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Toward Carbon Nanotube Based Thermal Interface Materials

C. Rochford, S. J. Limmer, S. W. Howell, T. E. Beechem, M. P. Siegal,
Sandia National Laboratories, Albuquerque, NM

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Motivation

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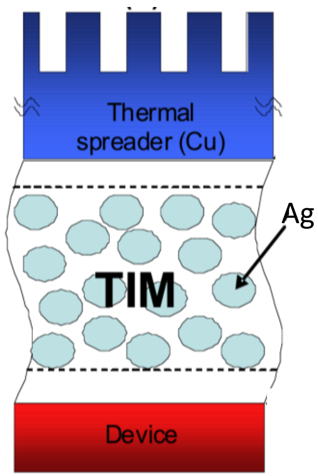
Removing heat generated by high-power electronics is often the limiting factor in system performance

Traditional TIM (e.g. Ag paste)



Thermal conductivity

Ag	420 W/m•K
Cu	401 W/m•K
Al	237 W/m•K
Au	317 W/m•K
Si	148 W/m•K
In	82 W/m•K
Epoxy	0.23 W/m•K

Unfortunately, the thermal conductivity of metal-filled epoxies are dominated by percolation through the epoxy, resulting in values ≈ 1 W/m•K*.

*** From commercial data sheets**

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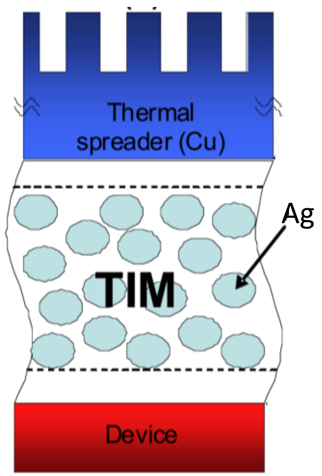

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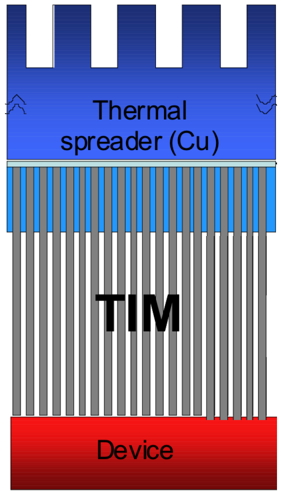
CNT-based TIM



Thermal conductivity

CNTs	10-3000 W/m•K

Eliminate the epoxy

TIM performance is only as good as the CNTs in the array

It should be possible to improve TIM performance by multiple orders-of-magnitude

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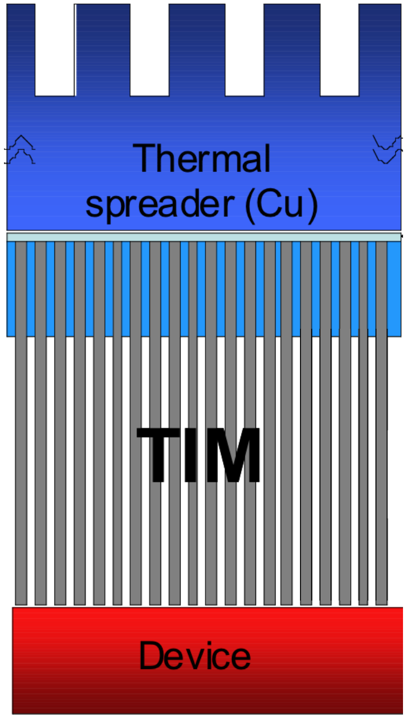
An ideal CNT-based TIM



Desired Properties:

High density aligned array
Increase the number of thermal pathways

High quality CNTs with good thermal conductivity
Decrease phonon scattering

Good thermal contact to heat sink
Eliminate the thermal bottleneck of the adhesive

Good thermal contact to the hot device
Maximize heat transfer to the TIM

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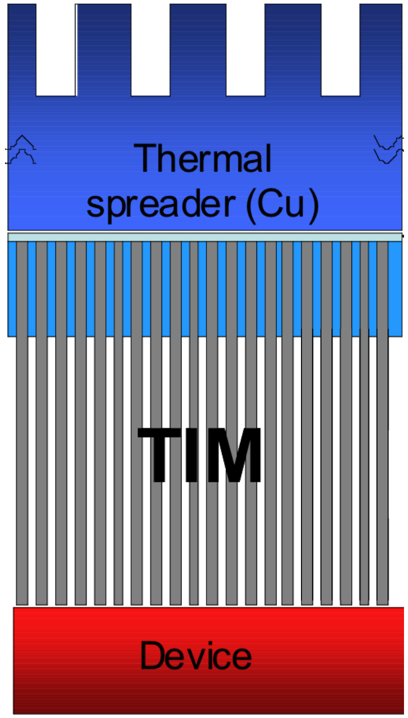

