Applications of carbon nanotubes

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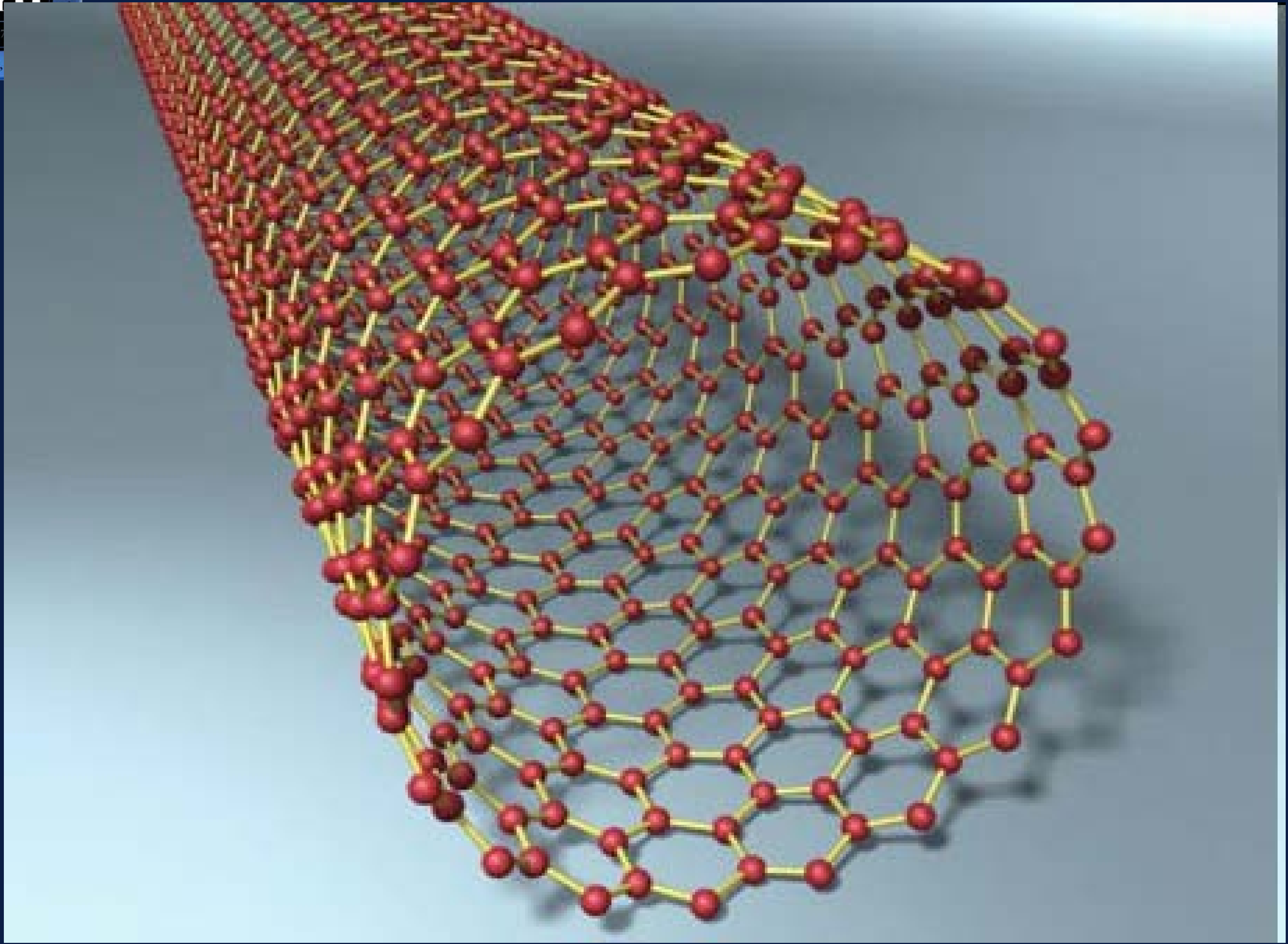
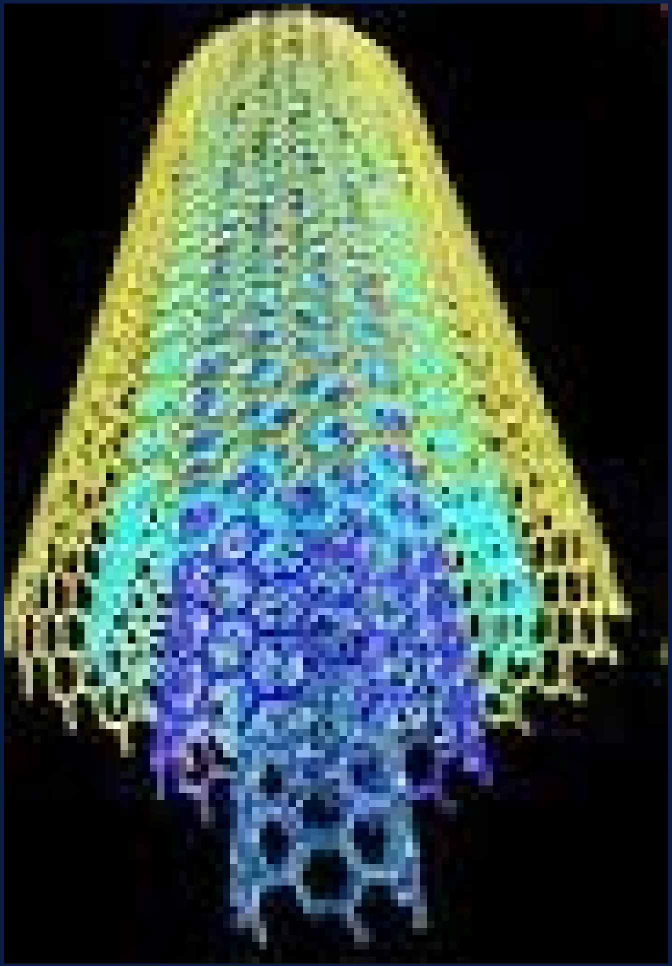
734-0418, 422-3489



Multiwall tubes



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CVD system adaptation and qualification.

Differences at BYU

1. Furnace length and number of zones
2. Gas control via MFC- We calibrate.
3. Tube Diameter same


LINDBERG/BLUE
LINDBERG/BLUE

CVD system adaptation and qualification.

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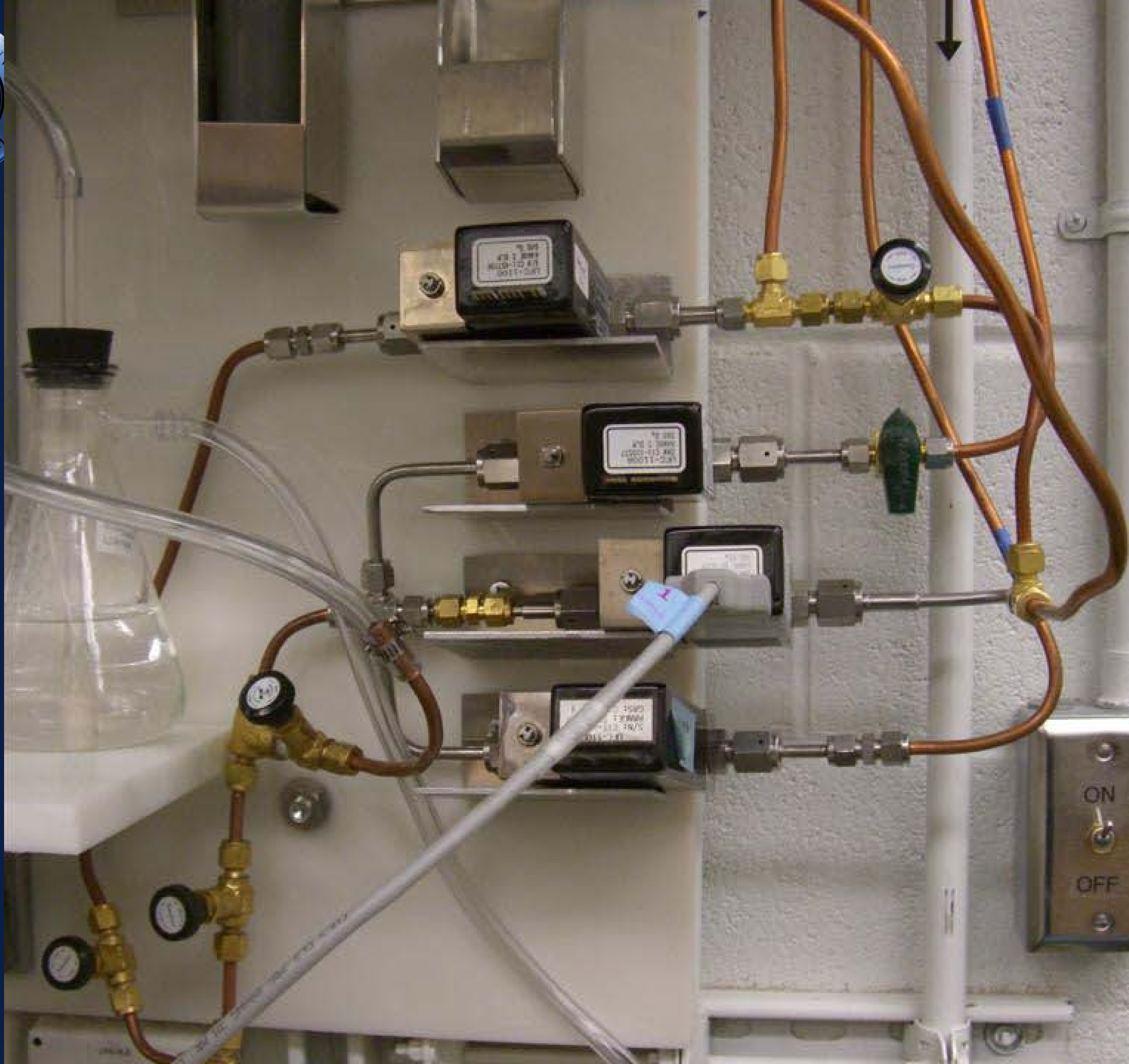
ON
OFF


Purge
ON
MFC output
R output
OFF = CLOSED
Valve
URS-100-5
UNIT INSTRUMENTS
-02.4
-00.0
-00.1
-00.0
00.0
AUTO
OFF
MANUAL
SET
FLOW
EXPO
BOLD COLOR DRY ERASE

CVD system adaptation and qualification.

Differences at BYU

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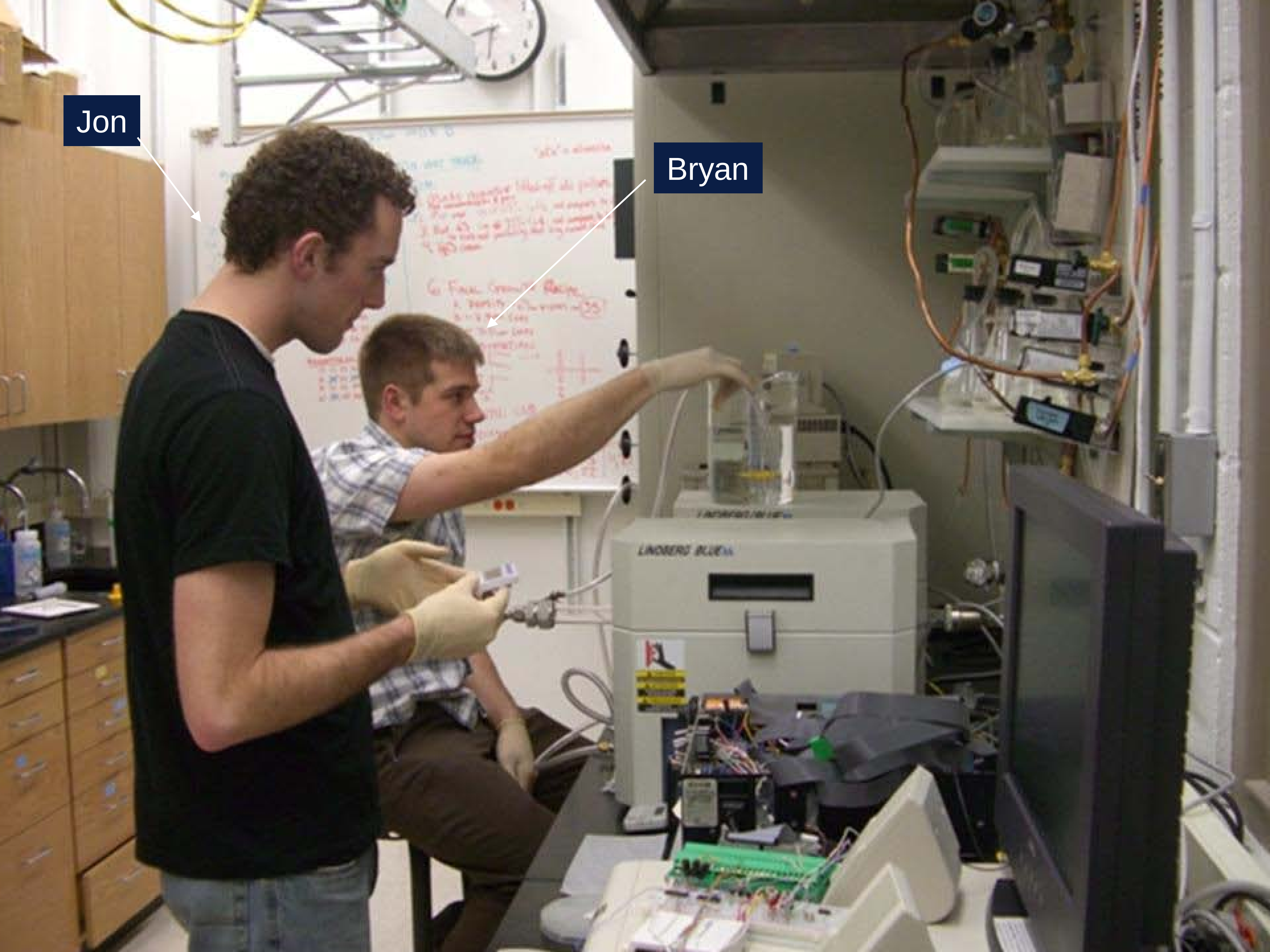

Jon
Bryan

High Aspect Ratio Microfabrication by Chemical Infiltration of Carbon Nanotube Frameworks

MRS 2009 Talk by Prof. Robert C. Davis
Department of Physics and Astronomy
Brigham Young University

allred@byu.edu

CNT MEMS Researchers

BYU Physics

- David Hutchison
- Brendan Turner
- Katherine Hurd
- Matthew Carter
- Nick Morril
- Jun Song
- Adam Konniker
- Ricky Wymant
- Taylor Wood
- Dr. Richard Vanfleet
- Dr. Robert Davis
- Dr. David Allred

BYU Mechanical Engineering

- Quentin Aten
- Dr. Brian Jensen
- Dr. Larry Howell

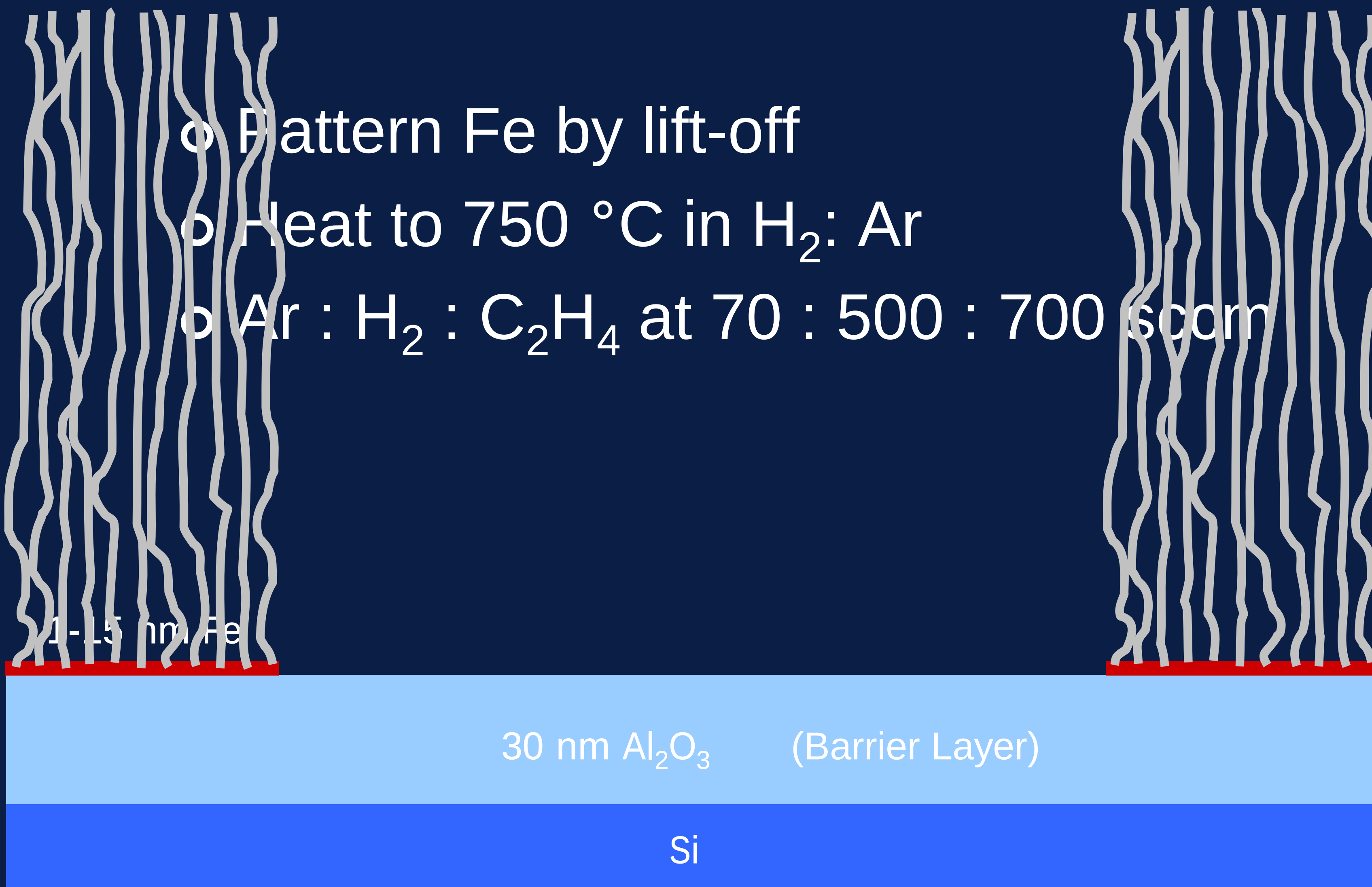
National Science Foundation

Brigham Young University Environment for Undergraduate Mentoring Grant

Partial funding provided by Moxtek Inc.

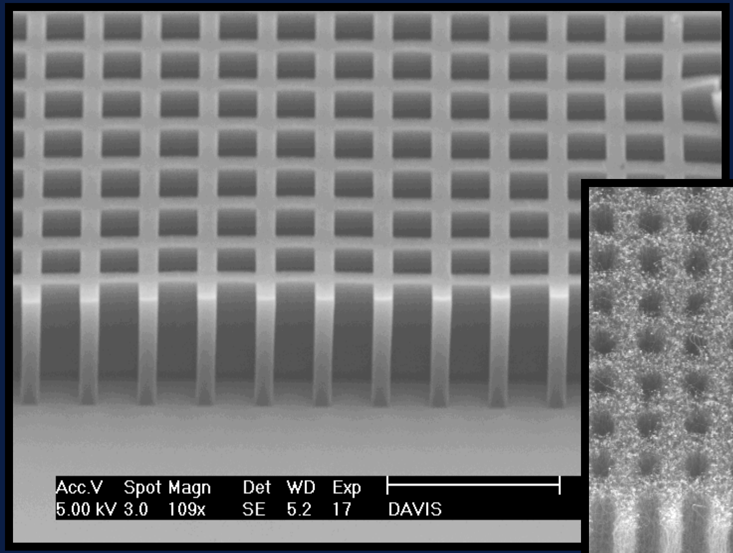
VACNT growth details

- Pattern Fe by lift-off
- Heat to 750 °C in H_2: Ar
- Ar : H_2 : C_2H_4 at 70 : 500 : 700 sccm

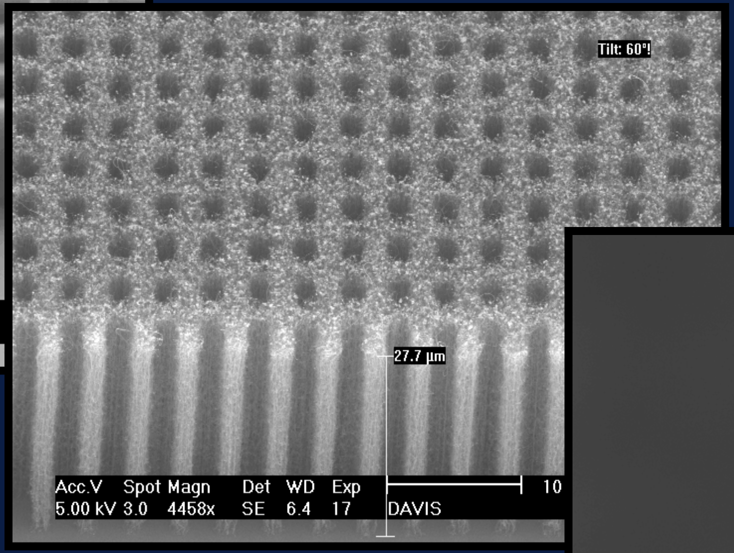


SEM - VACNT forest

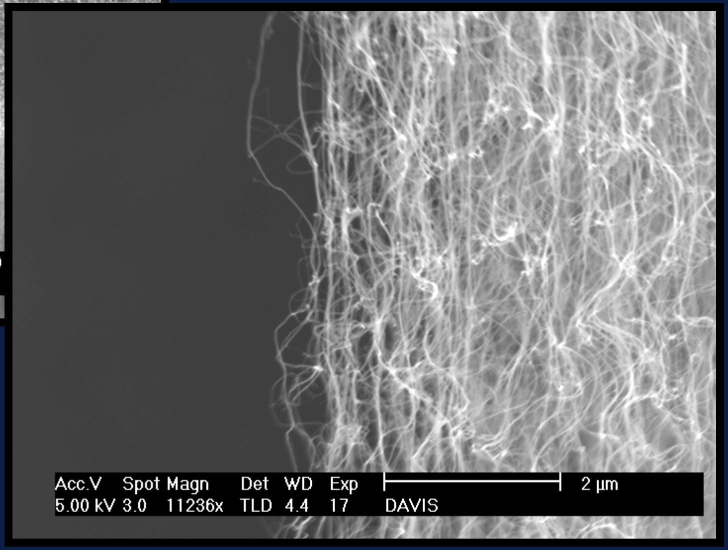
Can top surface and edge roughness be improved?



