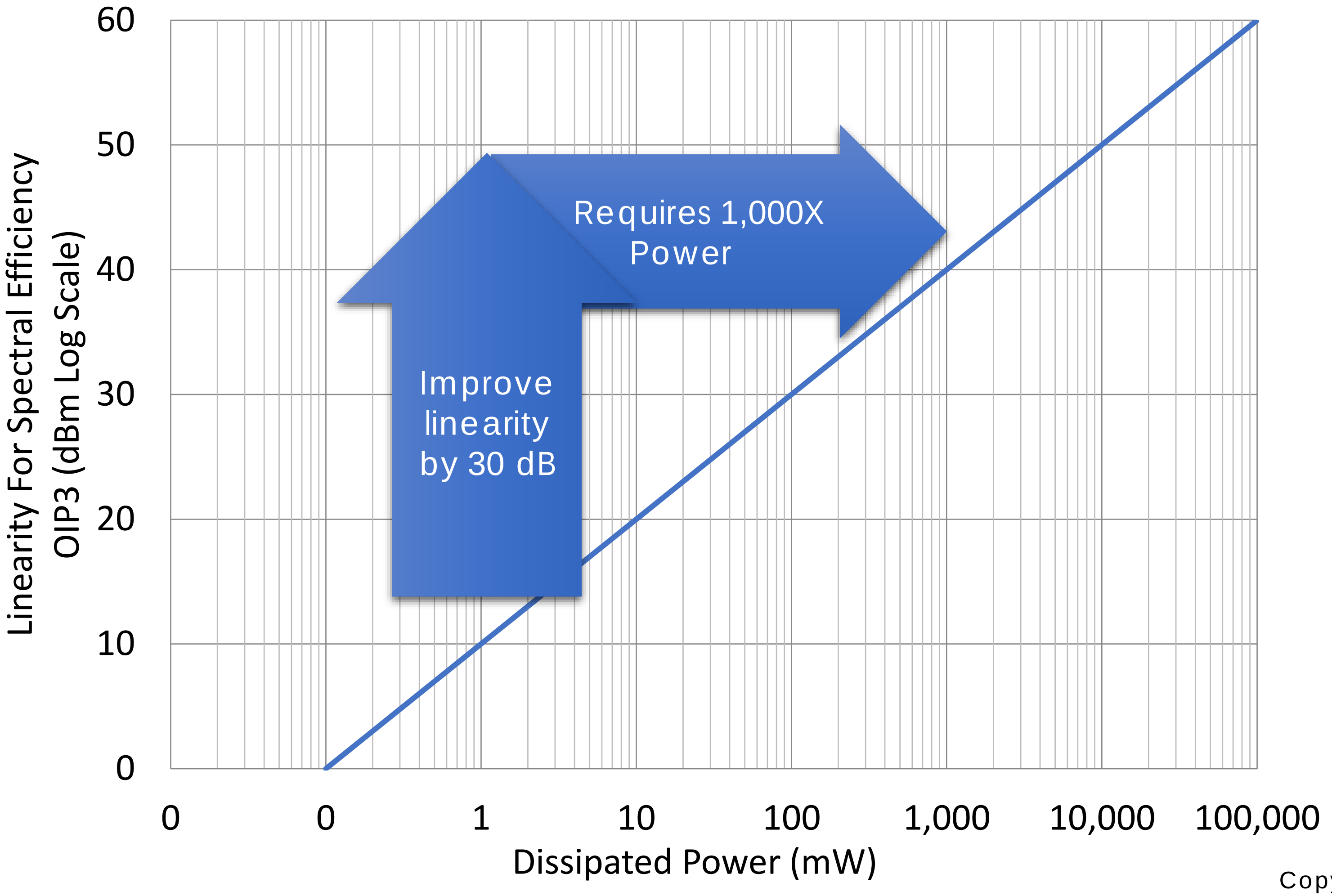
- Mobile data growth remains rapid
- 5G needs ~$1 trillion in basestations and spectrum
- CTI's Linear CNTFETs will save $100billions

Current Comms Semis Burn Power to Deliver Linearity/Data

Bulk Semi Rule of thumb

$OIP3 = P_{diss} + 10dBm$

OIP3 = output third order intercept linearity measure



CARBON TECHNOLOGY INC

Graphene and Nanotube Folding

Aligned Carbon