Desired Properties:	We Will Achieve By:
High density aligned array *Increase the number of thermal pathways*	**Growth of CNTs in nanopore template**
High quality CNTs with good thermal conductivity *Decrease phonon scattering*	**Thermal chemical vapor deposition**
Good thermal contact to heat sink *Eliminate the thermal bottleneck of the adhesive*	**Growth directly on heat sink material**
Good thermal contact to the hot device *Maximize heat transfer to the TIM*	**Untangled CNTs that are planarized to uniform heights**

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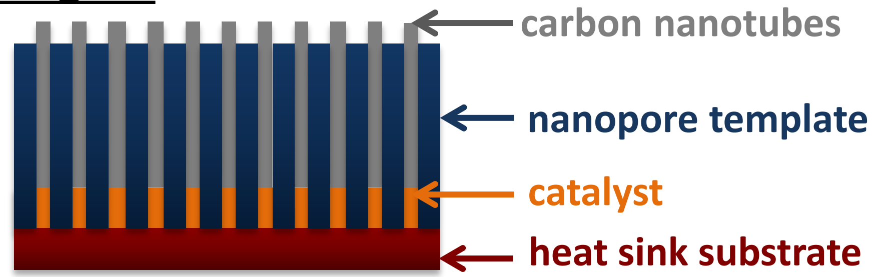
Template formation

The goal:



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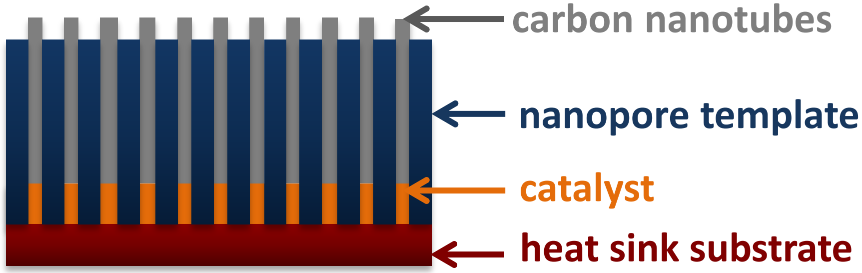
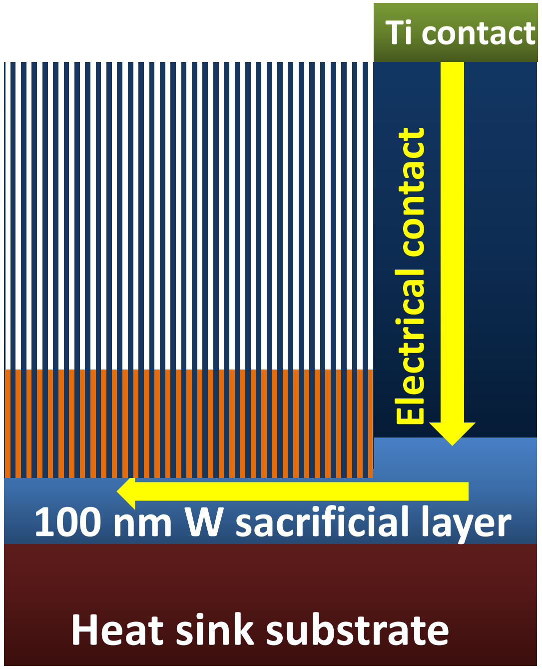
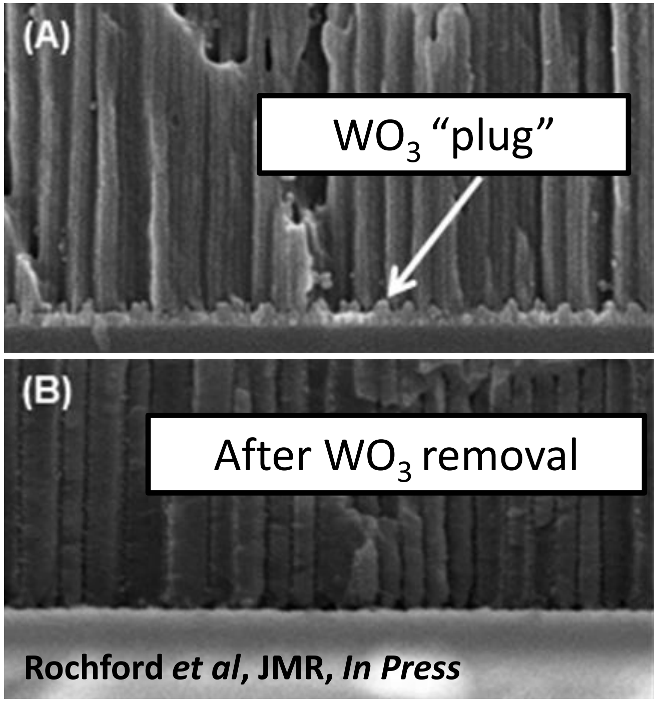