100X – 50 µm holes



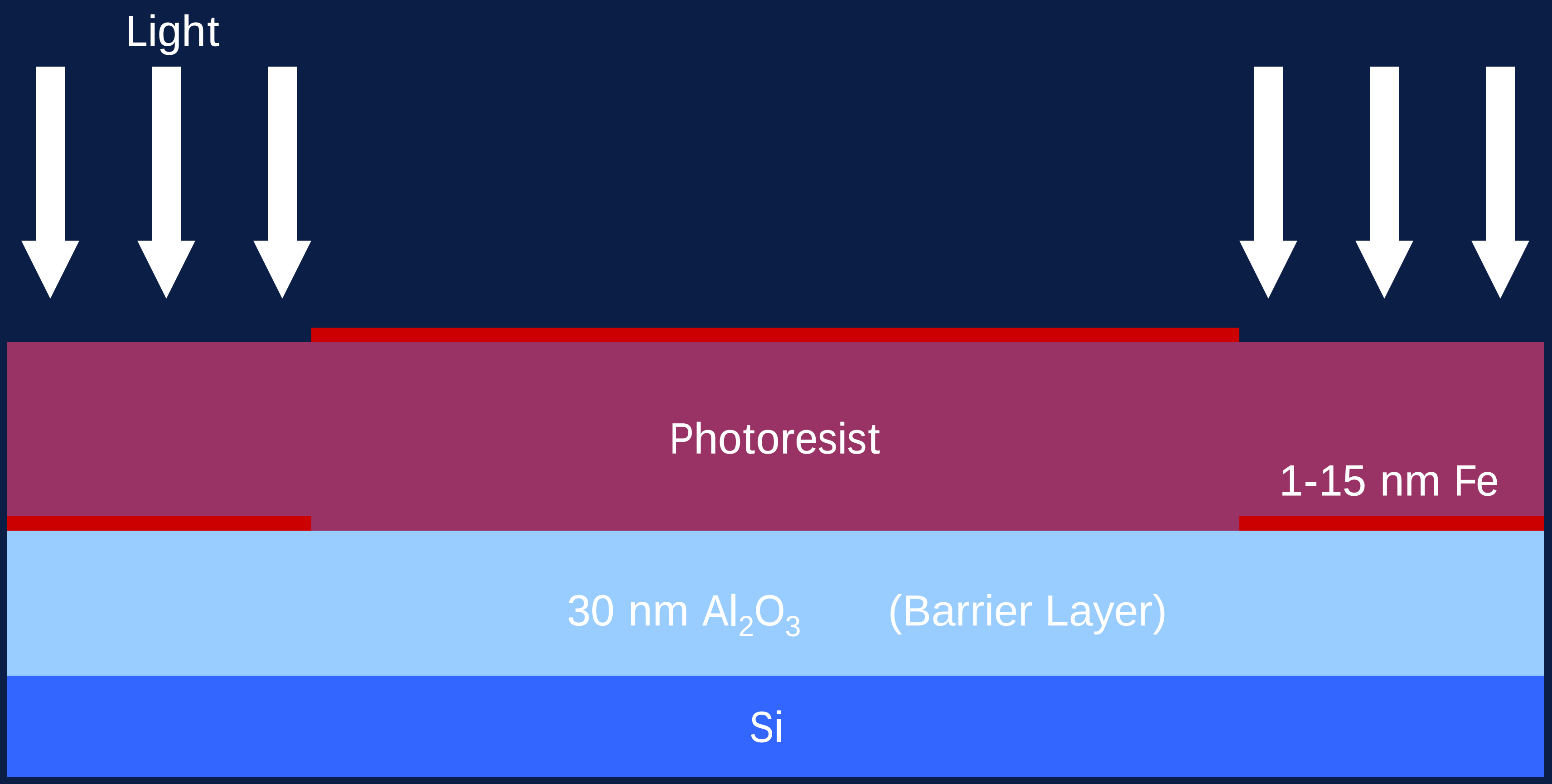
4500X – 3 µm holes



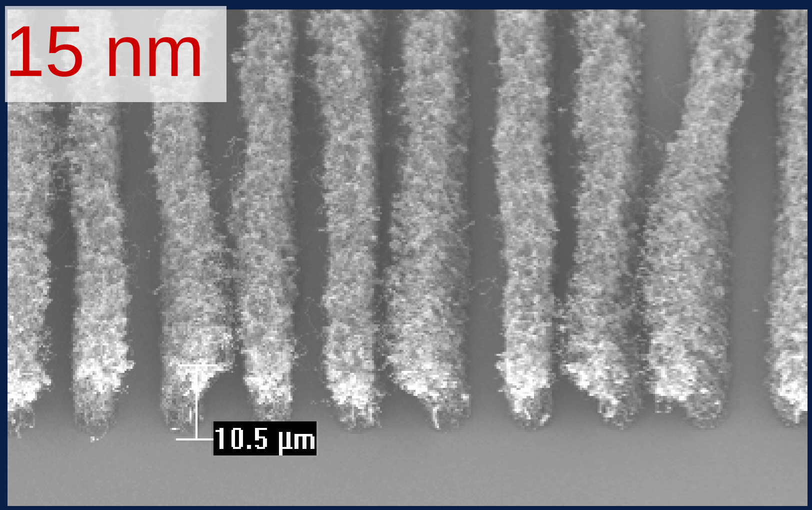
30000X – edge

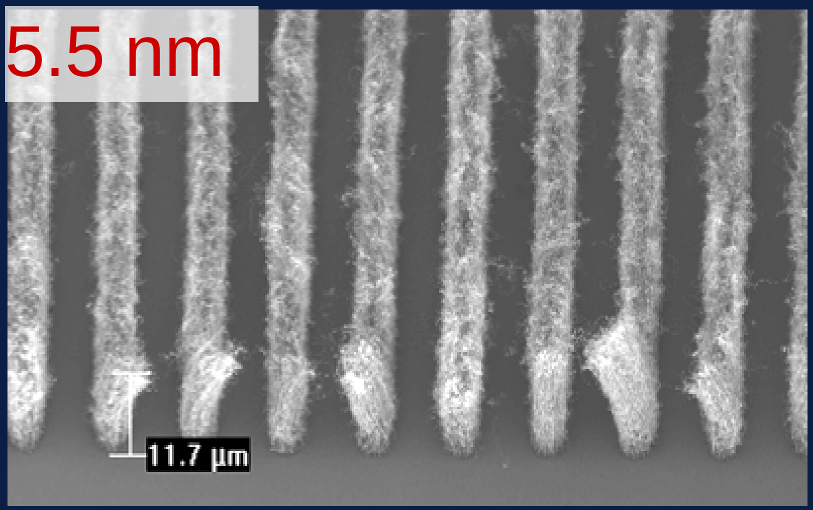
VACNT growth process

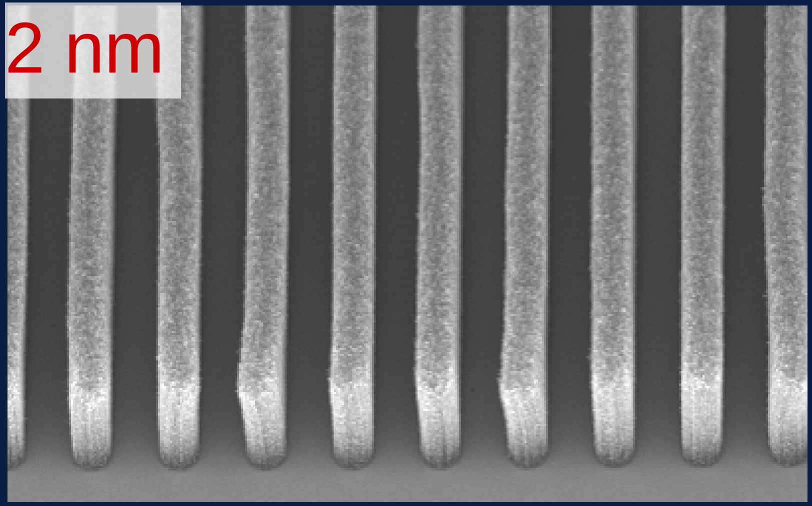
- Photolithography & lift-off

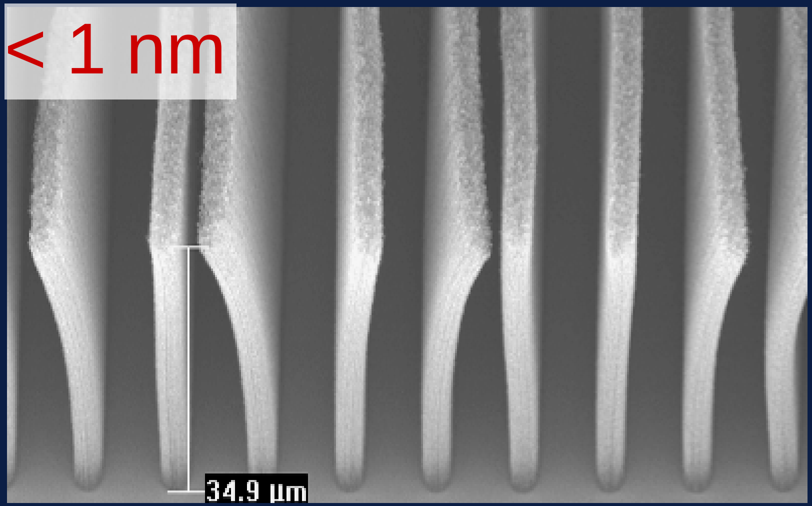


Dependence on Fe Thickness









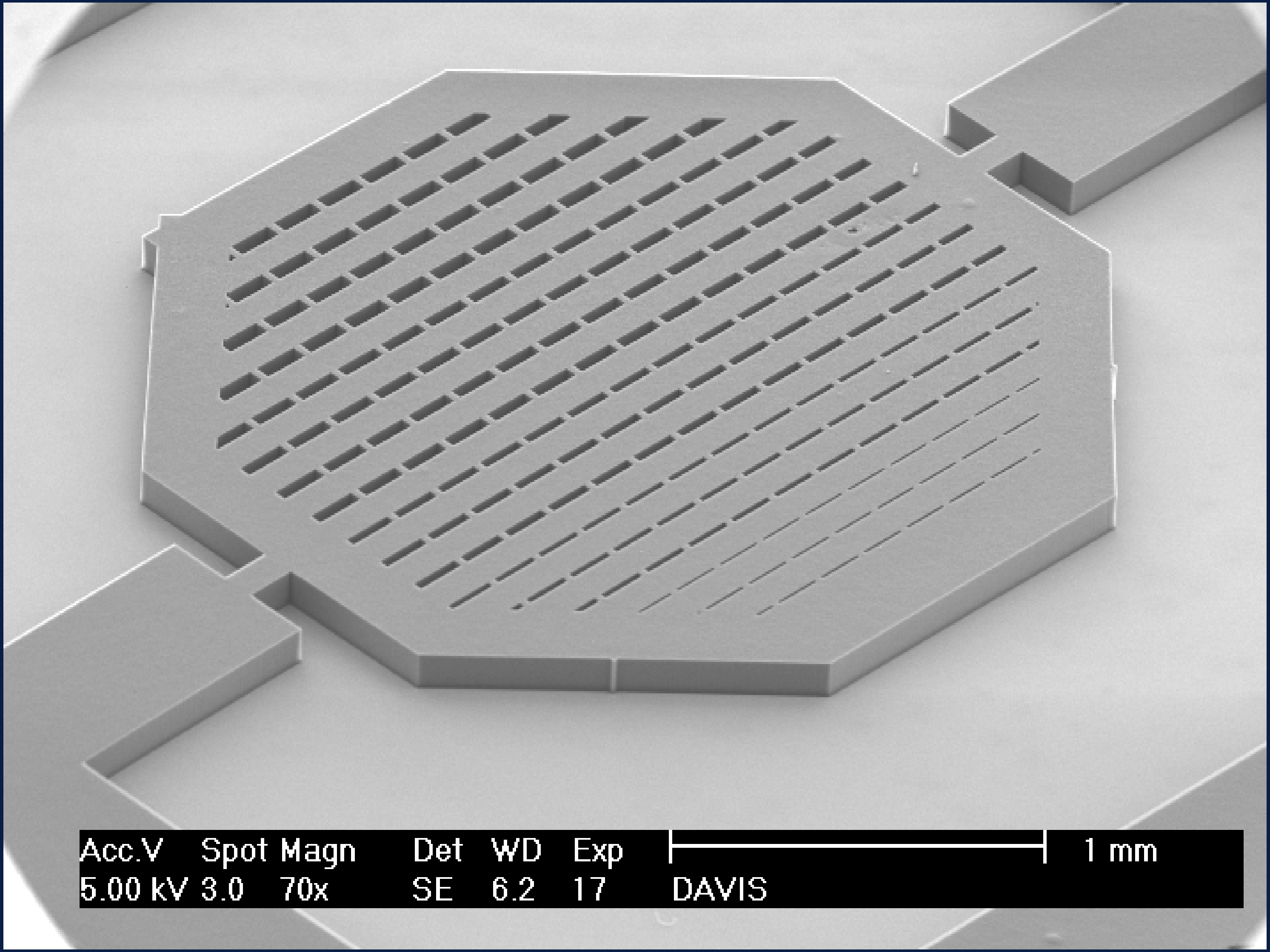
Good repeatability

Rate strongly dependant on thickness

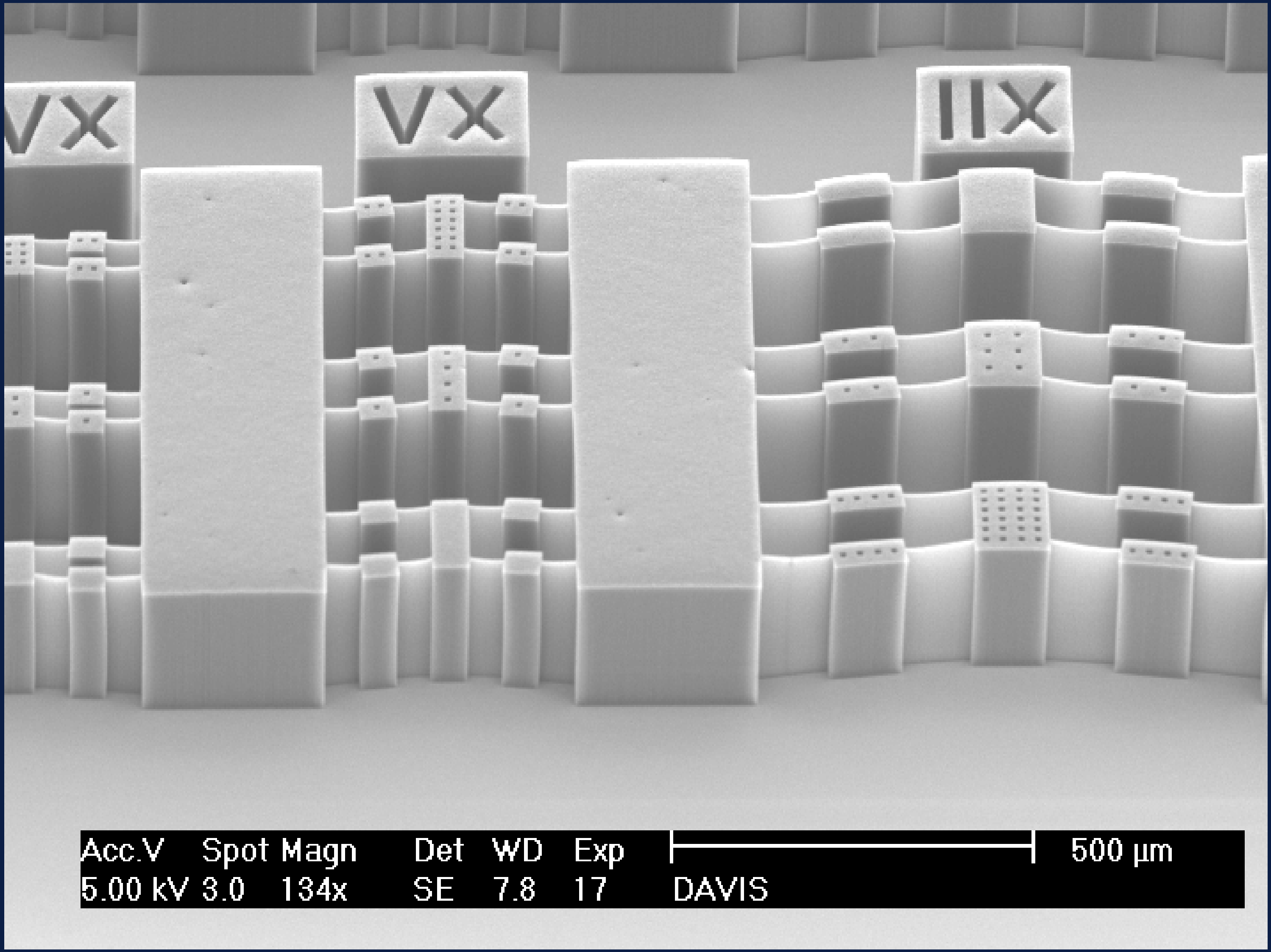
2 nm Fe on Al_2O_3

- Small voids (< 200 nm across)
- Sharp features (few stray tubes); Sidewall roughness < 200 nm
- High growth rate ~50 µm/min

TEM Grid



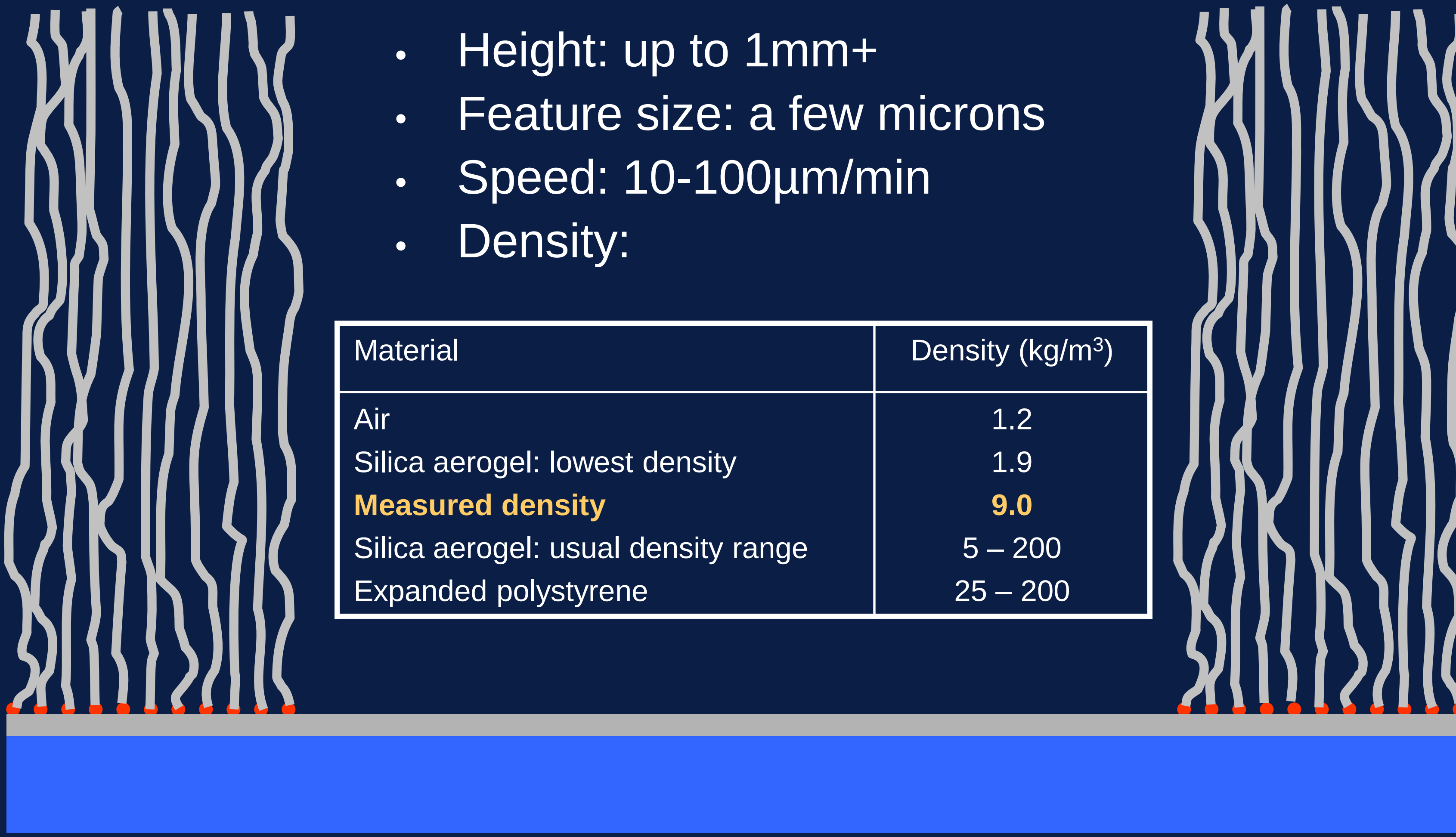
Bistable Mechanisms



Nanotube “forest” growth

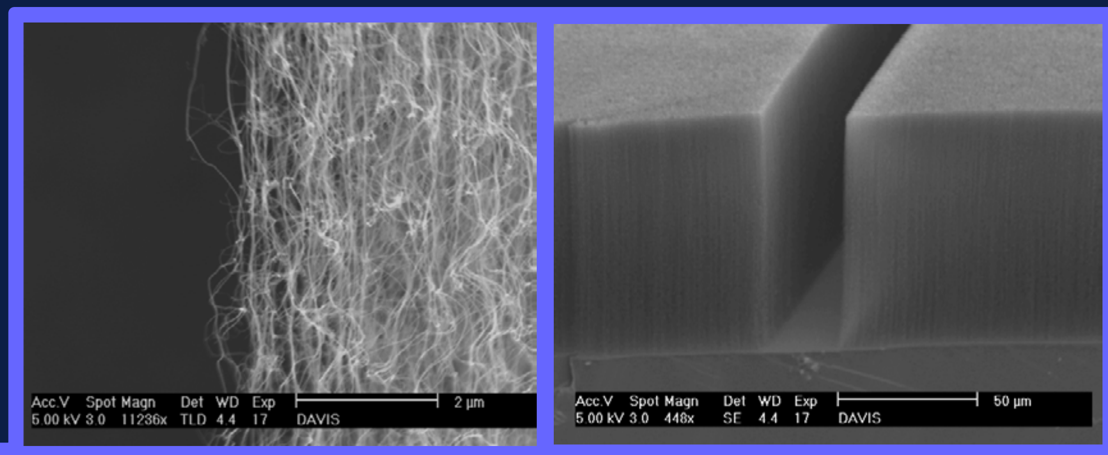
- Height: up to 1mm+
- Feature size: a few microns
- Speed: 10-100µm/min
- Density:

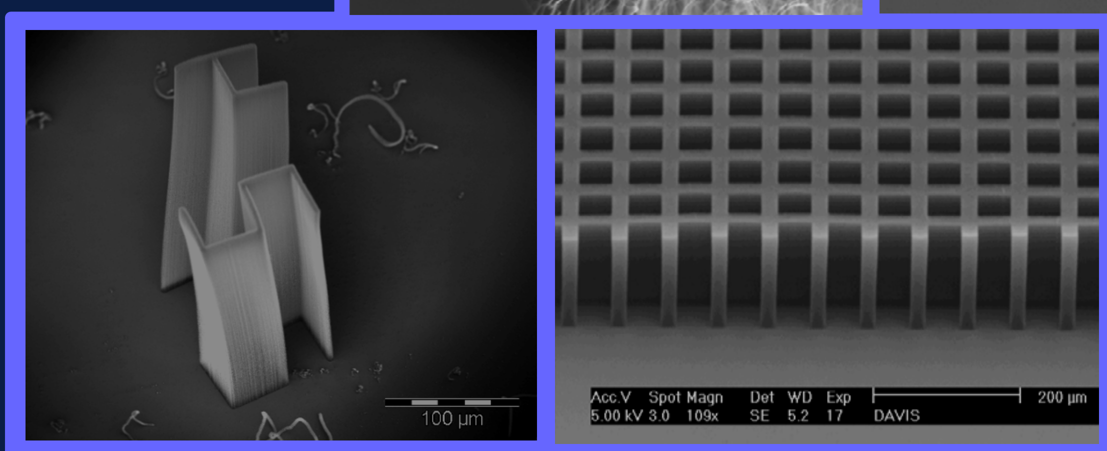
Material	Density (kg/m^3)
Air	1.2
Silica aerogel: lowest density	1.9
Measured density	**9.0**
Silica aerogel: usual density range	5 – 200
Expanded polystyrene	25 – 200



Vertically Aligned Carbon Nanotube (VACNT)Growth

Individual nanotubes wander but…



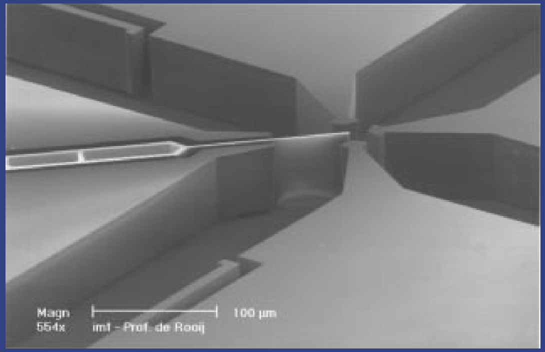


…forest grows perpendicular to growth substrate

Extraordinary growth among materials growth systems

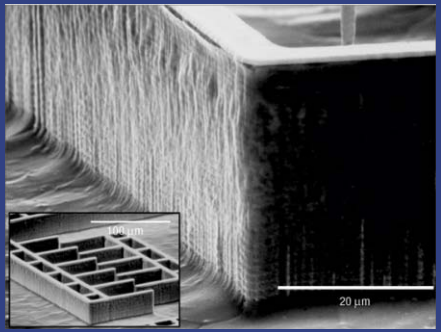
High Aspect Ratio Micromachining

Deep Reactive Ion Etching (Si)



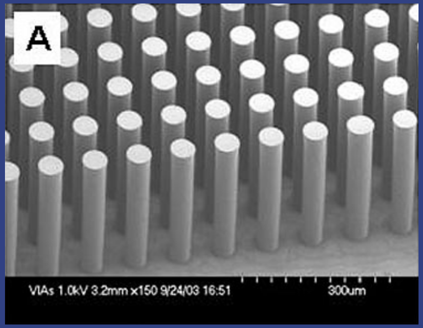
"Vertical Mirrors Fabricated by DRIE for Fiber-Optic Switching Applications," C. Marx et al., J. MEMS **6,** 277, (1997)

MARIO Process (Titanium)



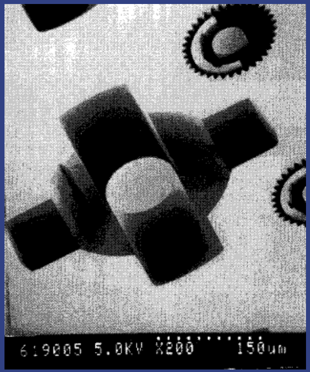
"High-aspect-ratio bulk micromachining of titanium," Aimi *et al.,* Nature Mat. **3,** 103-5 (2004)

SU-8 / C-MEMS (photoresist / carbon)



"C-MEMS for the Manufacture of 3D Microbatteries," Wang *et al.,* Electrochem. Solid-State Lett. **7** (11) A435-8 (2004)

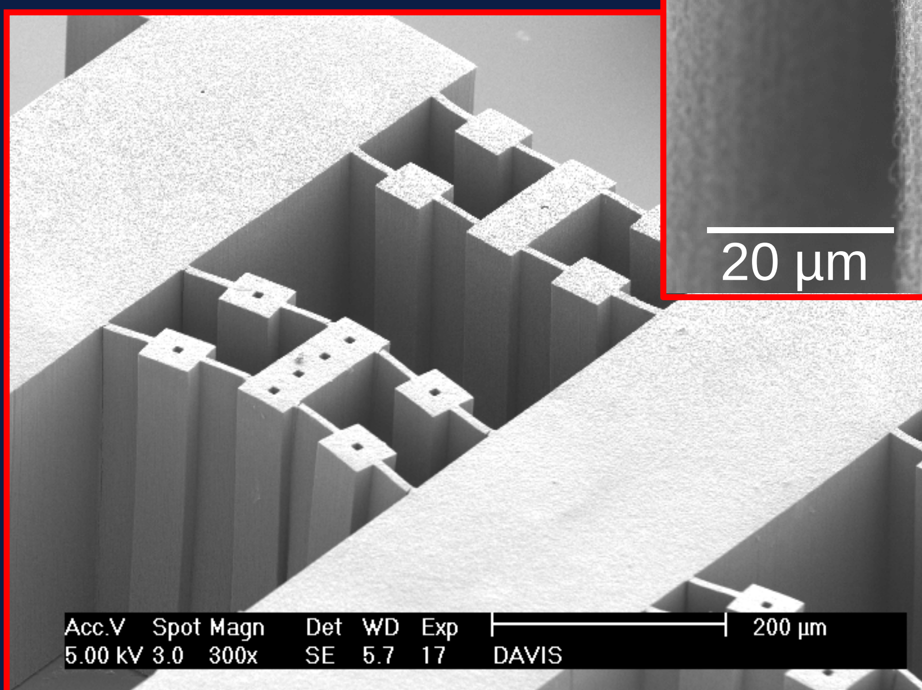
LIGA process (photoresist)

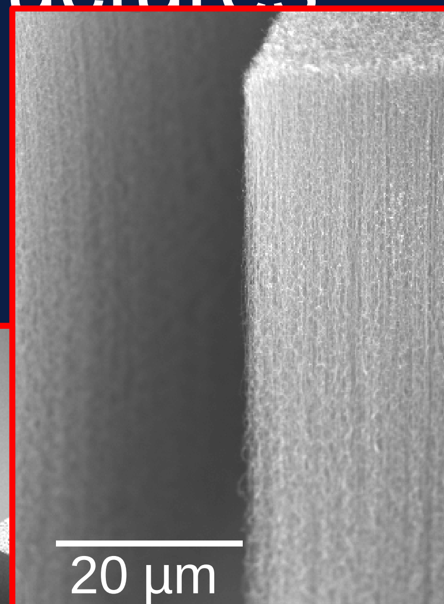


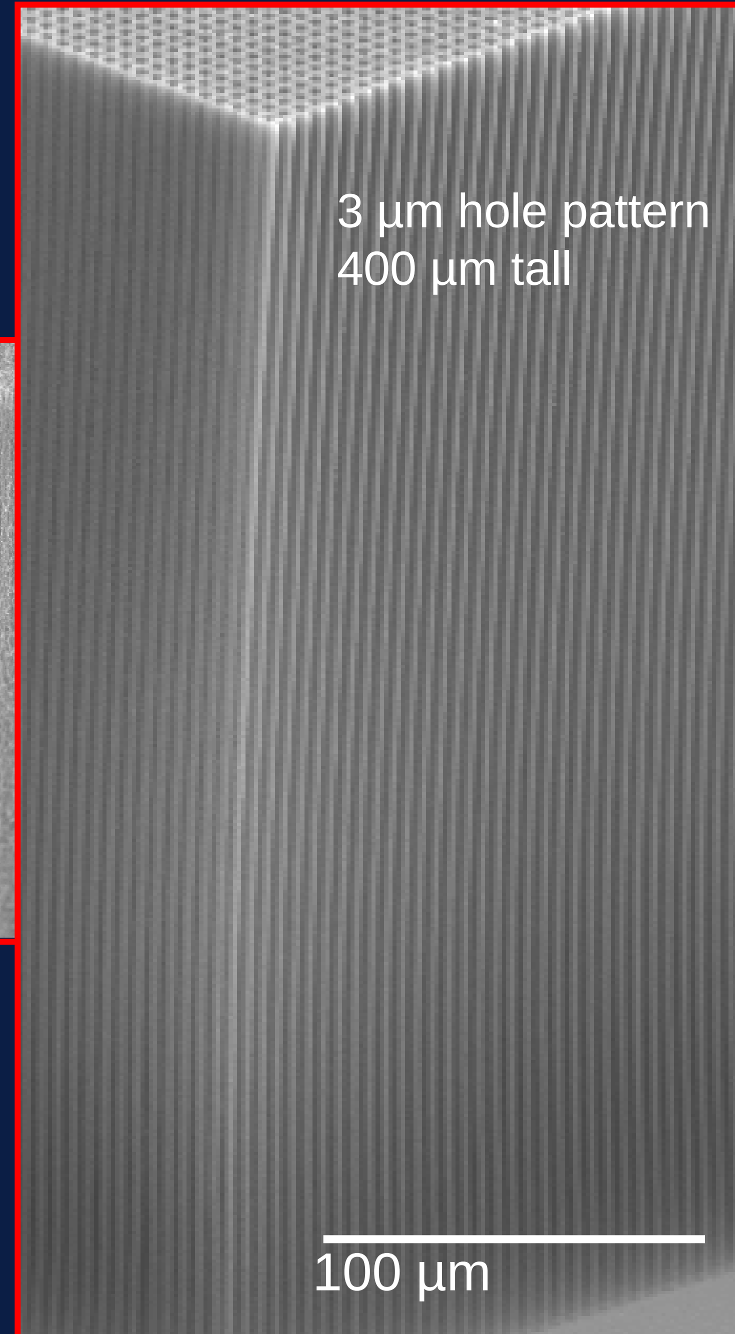
"Micromechanisms," H. Guckel, Phil. Trans. R. Soc. Lond. **353,** 355-66 (1995)

VACNT: Extreme Aspect-Ratio Microstructures

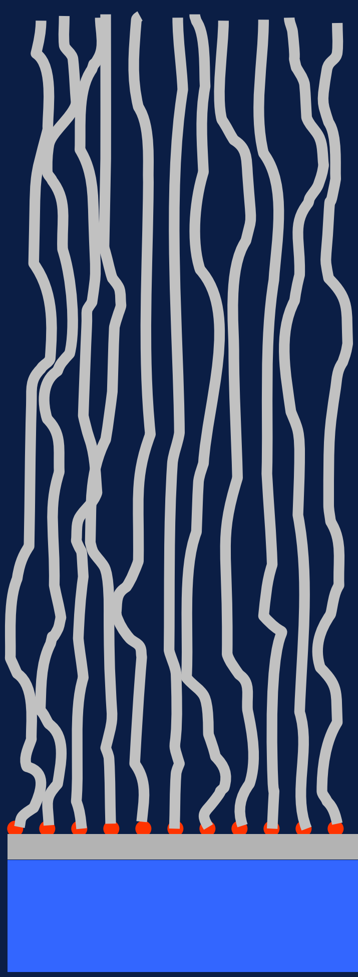
• Smooth sidewalls … <1 micron roughness
• Tall… up to several millimeters





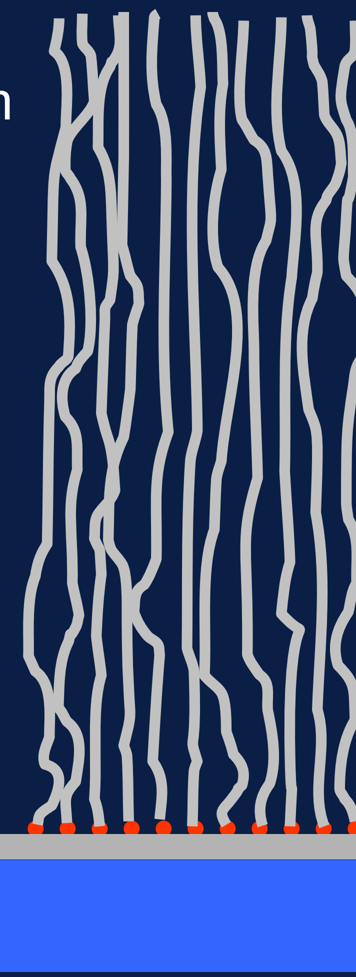


Patterned forest structure

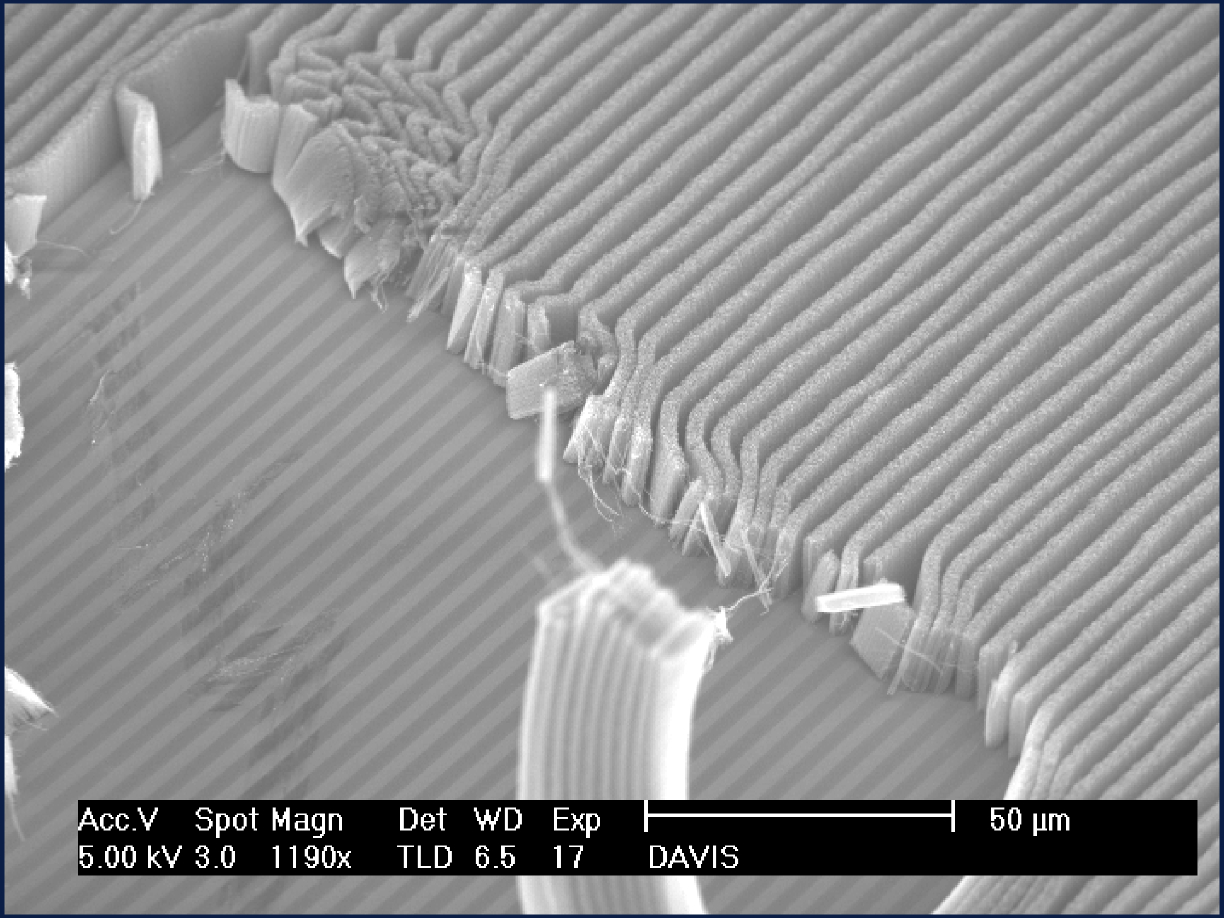


- Height: up to several milimeters
- Lateral feature size: down to 1 micron
- Speed: 10-100 µm/min
- Density:

Material	Density (kg/m^3)
Air	1.2
Silica aerogel: lowest density	1.9
Measured density	**9.0**
Silica aerogel: usual density range	5 – 200
Expanded polystyrene	25 – 200