Starting material: **Anodized aluminum oxide (AAO) nanopore templates on substrates**



A sacrificial W "valve" layer oxidizes partially through during anodization. The WO_3 is selectively removed to leave a conductive W layer at the pore bottoms. This facilitates catalyst electrodeposition, even on insulating substrates



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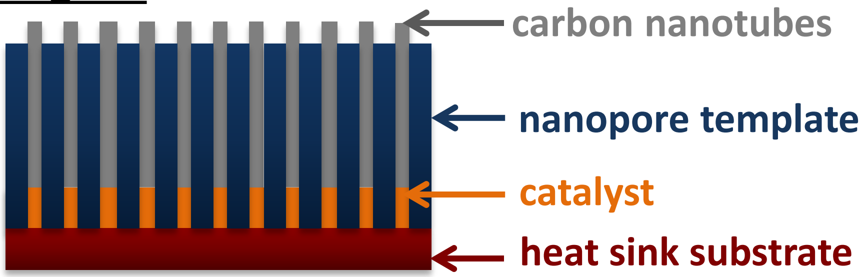
Catalyst deposition inside pores

The goal:

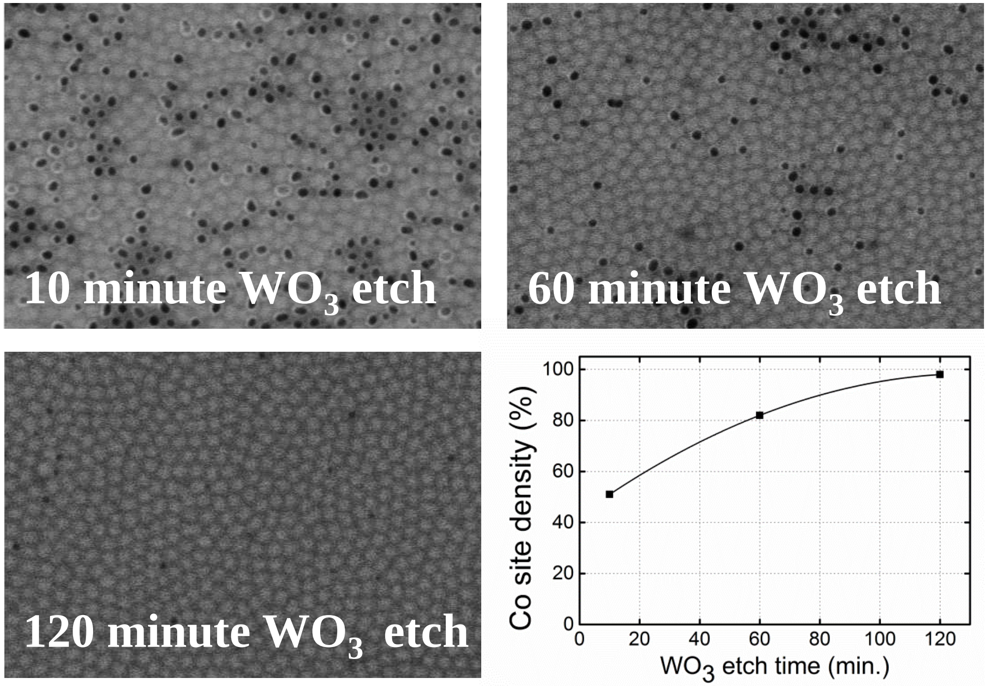


Catalyst for CNT growth: electrodeposited Co nanowires inside AAO pores

Nanotubes will only grow from catalyst-filled pores

Samples are ion milled so AAO and Co are flush to expose Co in pores

Controlling the duration of the WO_3 etch step controls the catalyst site density



Rochford *et al*, JMR, *In Press*

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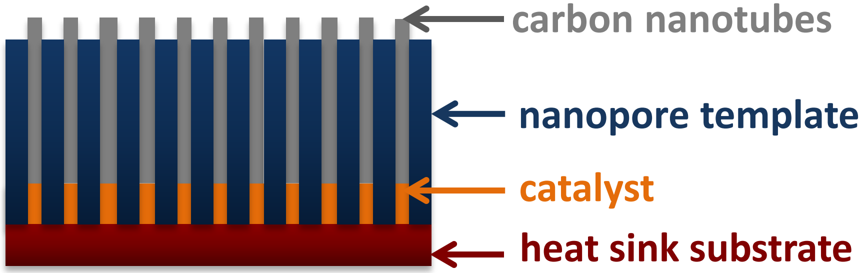
Nanotube growth

The goal:



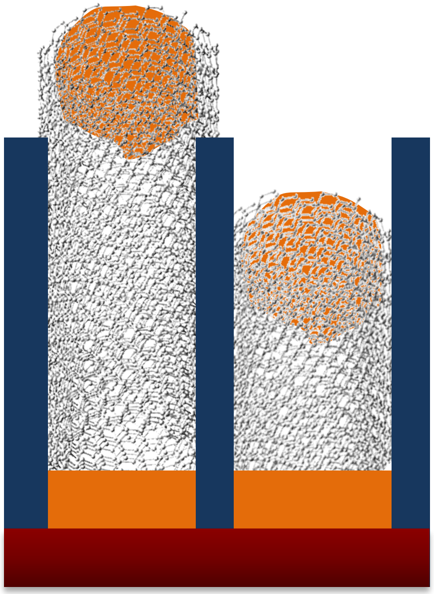
The process:

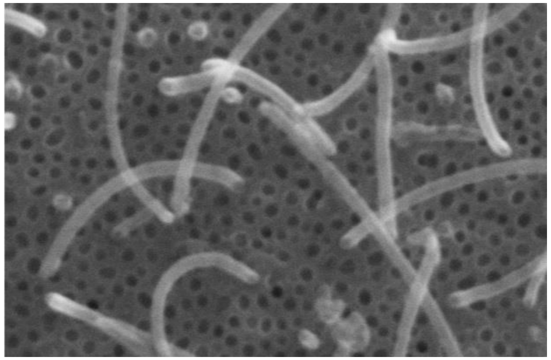
- Chemical vapor deposition
- Atmospheric pressure mix of C_2H_2, H_2, N_2
- Temperature between 450°C - 650°C

The catch:

AAO catalyzes the decomposition of C_2H_2 to conformally deposit amorphous carbon on the AAO

Amorphous carbon deposition can block emergence of CNTs from the pores





The aspect ratio of the open pore is the critical parameter

A factor of 2 can drop density by 2 orders of magnitude

Nanotube must get out of pore before a-C blocks the uplift or deactivates the catalyst

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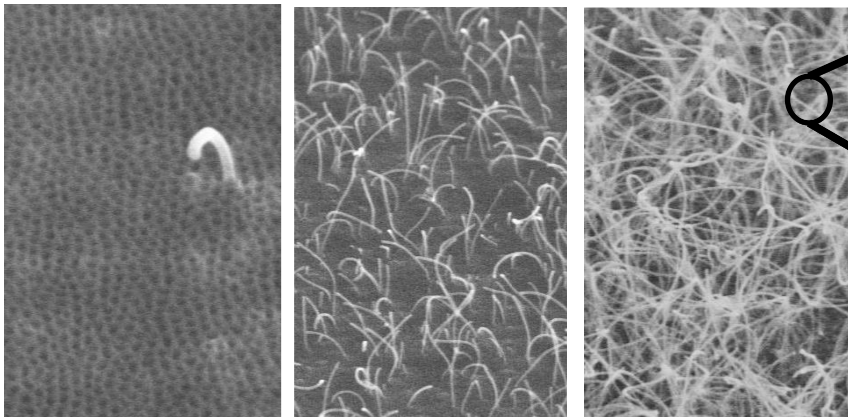
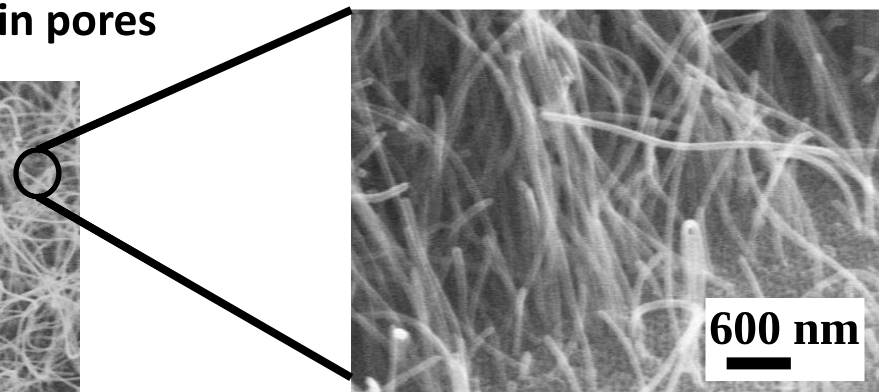
Nanotube growth

Nanotube density varies with Co height in pores





MWNTs emerge from pores straight & vertical

<u>Difficulty controlling Co height:</u>

- Co must be within ~ 750 nm of the pore opening for MWNTs to emerge from at least 1% of pores
- Small percentage of pores deposit Co rapidly and overplate with long depositions
- Thinner AAO templates crack with MWNT growth