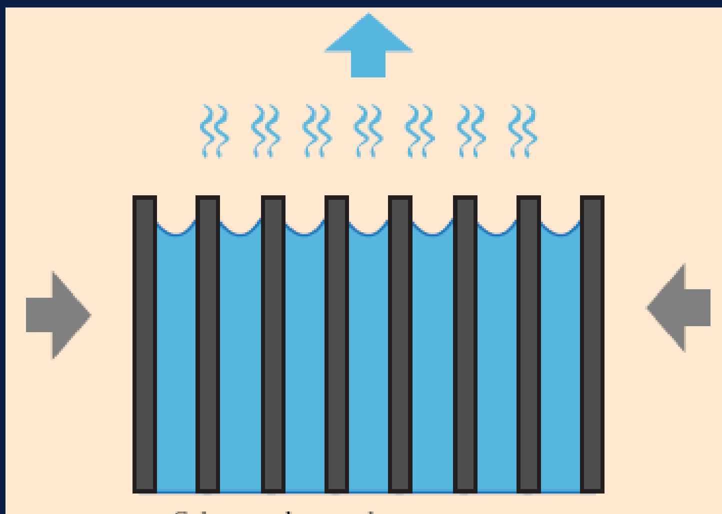
Low density, weakly bound material

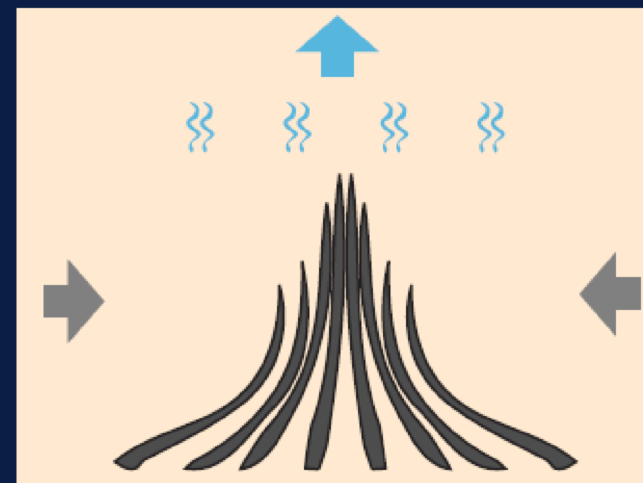


As-grown forests are flimsy and tear off the surface at the slightest touch

Dense Nanotube Structures

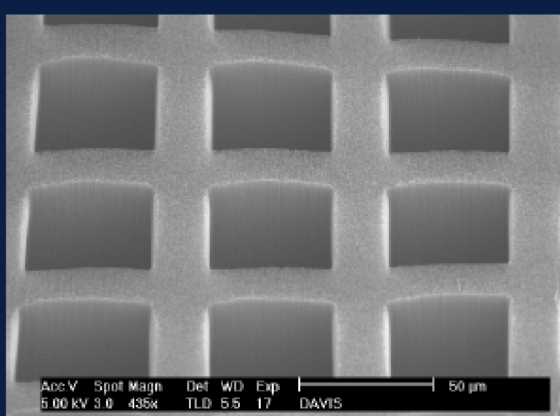
Liquid Induced Densification

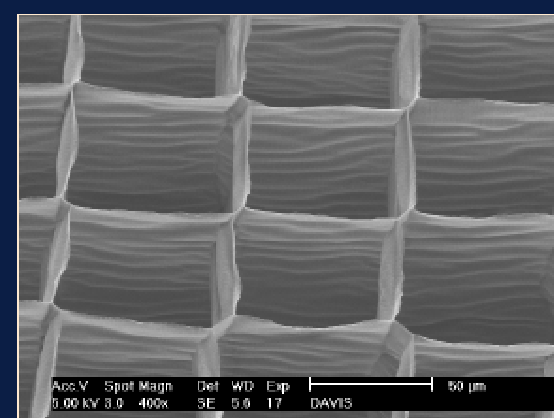




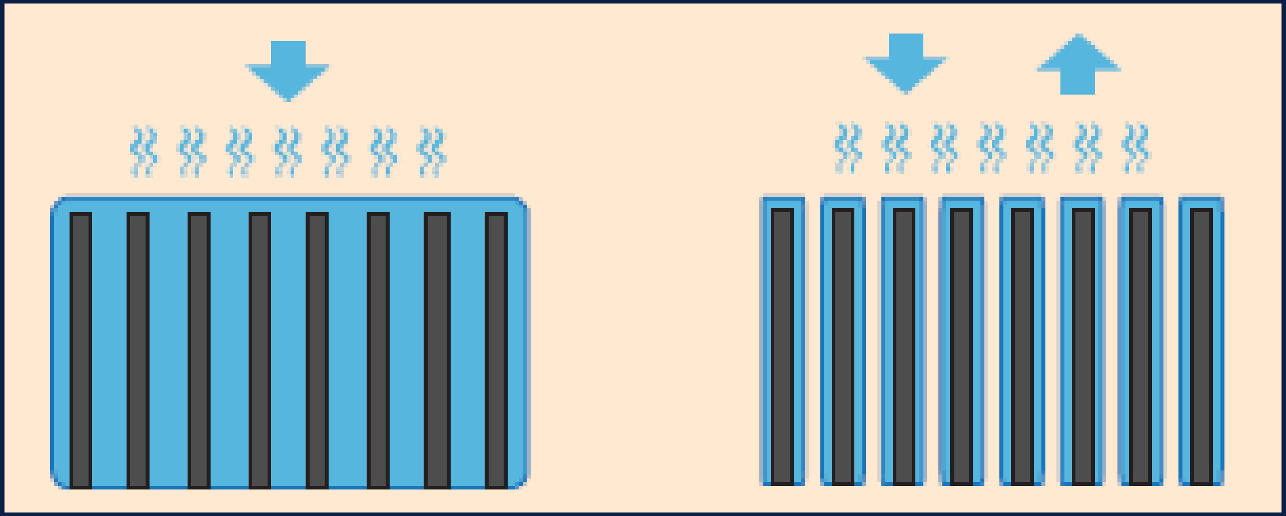
Submerged nanotube structures

Dried structure



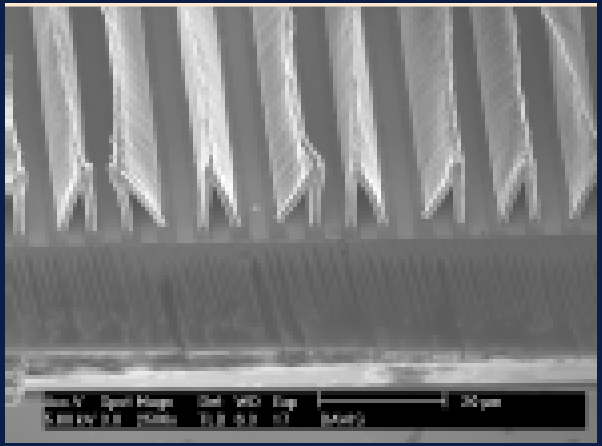


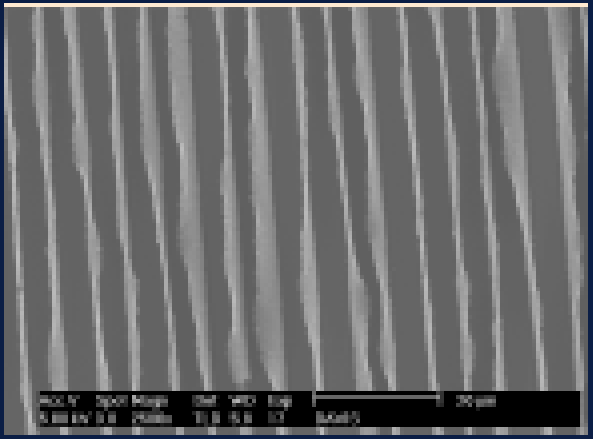
Vapor Condensation Induced Densification -- Lines



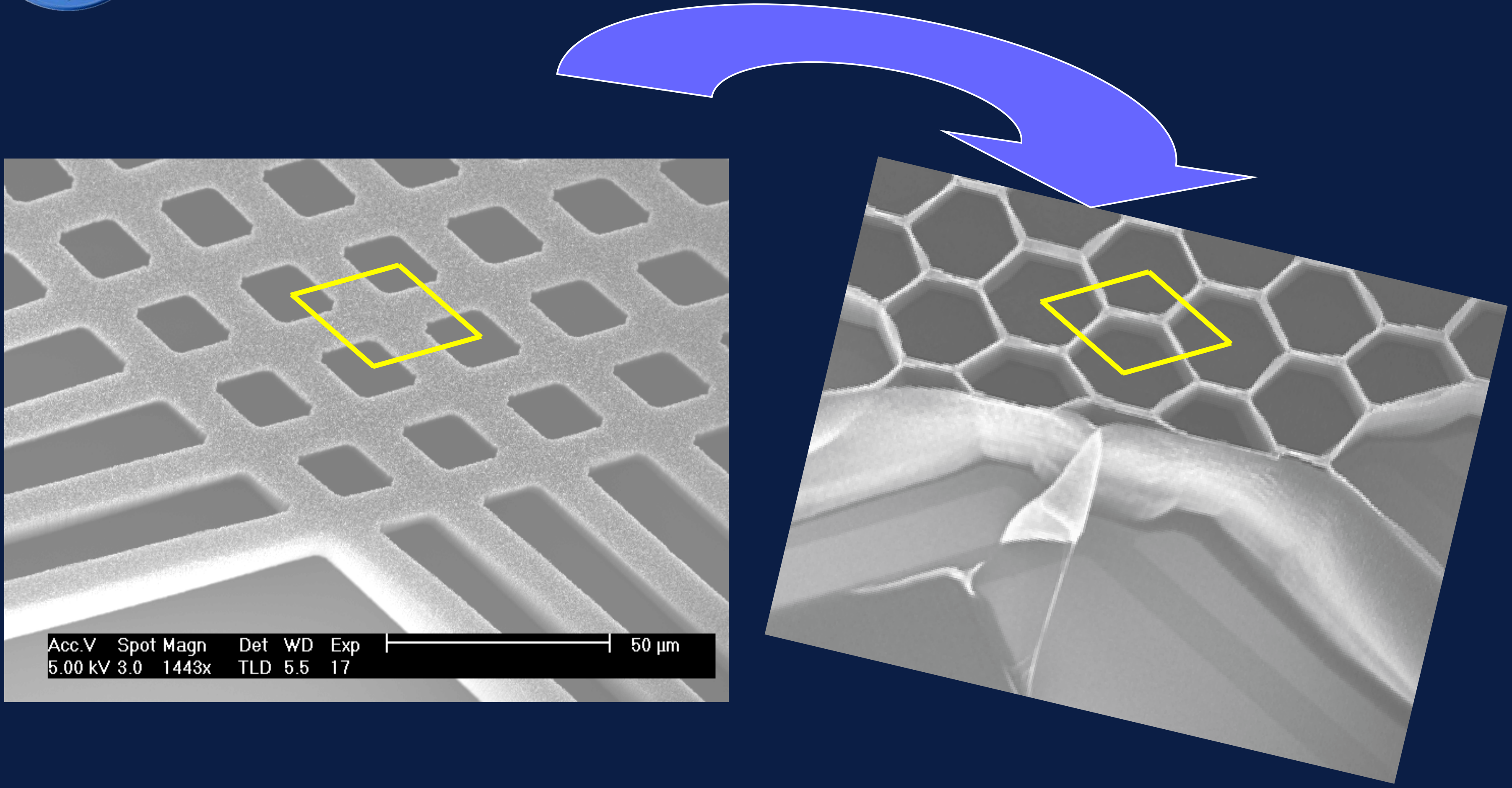
Longer exposure to vapor

Shorter exposure to vapor



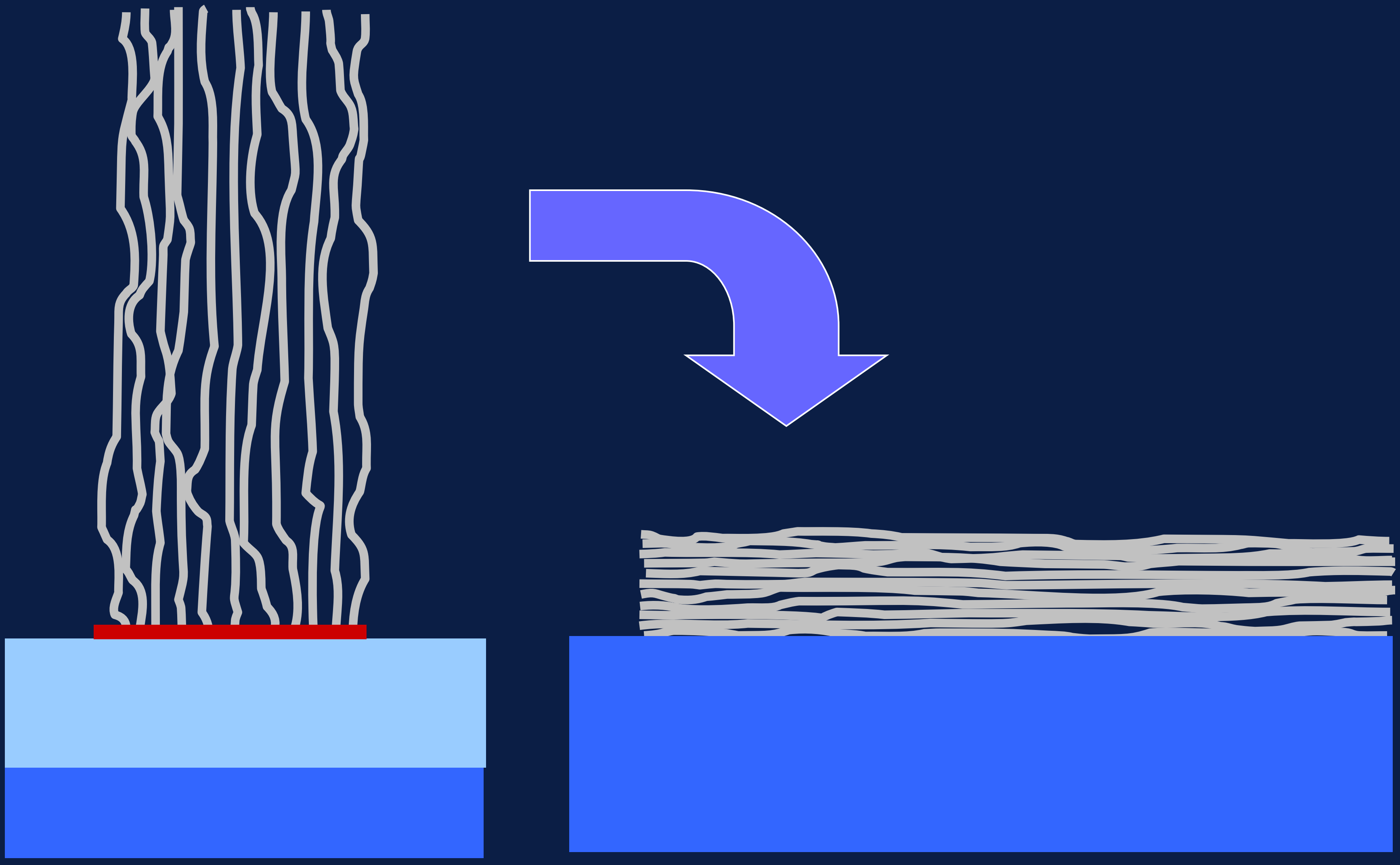


Surface forces dominates

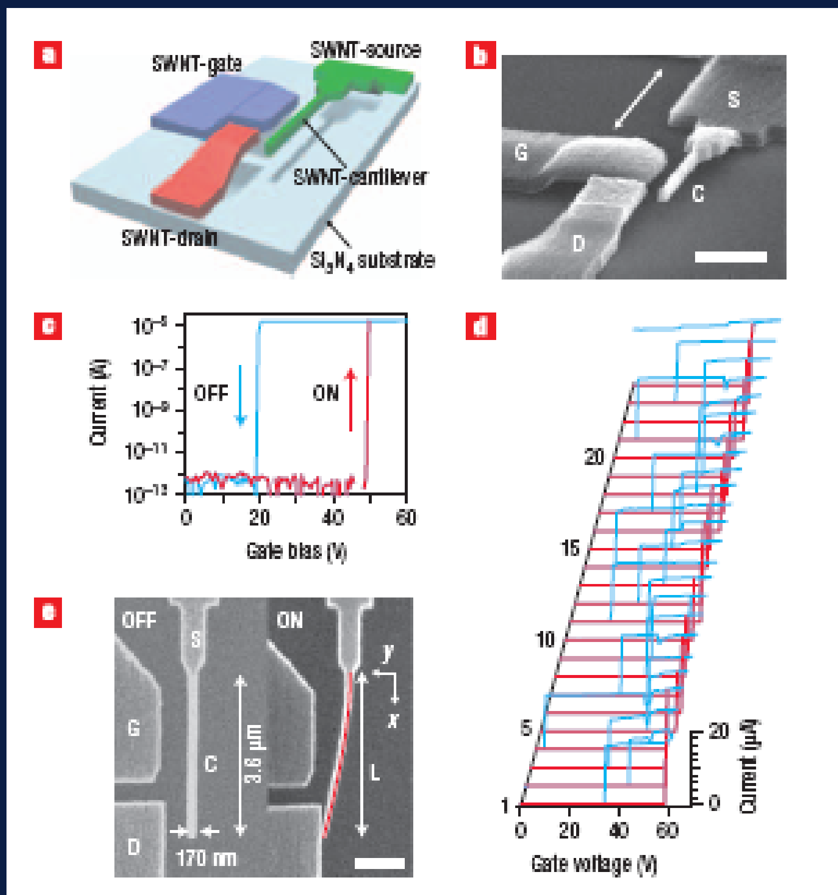


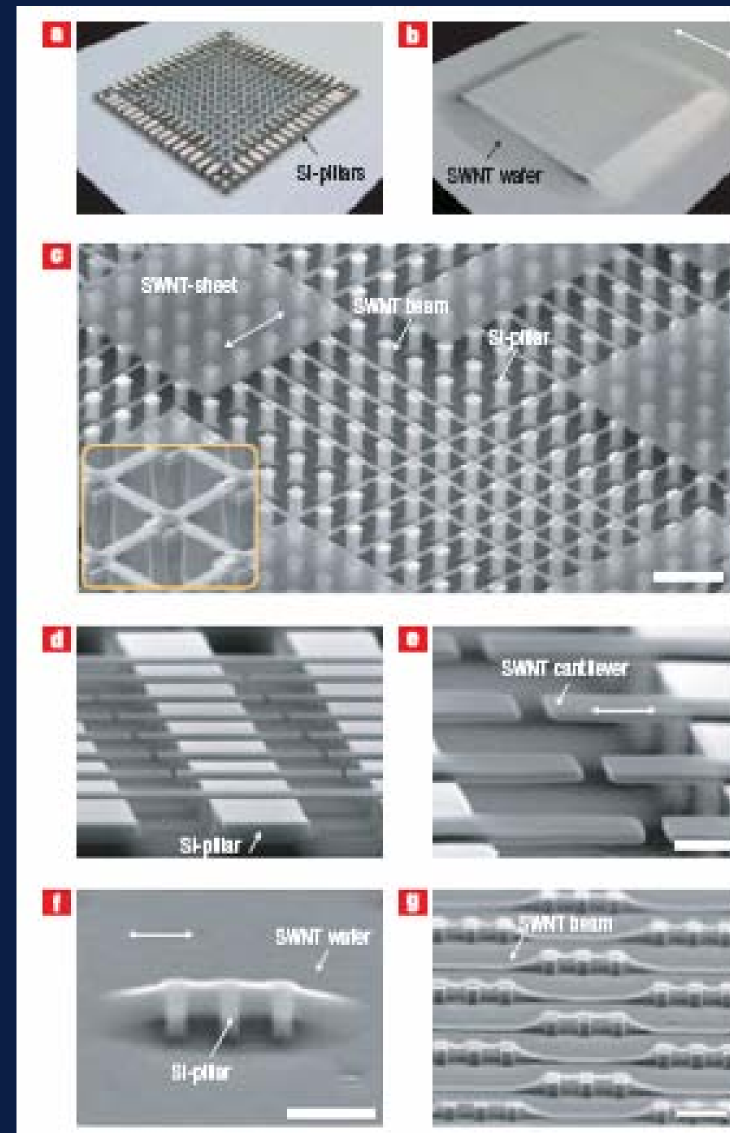
Unequal angles become equal angles.
Final structure depends on initial structure surface forces
Difficult to control what results!

Horizontal Aligned CNT films



AIST Japan group working on in-plane aligned CNT MEMS

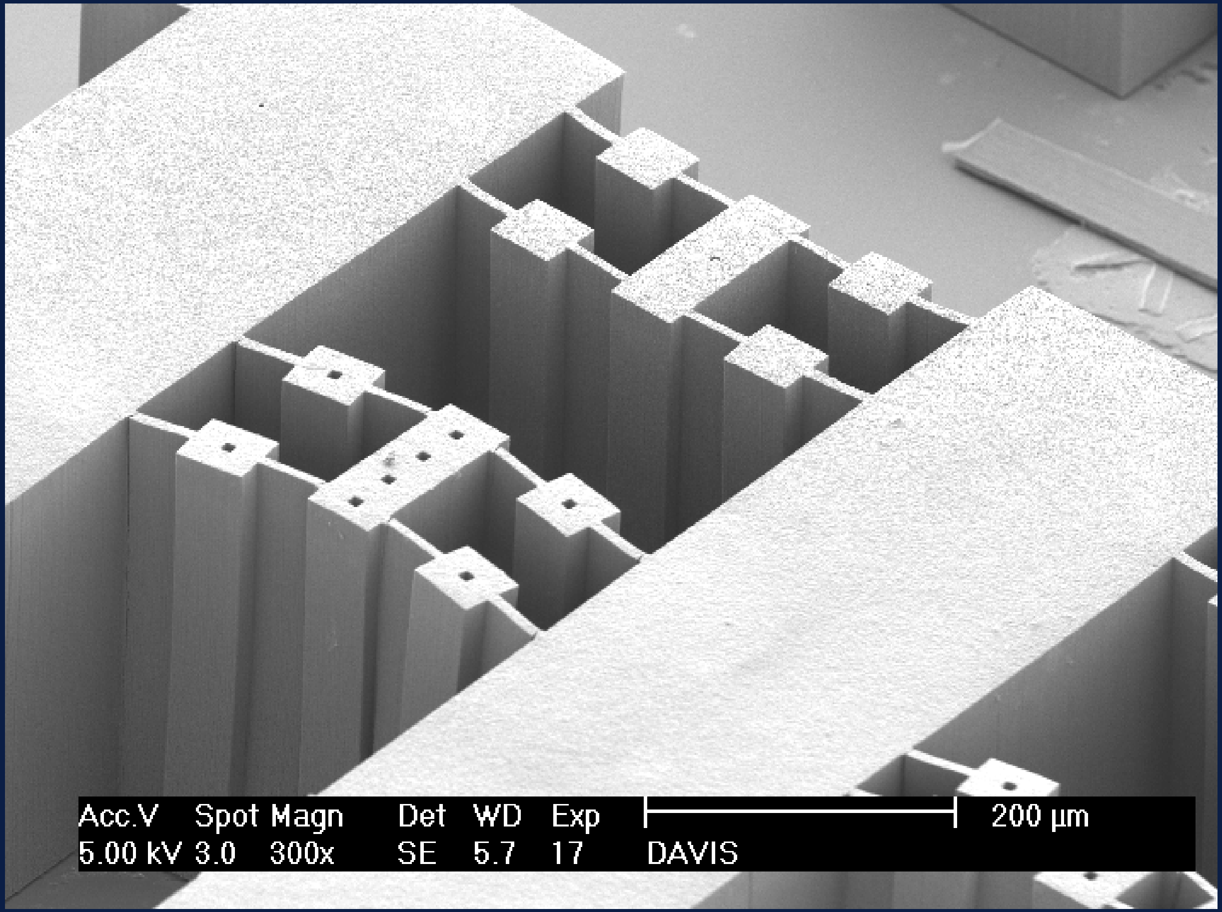




Yuhei Hayamizu, Takeo Yamada, Kohei Mizuno, Robert C. Davis, Don N. Futaba, Moto
Yumura, & Kenji Hata **Nature Nanotechnology** 3, 241 (2008).

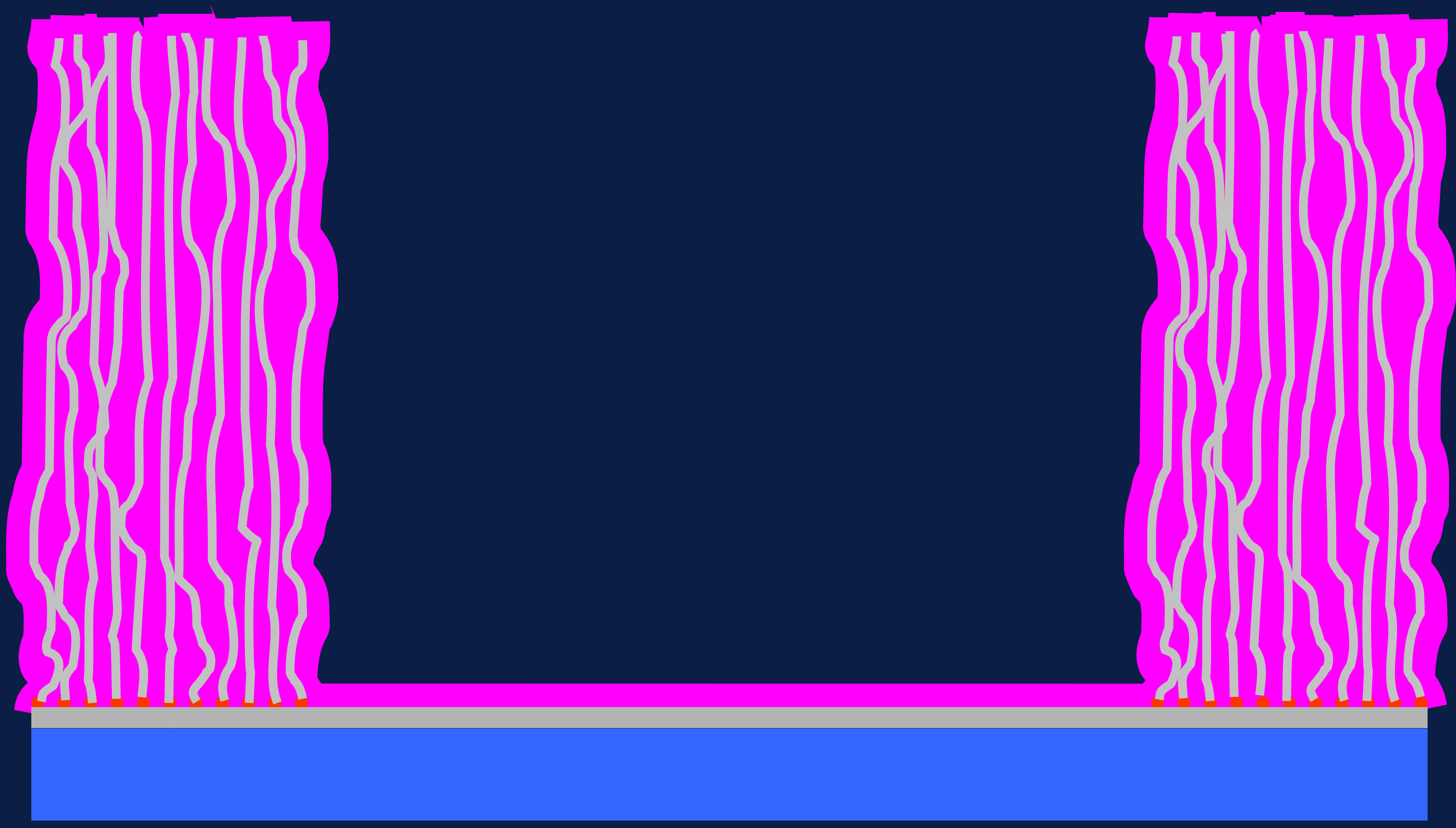
Microstructured VACNT Composites

Leave the nanotubes vertical?