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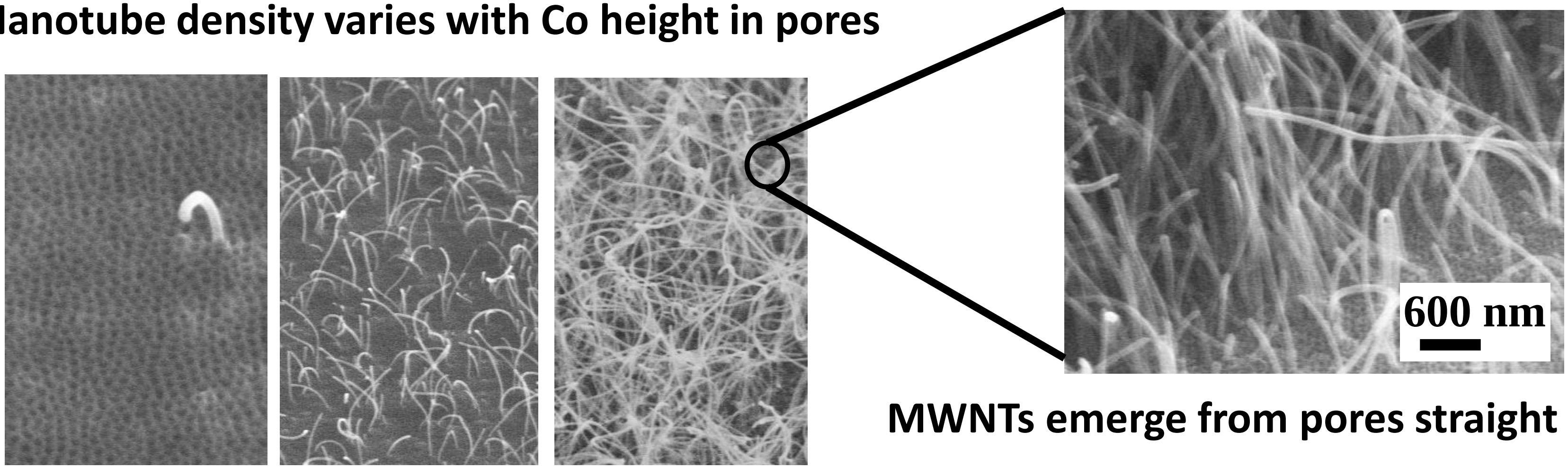

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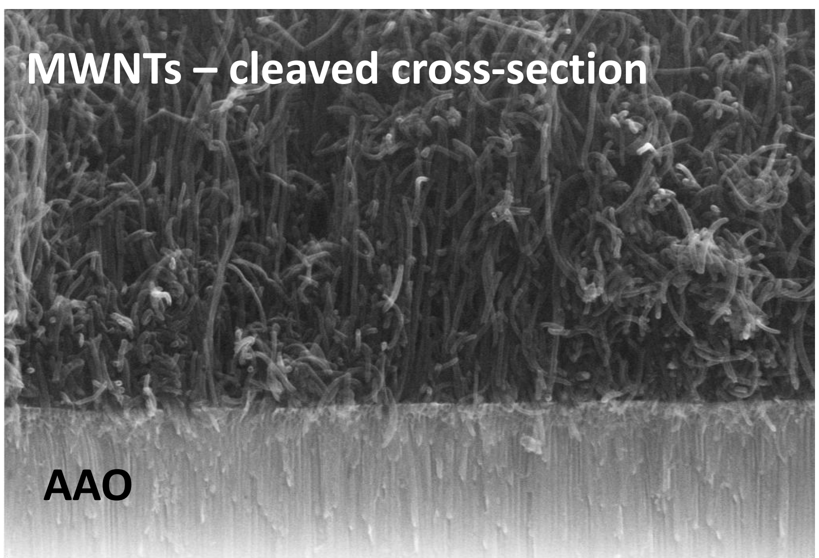

Alternate approach:

- **Allow Co to overplate**
- **Polish to remove excess Co**
- **Chemically etch back to desired depth**

Nanotube growth

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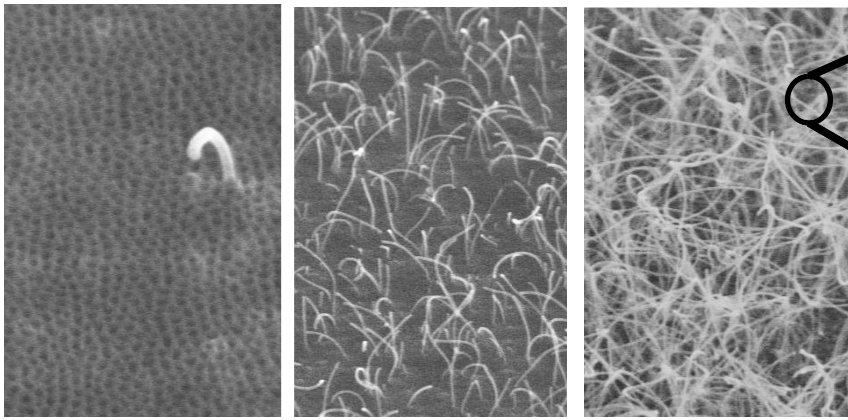
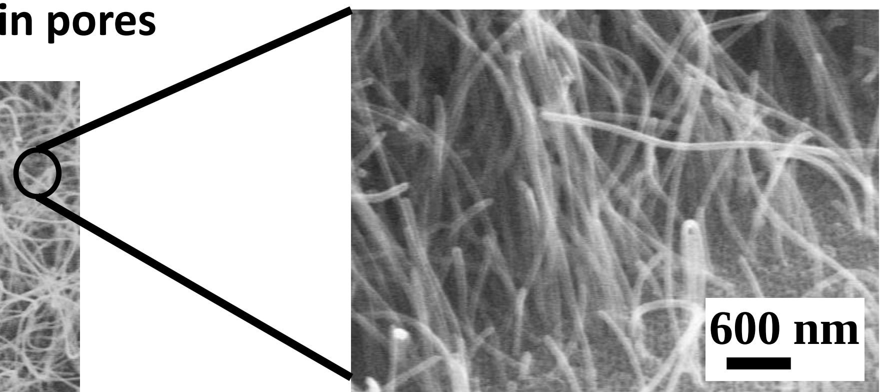
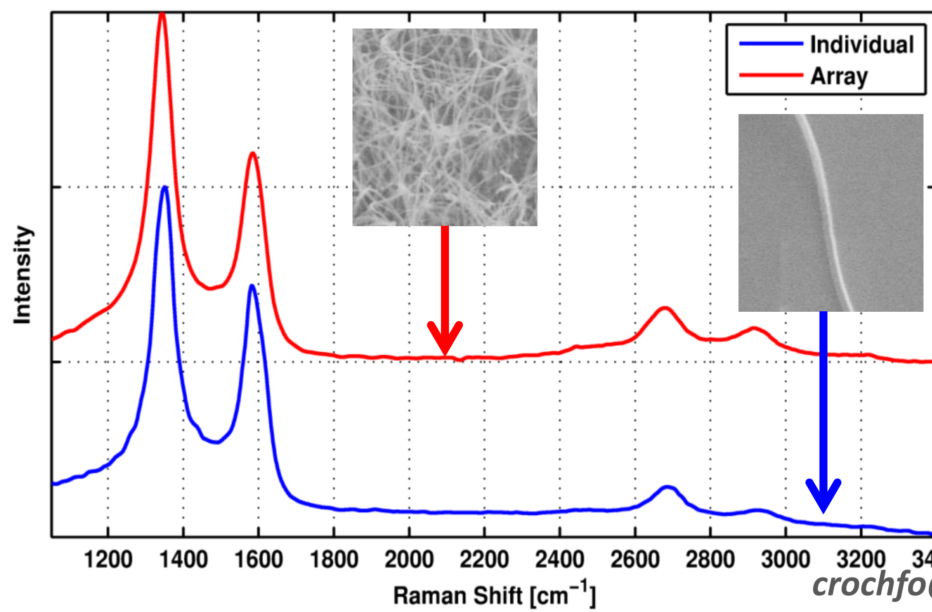
Nanotube density varies with Co height in pores





MWNTs emerge from pores straight & vertical

- *Little variation between MWNTs*
- *I(D)/I(G) of 1.9 implies moderate disorder*
- *Consistent with non-graphitized CVD-grown MWNTs*



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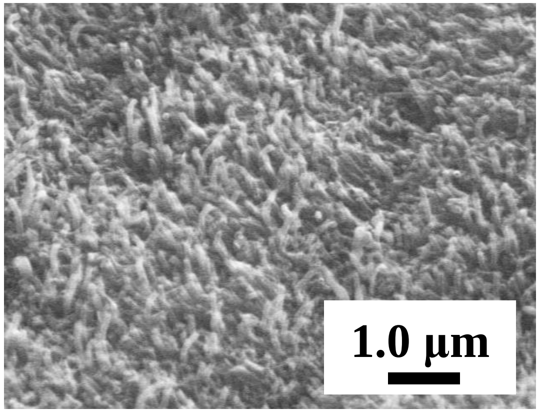
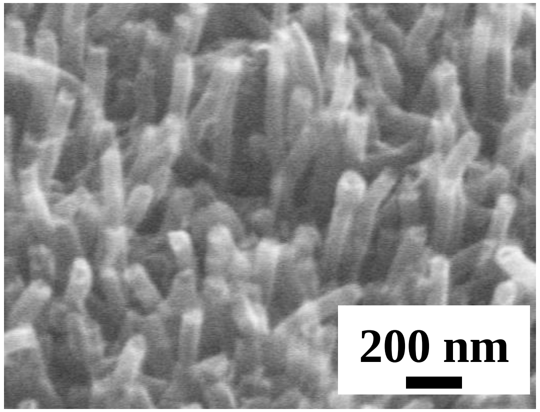
Array planarization

MWNTs of the same height are desired for contact to the hot die

Achieved with ultrasonication in solution. MWNTs cut to fairly uniform heights above the AAO

***Critical point drying can eliminate clumping**





Nanotubes are like cantilevers. Stress caused by vibration is largest near the pore mouth.