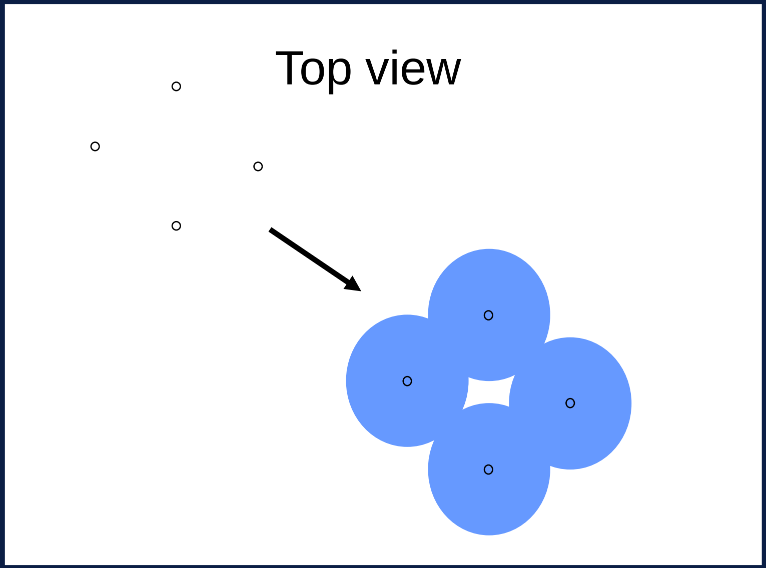


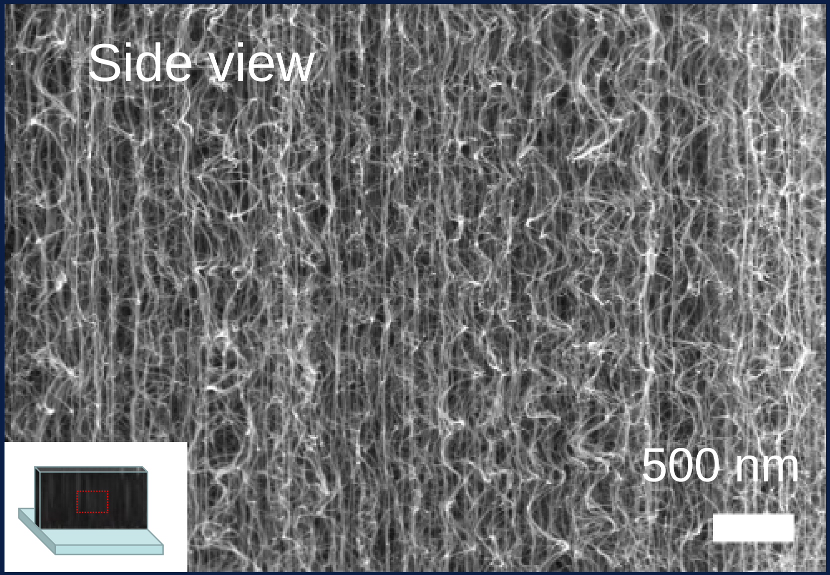
VACNT Composites

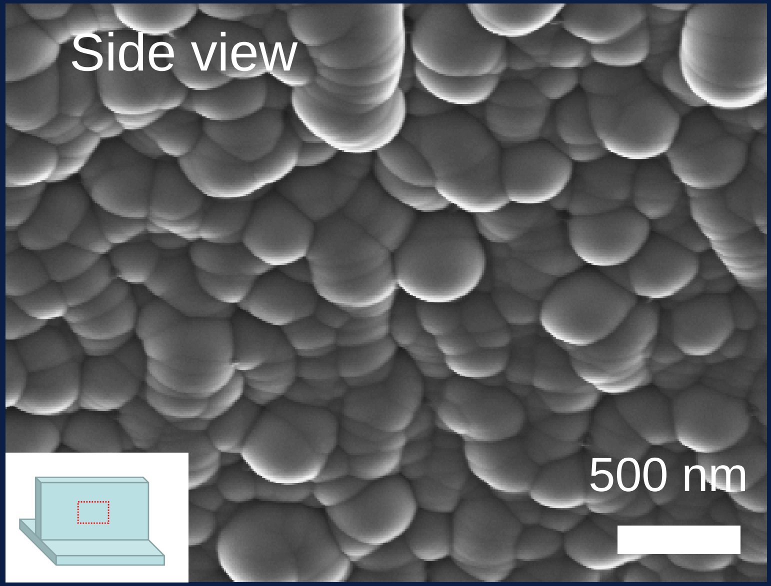
Filling in with Si by LPCVD

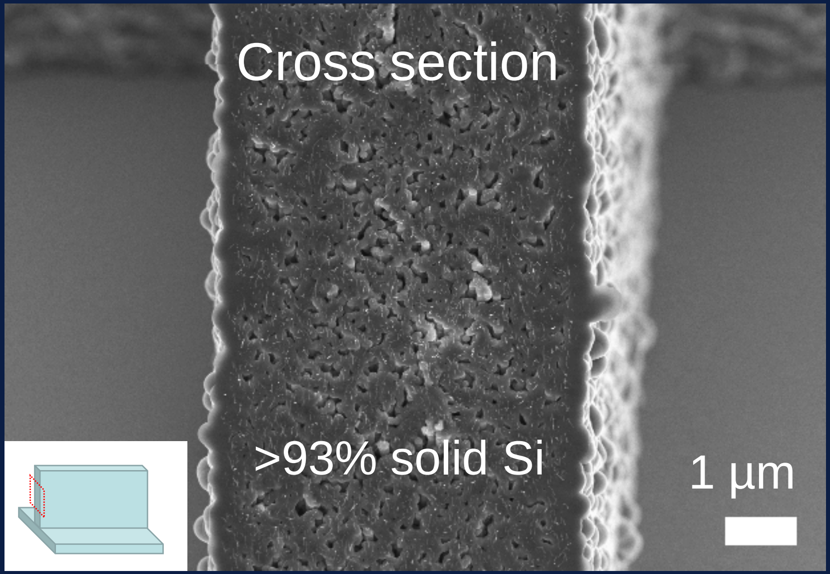


Nearly complete Si infiltration

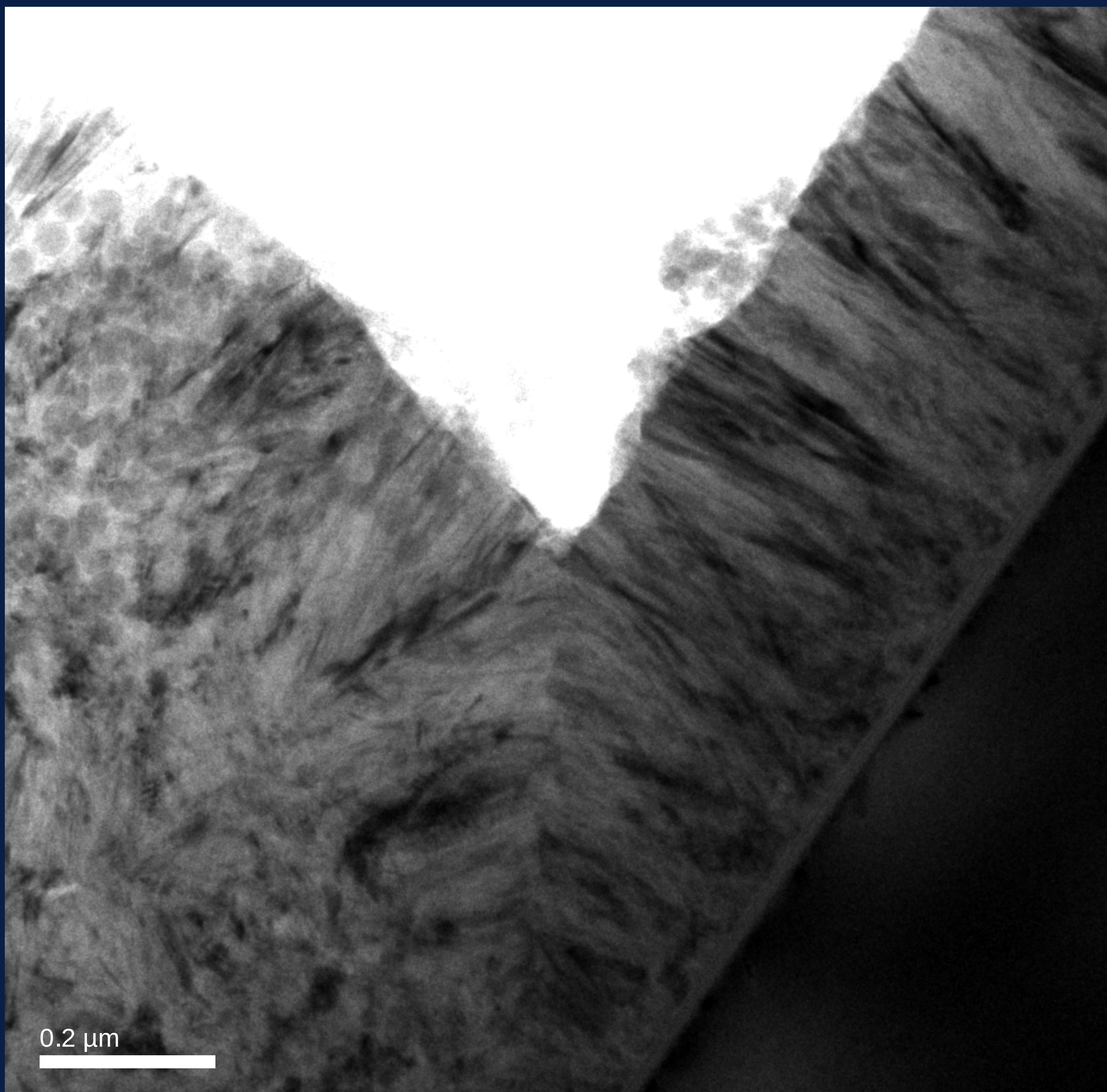




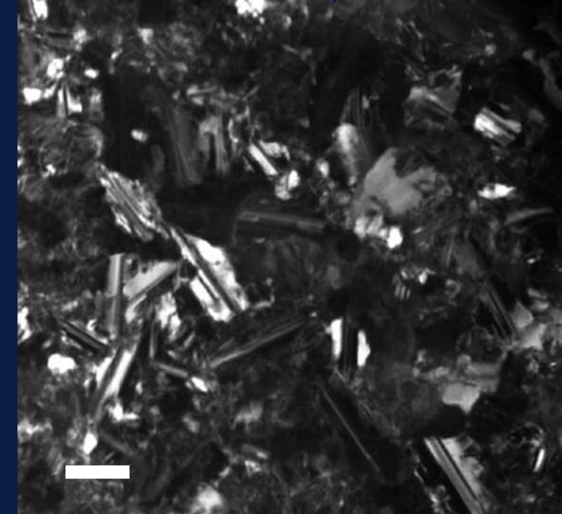


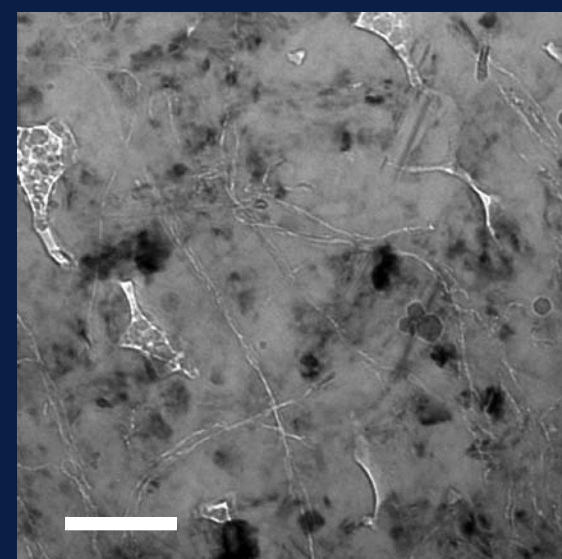


Microstructure: Poly-Si

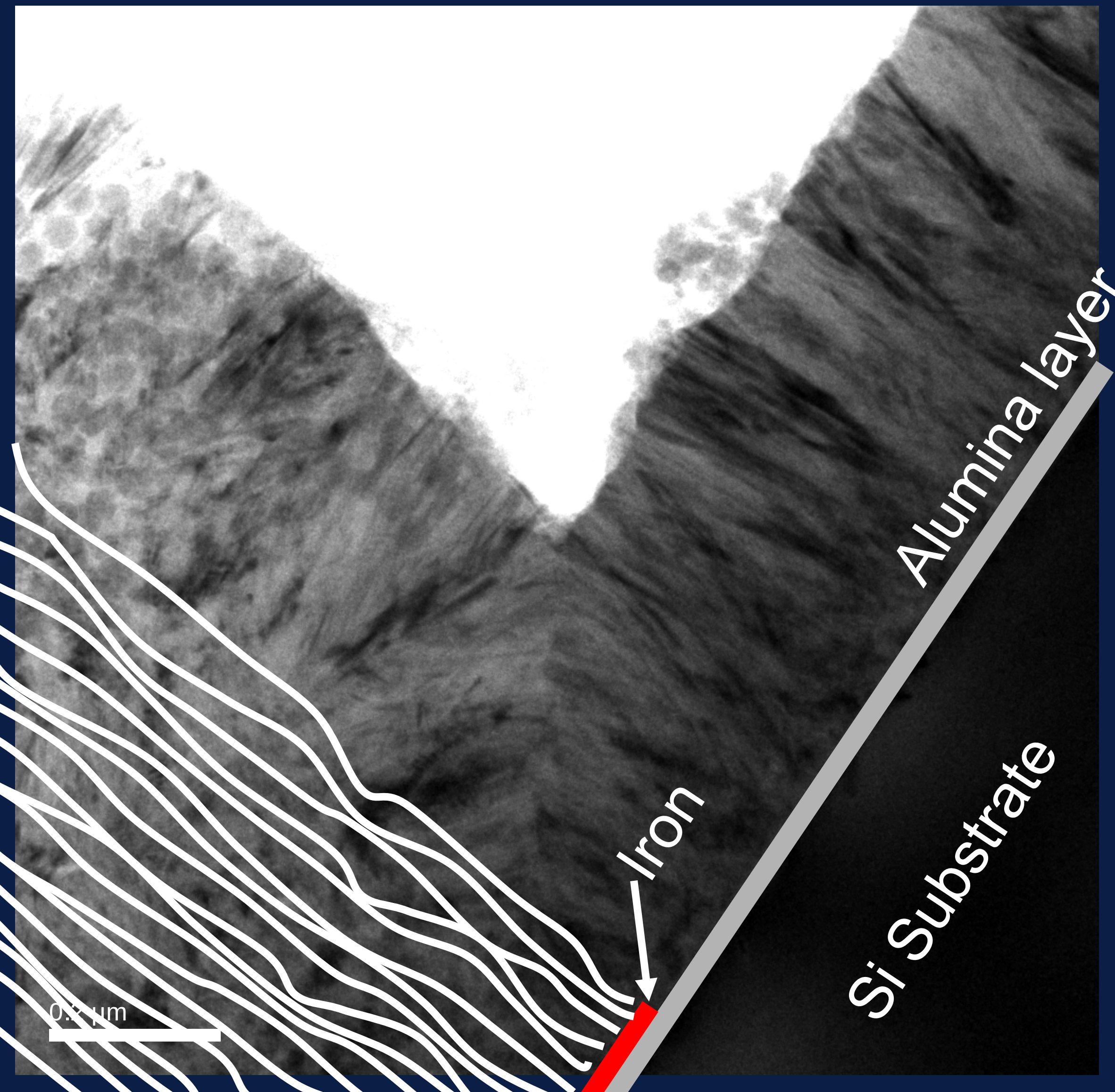


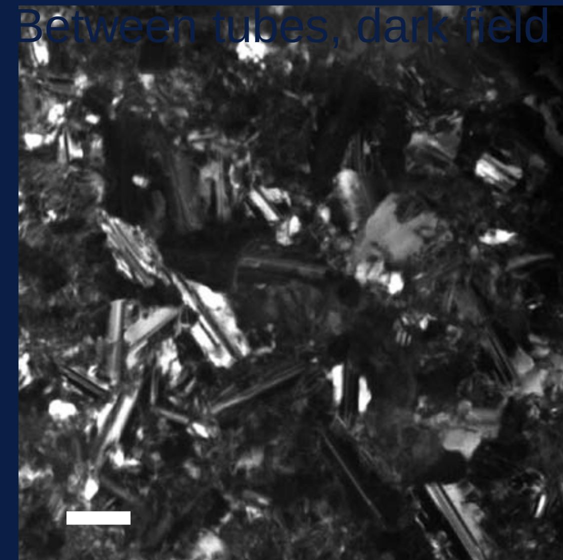
Between tubes, dark field

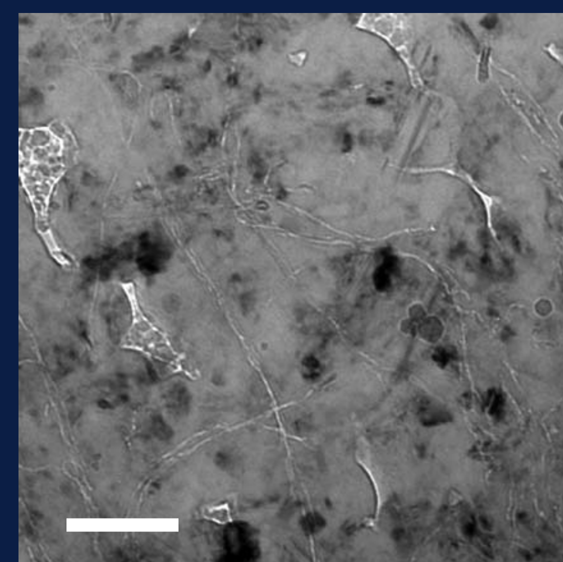




Properties: Poly-Si







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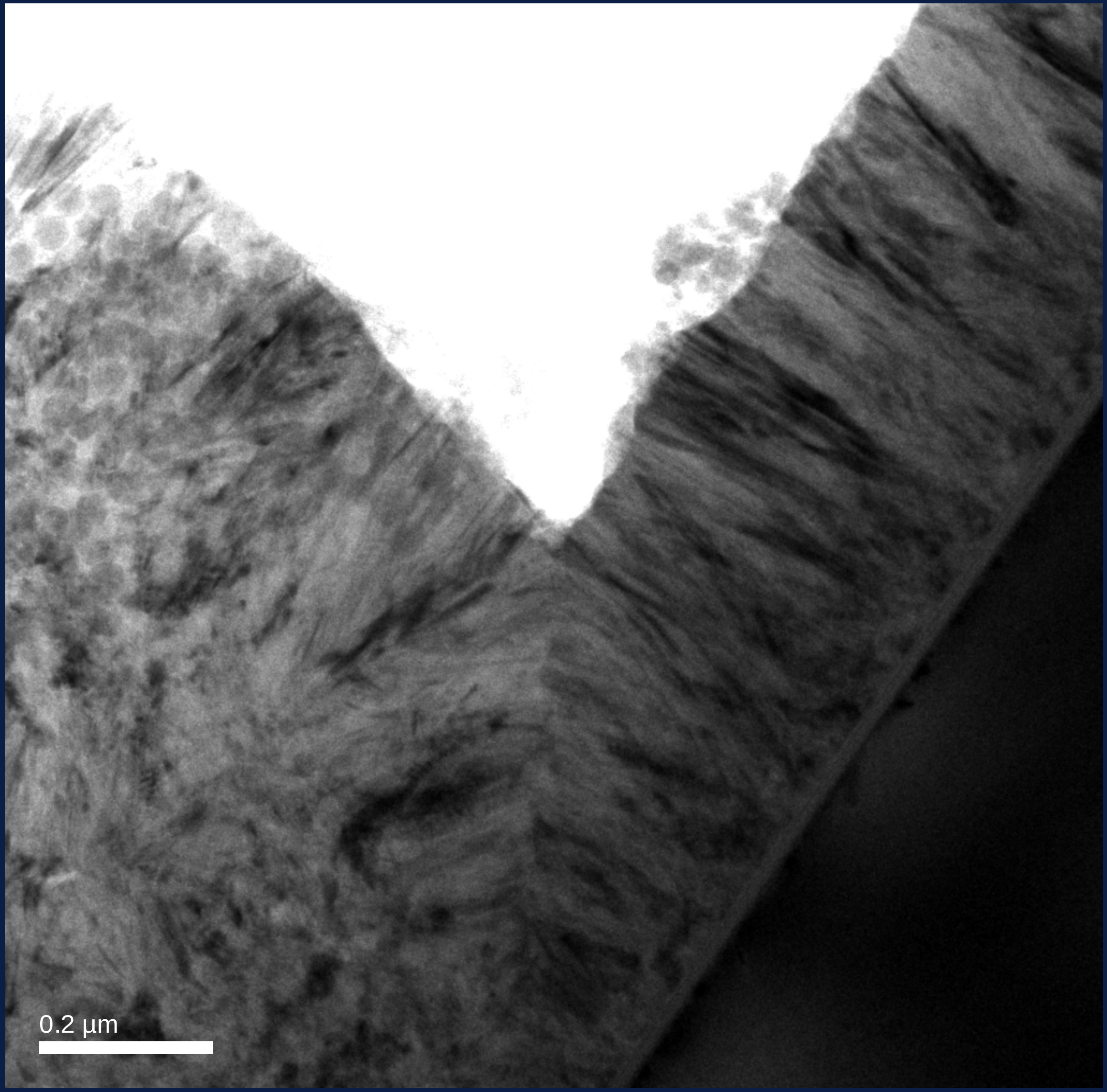

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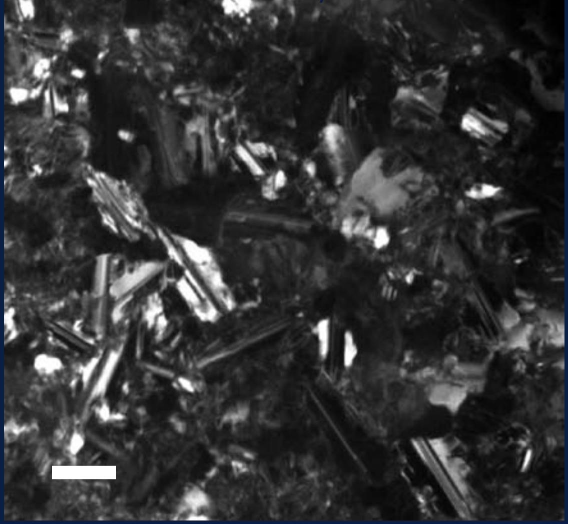

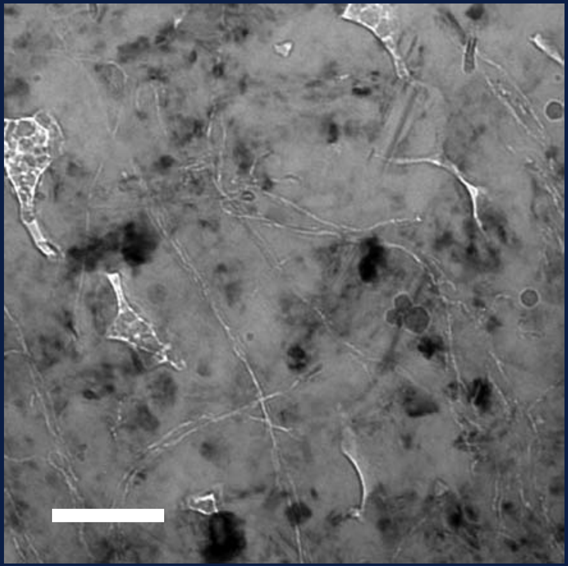

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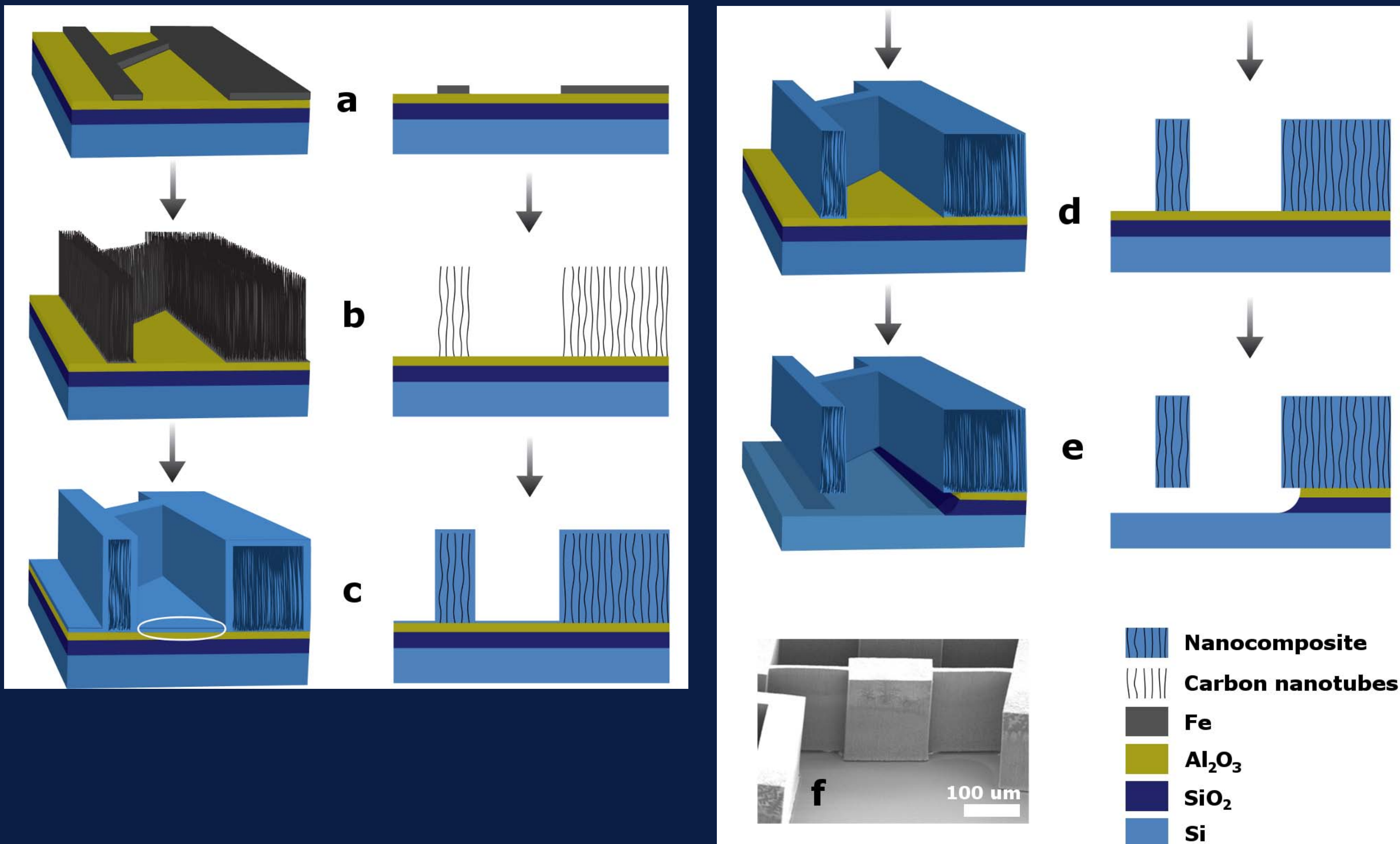
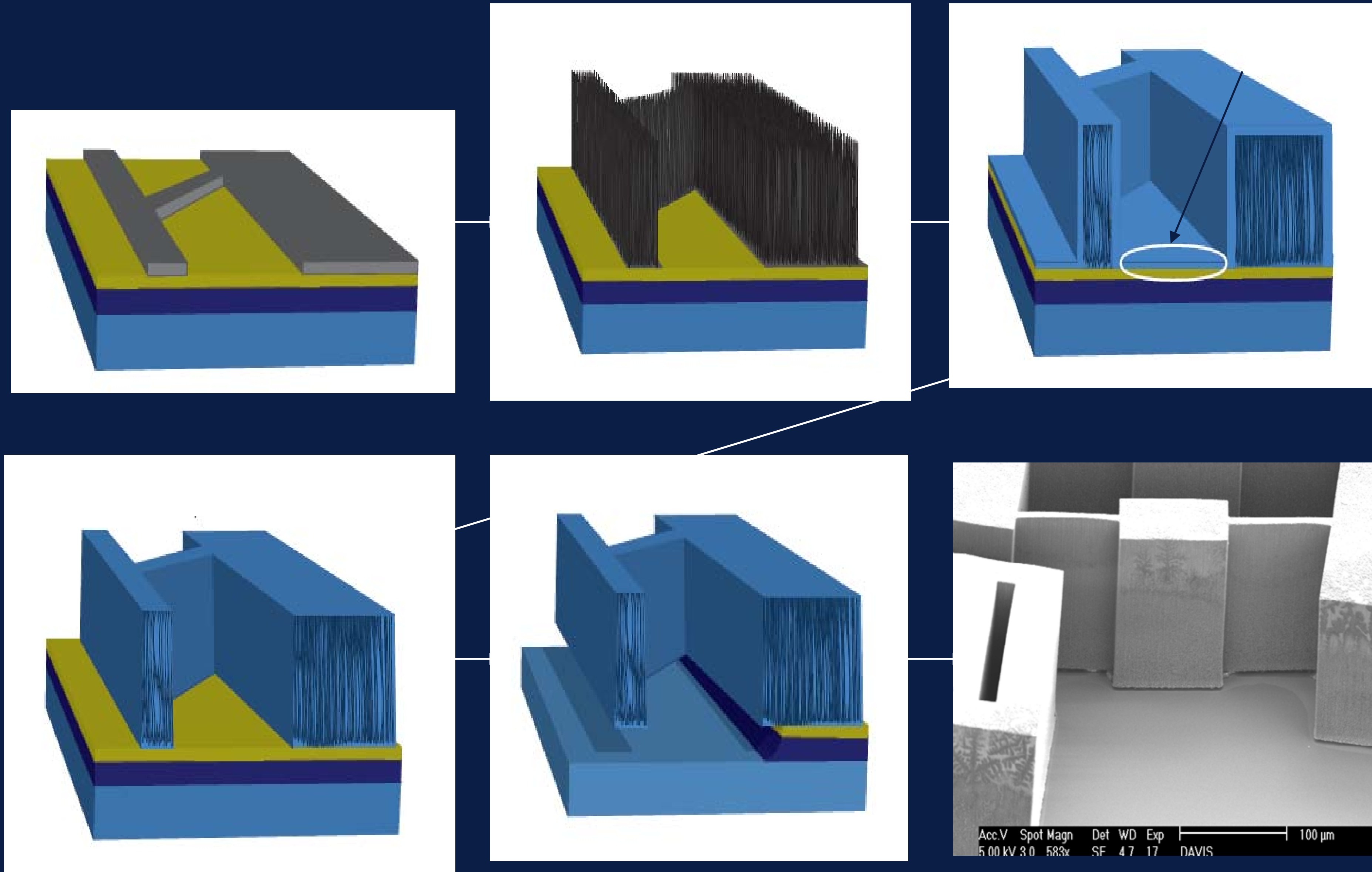
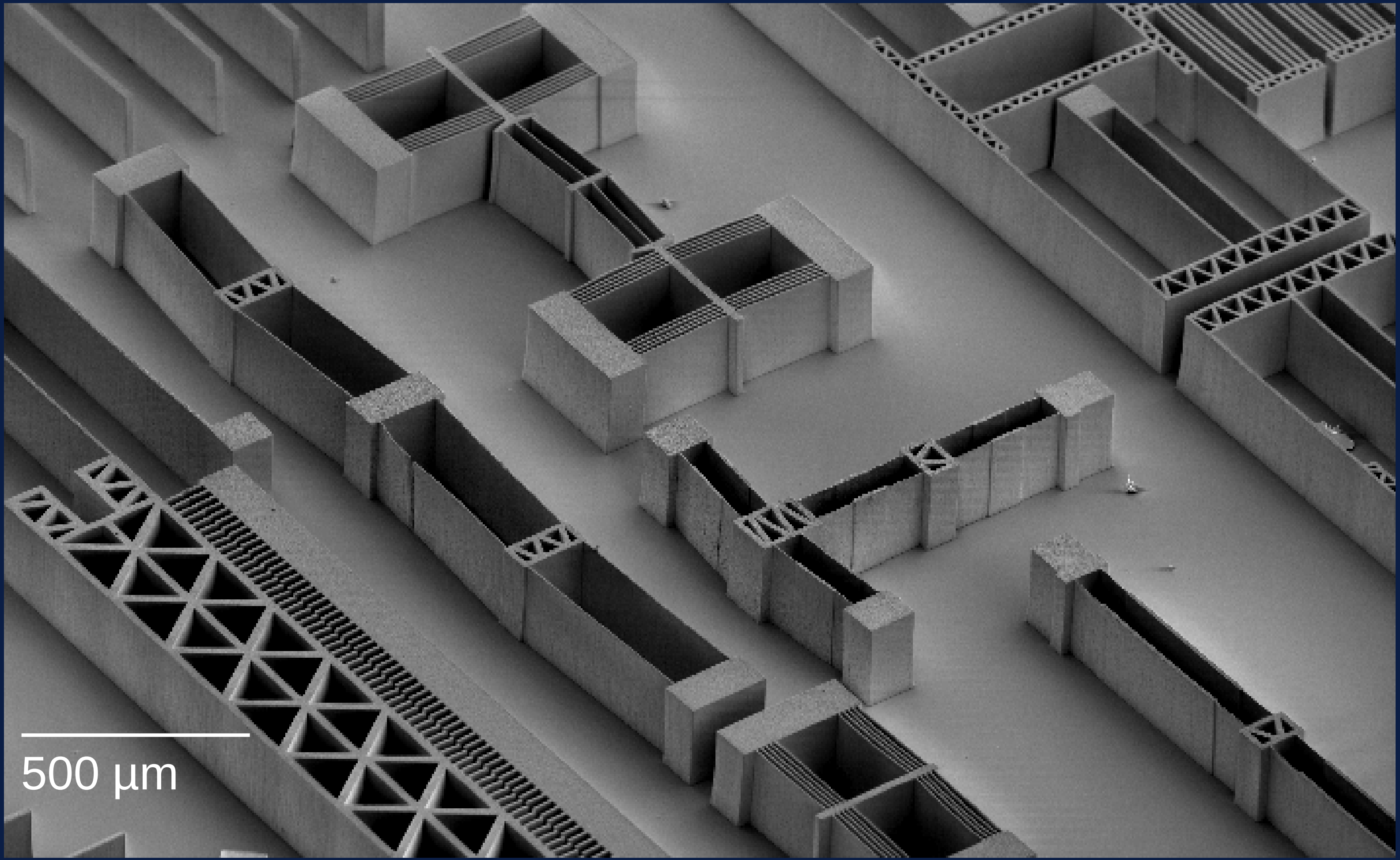