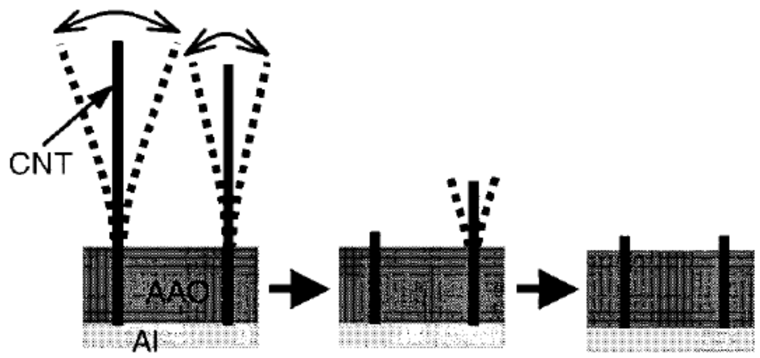


Figure 5. Schematic of the cutting sequence of the CNTs during sonication.

S-H Jeong *et al* Chem. Mater. 14, 1859 (2002)

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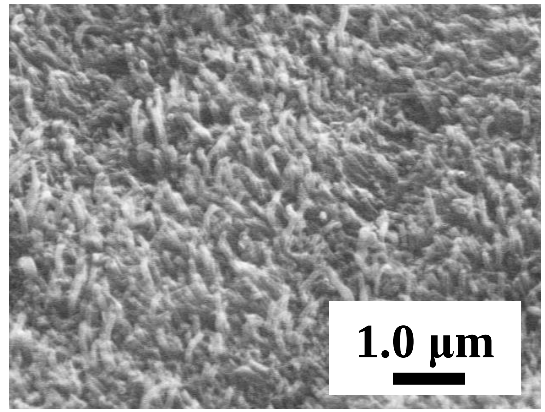
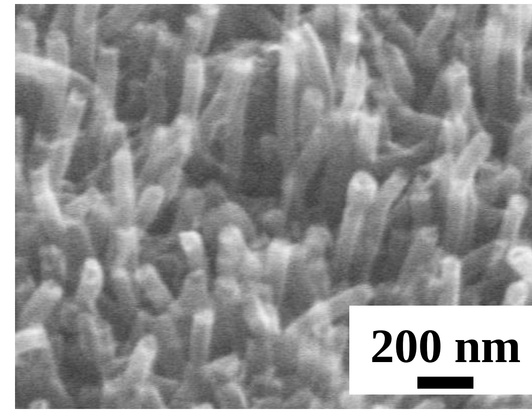
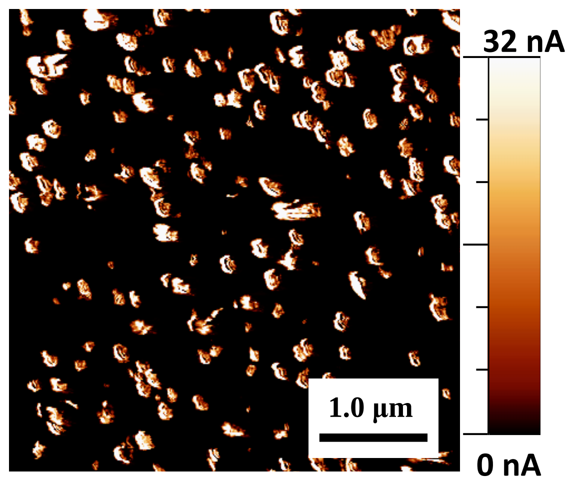
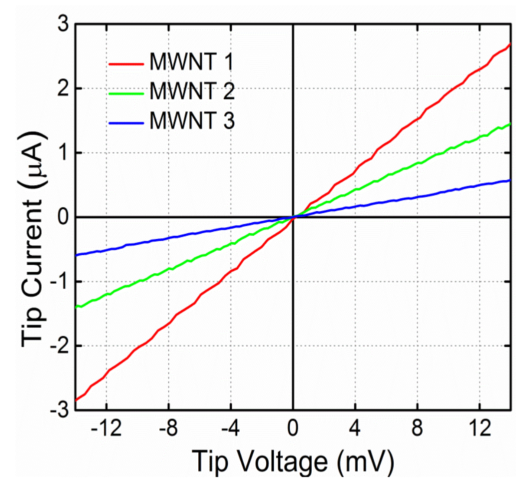