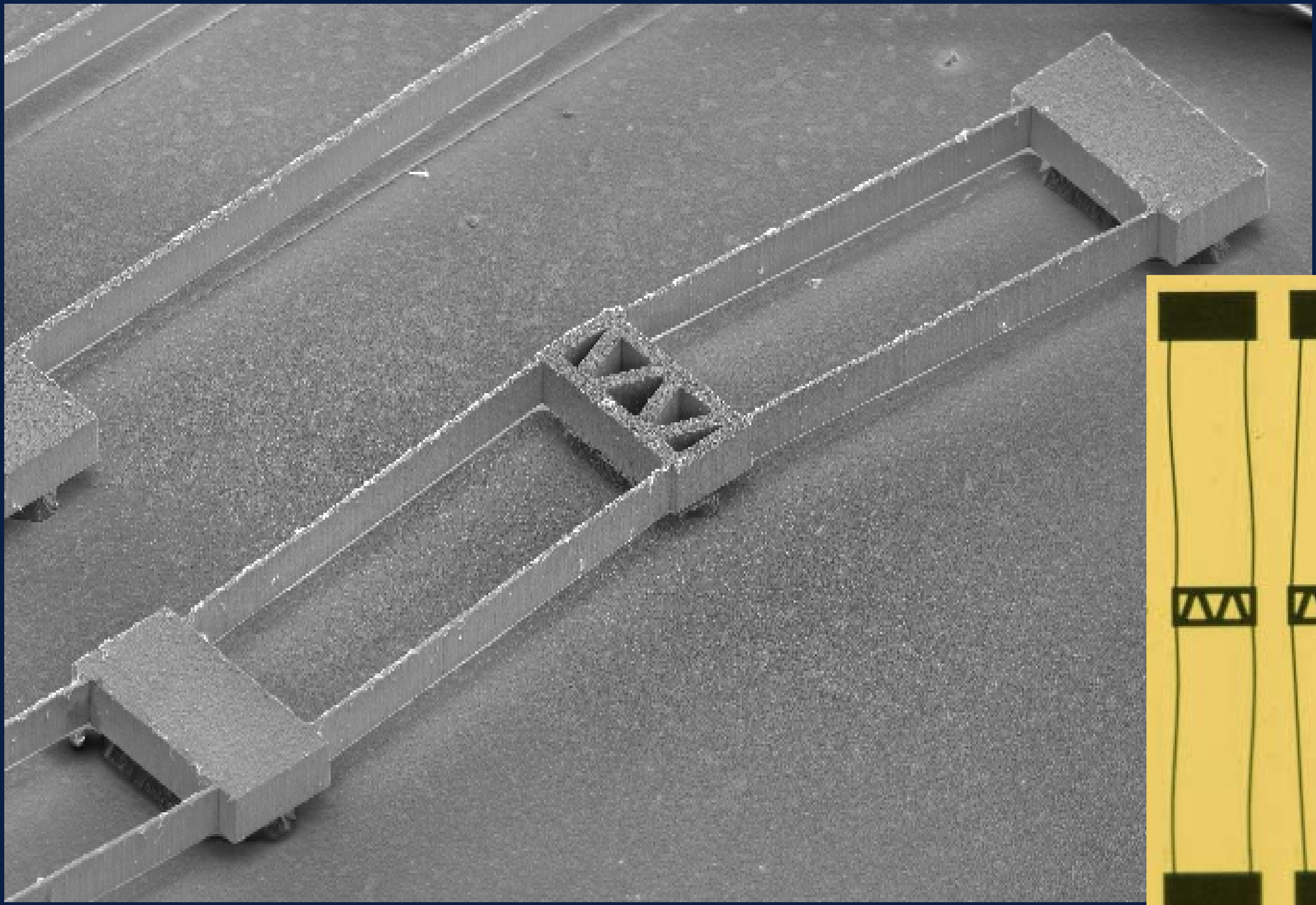
VACNT Composite MEMS Process

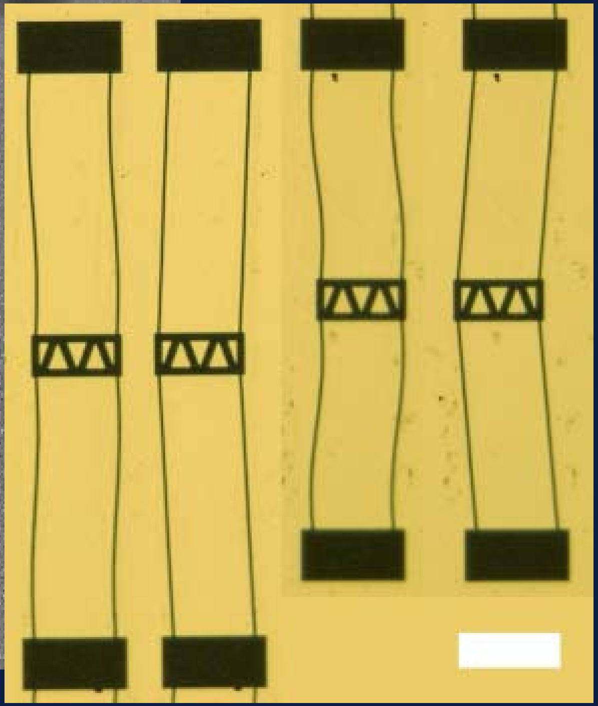


VACNT Templated Microstructures



Bi-stable Mechanism





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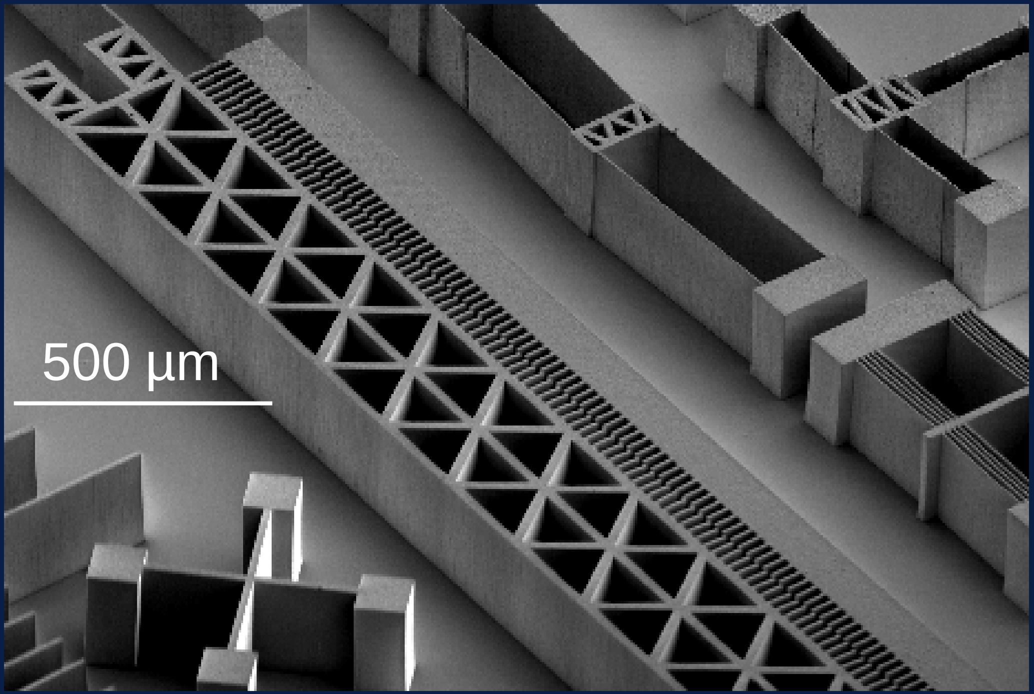
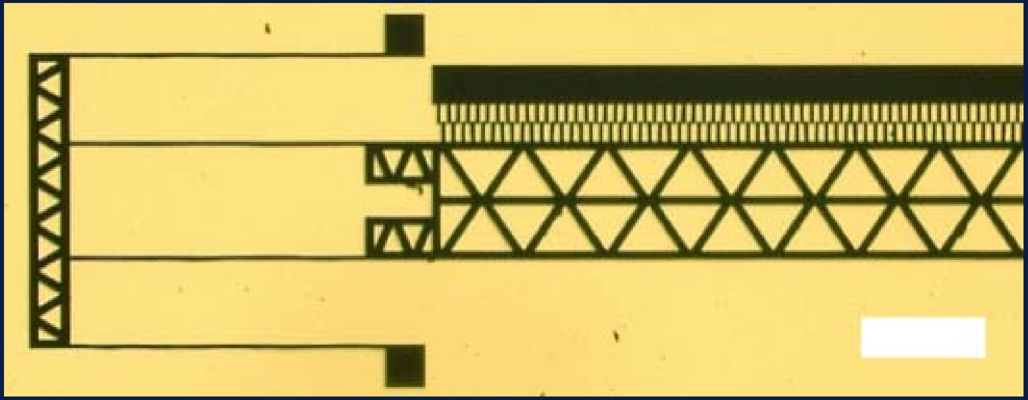
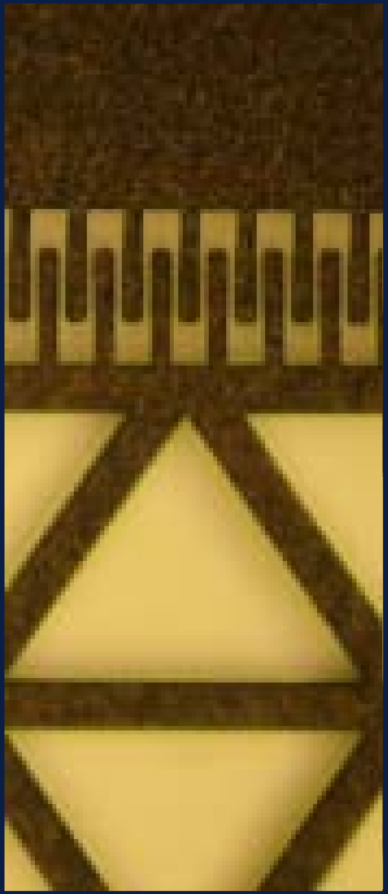
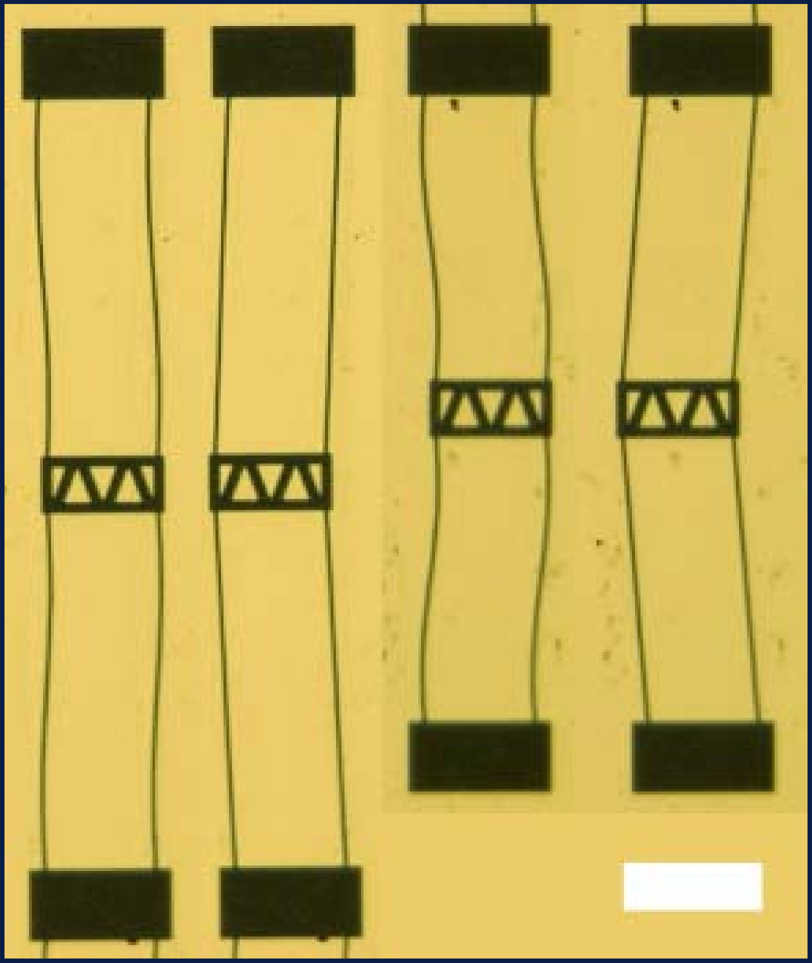
Comb Drive



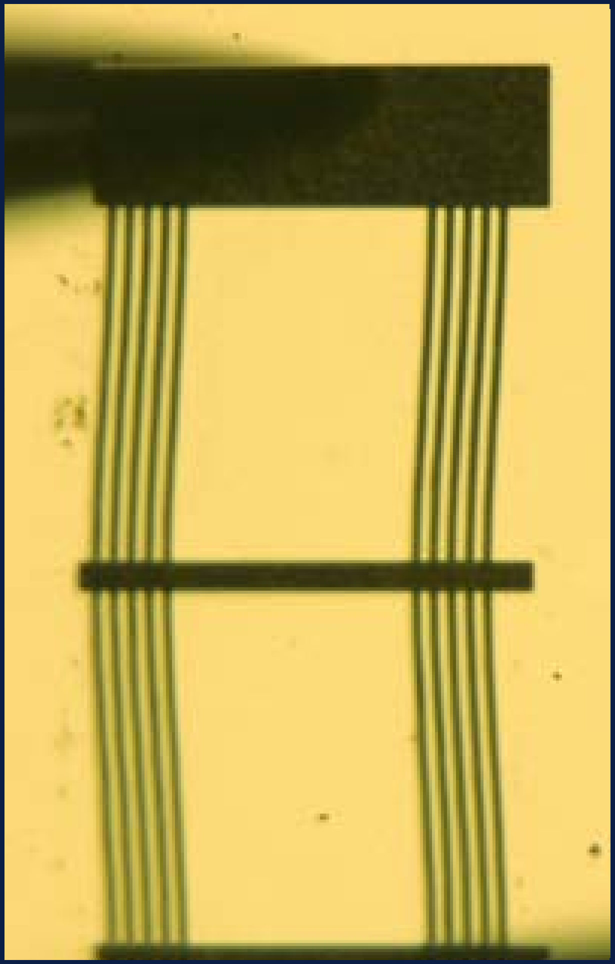




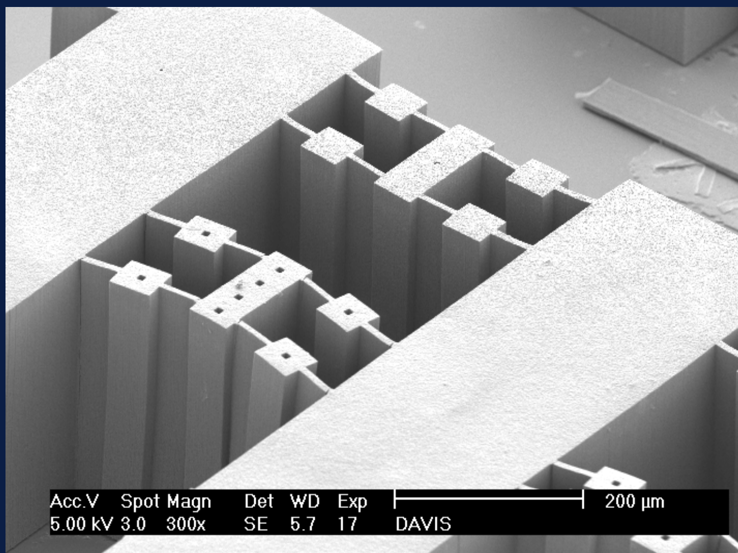
Bistable Mechanisms

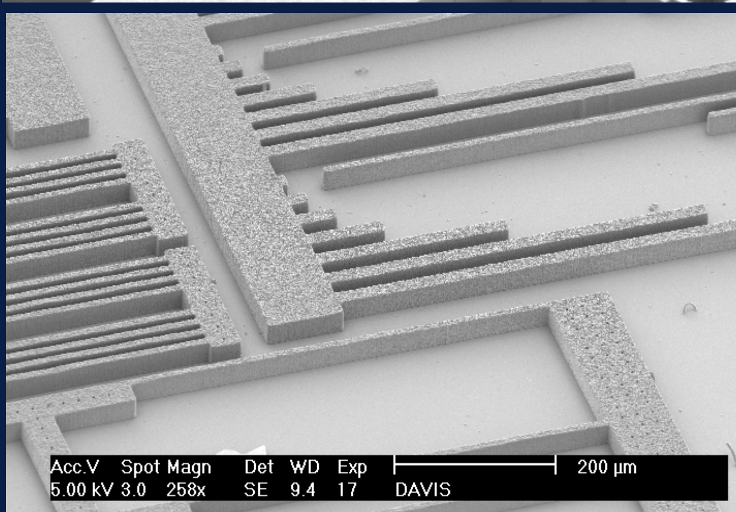


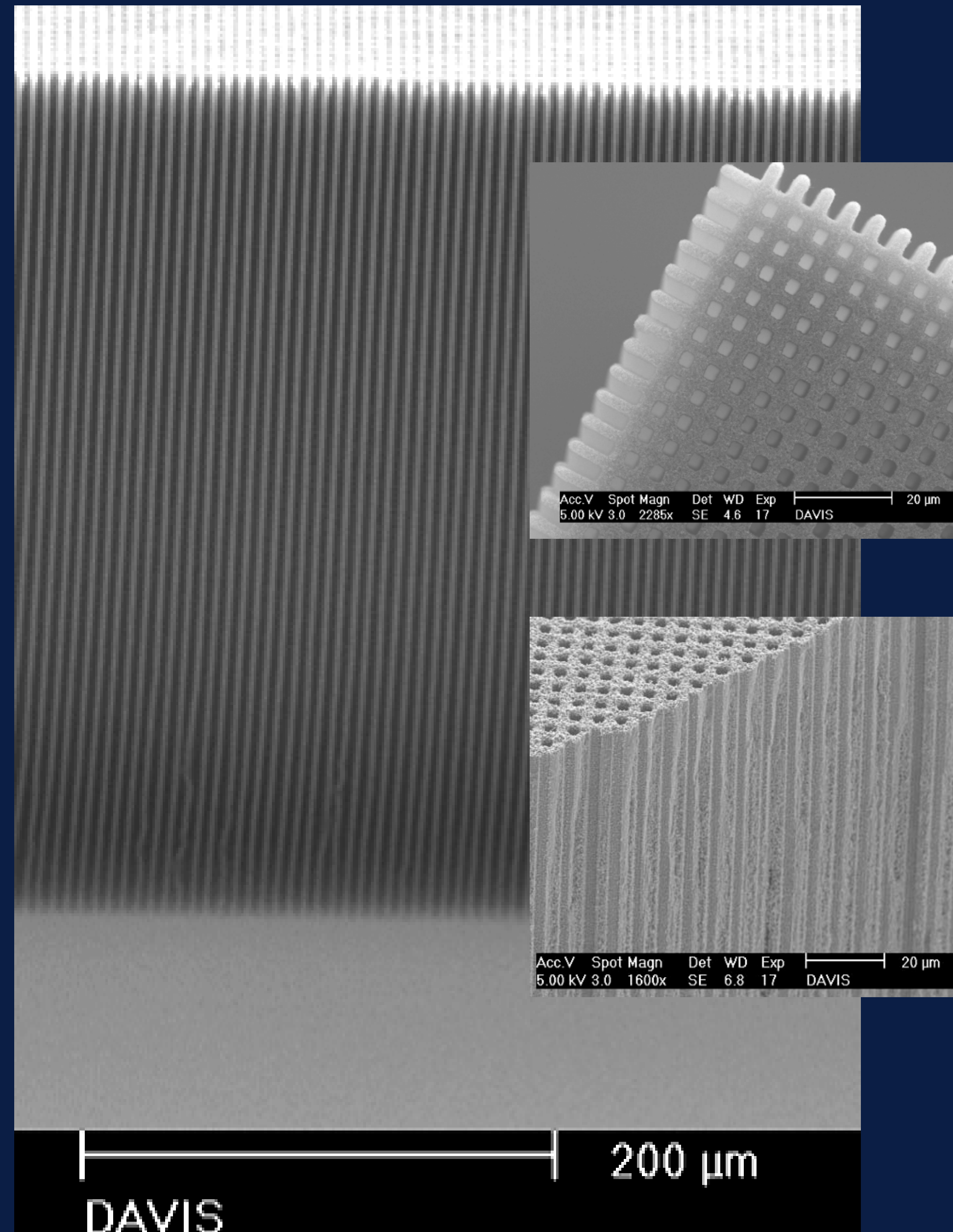
Thermomechanical In-Plane Microactuator (TIM)