Conductive AFM confirms that electrical continuity to the substrate is preserved after ultrasonic cutting





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Ongoing and Future Work

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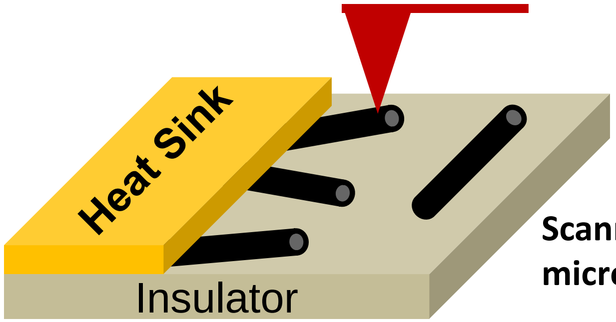
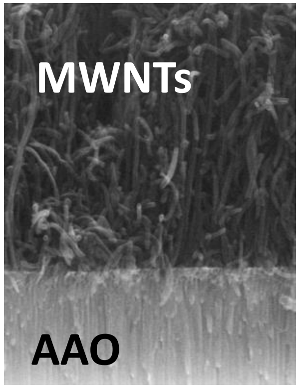
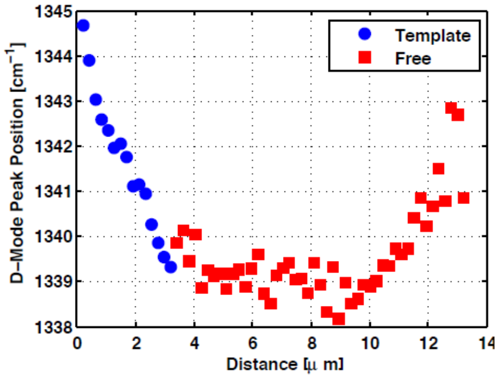


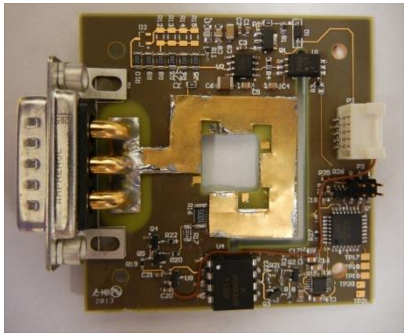
Scanning thermal microscopy

Identify the best growth conditions:
→ TEM and thermal conductivity of nanotubes grown under various conditions





Understand the nature of template-grown MWNTs:
→ Cross-sectional Raman imaging



Characterize cooling capabilities of TIM:
→ Thermal test structure for power devices

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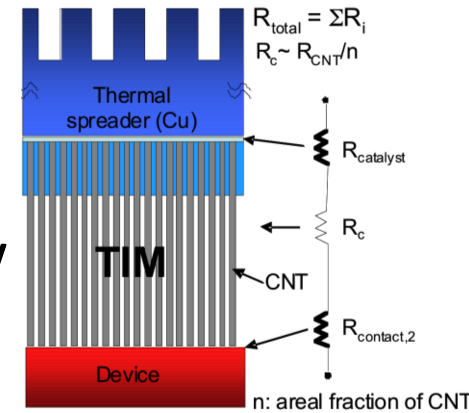
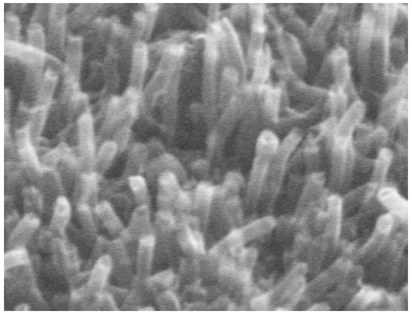
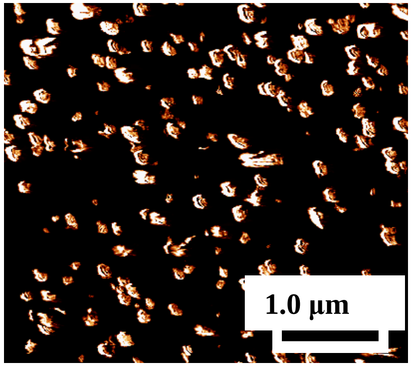
Summary

- **Removing heat generated by high-power electronics is often the limiting factor in system performance**
- **Thermal conductivity of metal-filled epoxy is dominated by the epoxy**
- **Carbon nanotube thermal interface materials could eliminate the epoxy and improve thermal interface material performance by orders of magnitude**
- **Growth by thermal CVD in a nanopore template directly on the heat sink material followed by planarization helps improve performance**
- **Competition between nanotube and amorphous carbon growth complicate growth in anodized aluminum oxide templates**
- **Planarization by ultrasonic cutting preserves electrical/thermal contact to the substrate**







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