Solid High Aspect Ratio Structures

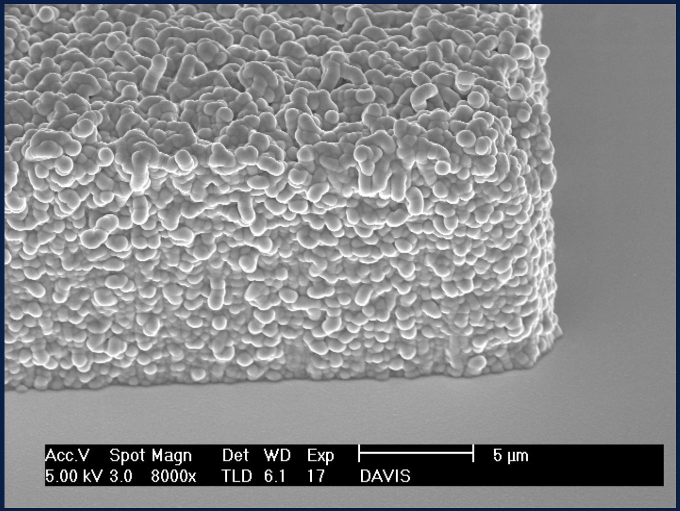


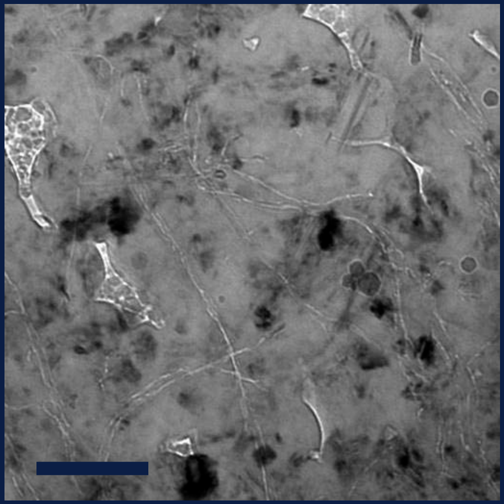




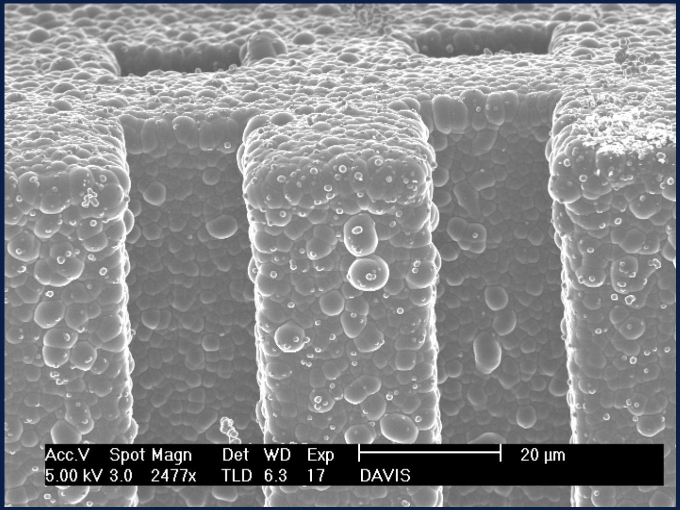
A variety of materials?

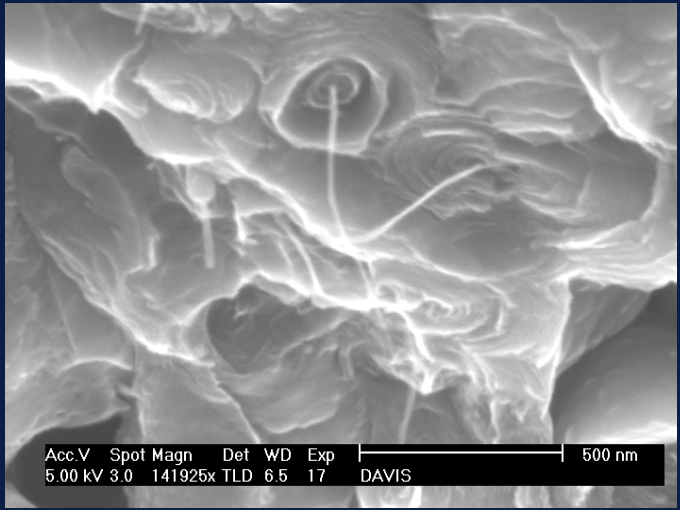
Filled with amorphous Si:





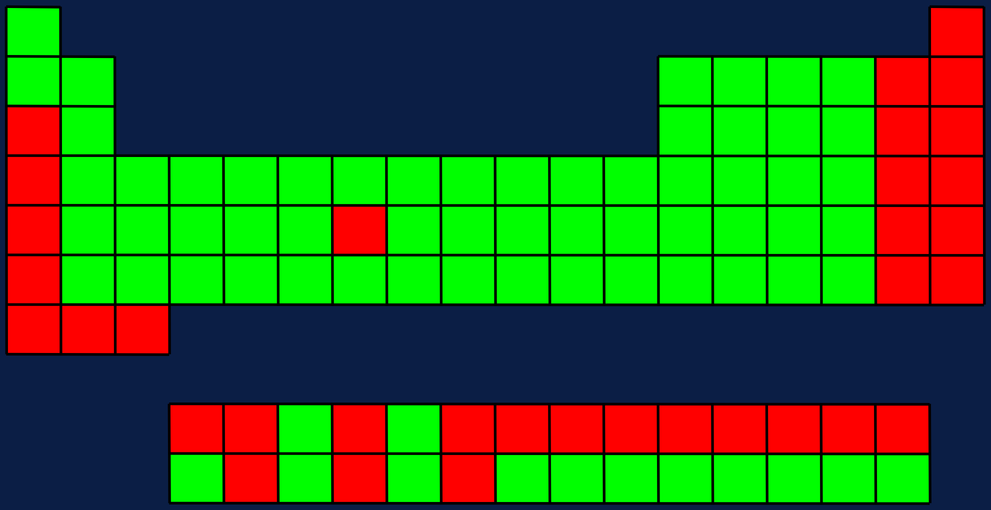
Filled with amorphous C:





High aspect ratio structures in a variety of materials?

Si, SiNx, C and SiO2



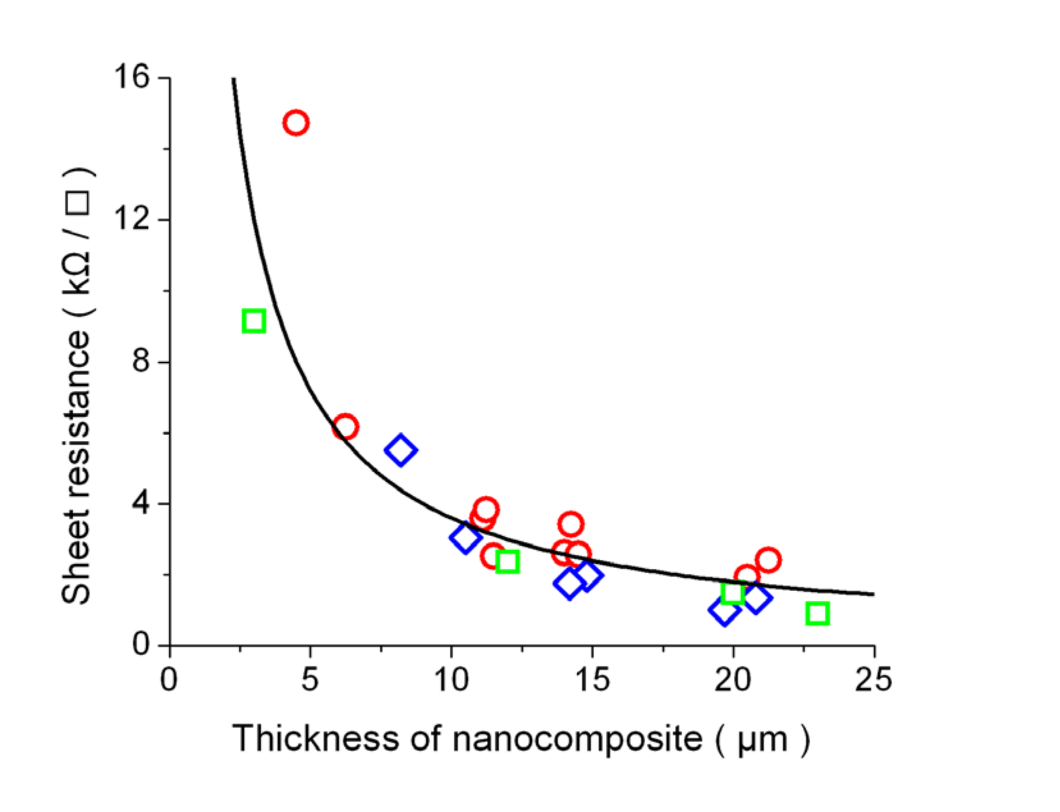
FROM: *Chemical Vapor Deposition*, ed. Jong-Hee Park, ASM International (2001)

Properties: Resistivity

- Isolated nanotubes: Can exhibit ballistic conduction over distances of several microns
- Undoped poly-Si: $\rho \sim 10^2\ \Omega$ cm
- Si-coated nanotubes: ρ ~ ?

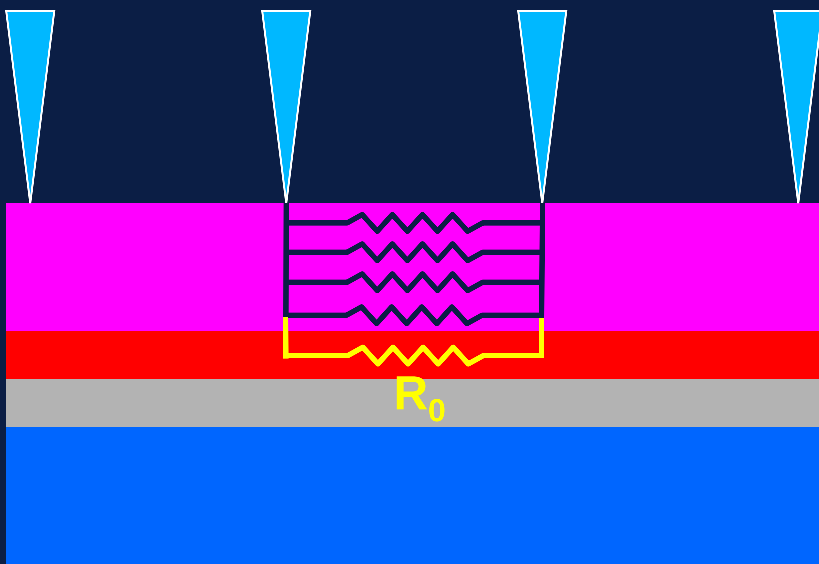
- Coat tubes with insulator → Conductive MEMS made from insulating materials?

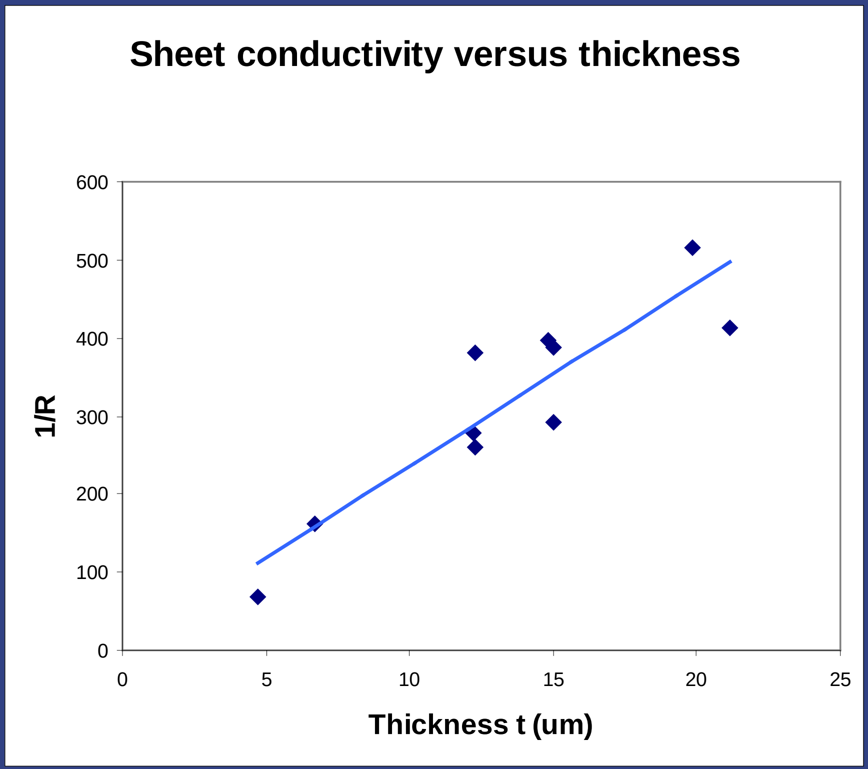
Properties: Resistivity



Sheet resistance versus thickness for silicon-filled forests (red circles), silicon nitride-filled forests (green squares), and 20 nm of silicon followed by filling with silicon nitride (blue diamonds) reveals the expected inverse proportionality relationship. The solid line is calculated for an infinitely thin sample with resistivity of 3.6 Ω cm.

Properties: Resistivity

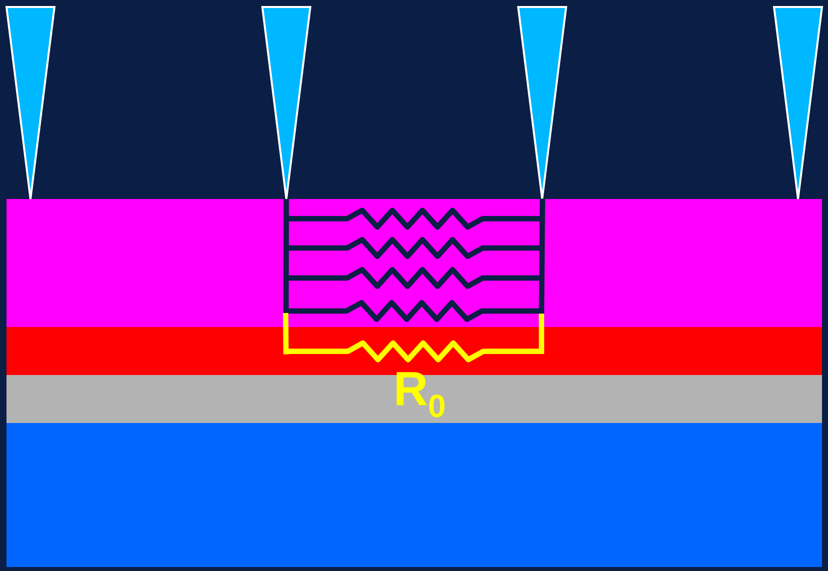


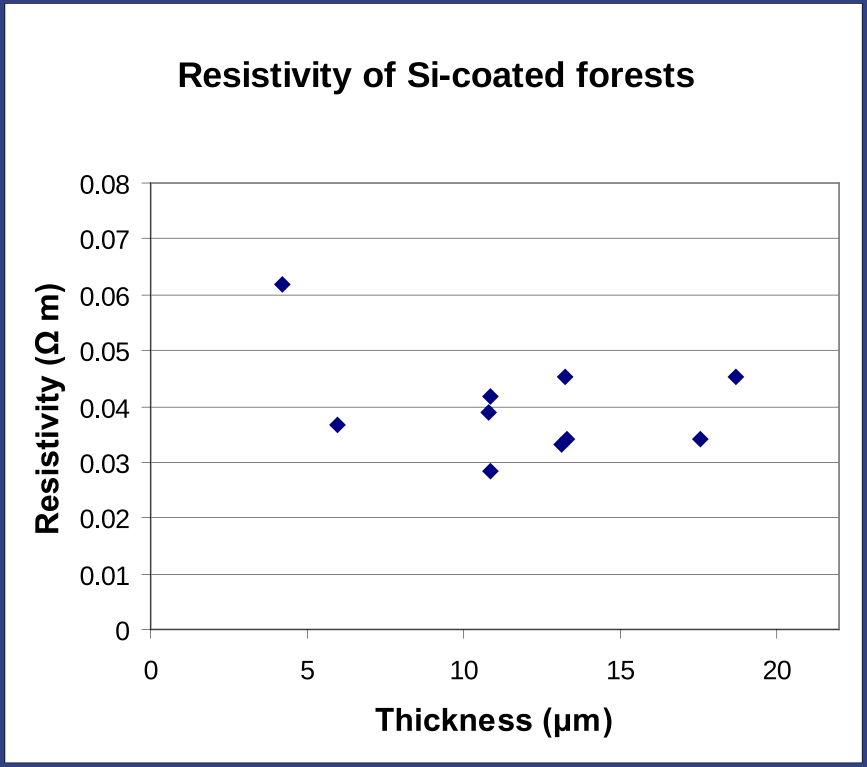


$$R_{sheet} = \frac{K_1}{t + K_2} \approx \frac{K_1}{t}$$

$K_1 = 42.6\ \Omega\ \mathrm{m}$
$K_2 = 0.04\ \mu\mathrm{m}$

Properties: Resistivity

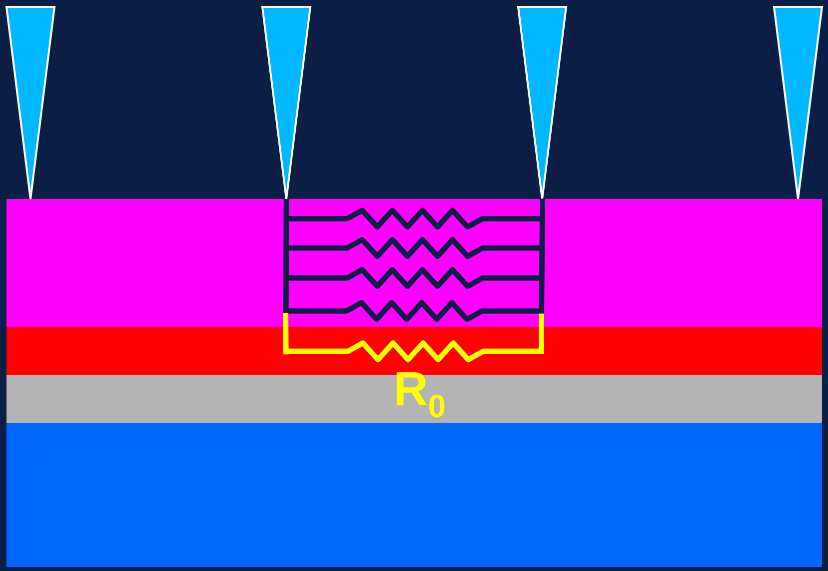


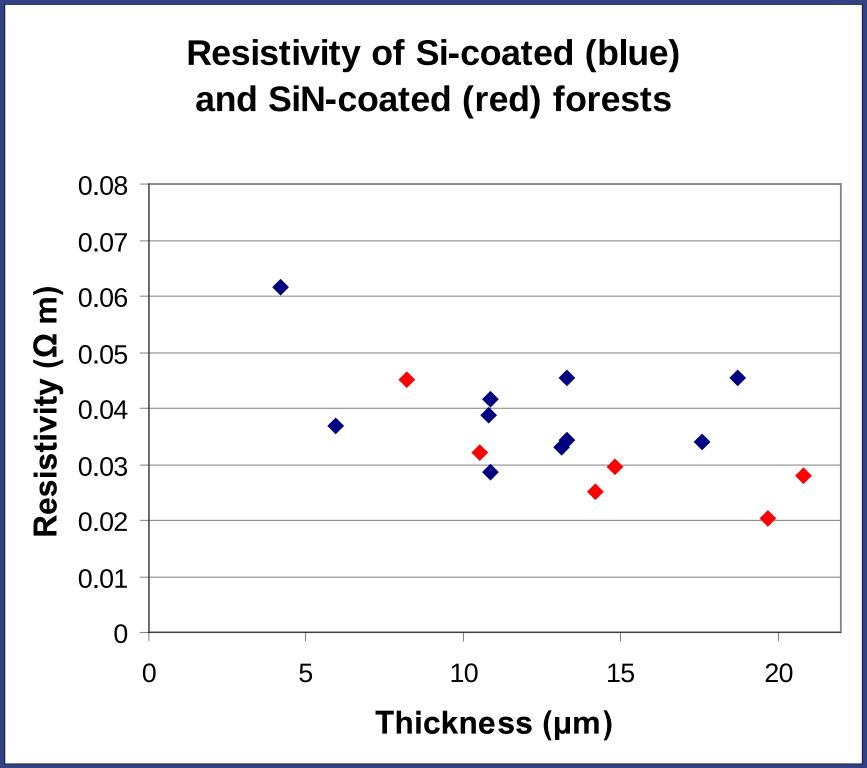


$\rho_{forest} \sim 4\ \Omega\ cm$

$\rho_{poly\text{-}Si\ alone} \sim 10000\ \Omega\ m$

Properties: Resistivity

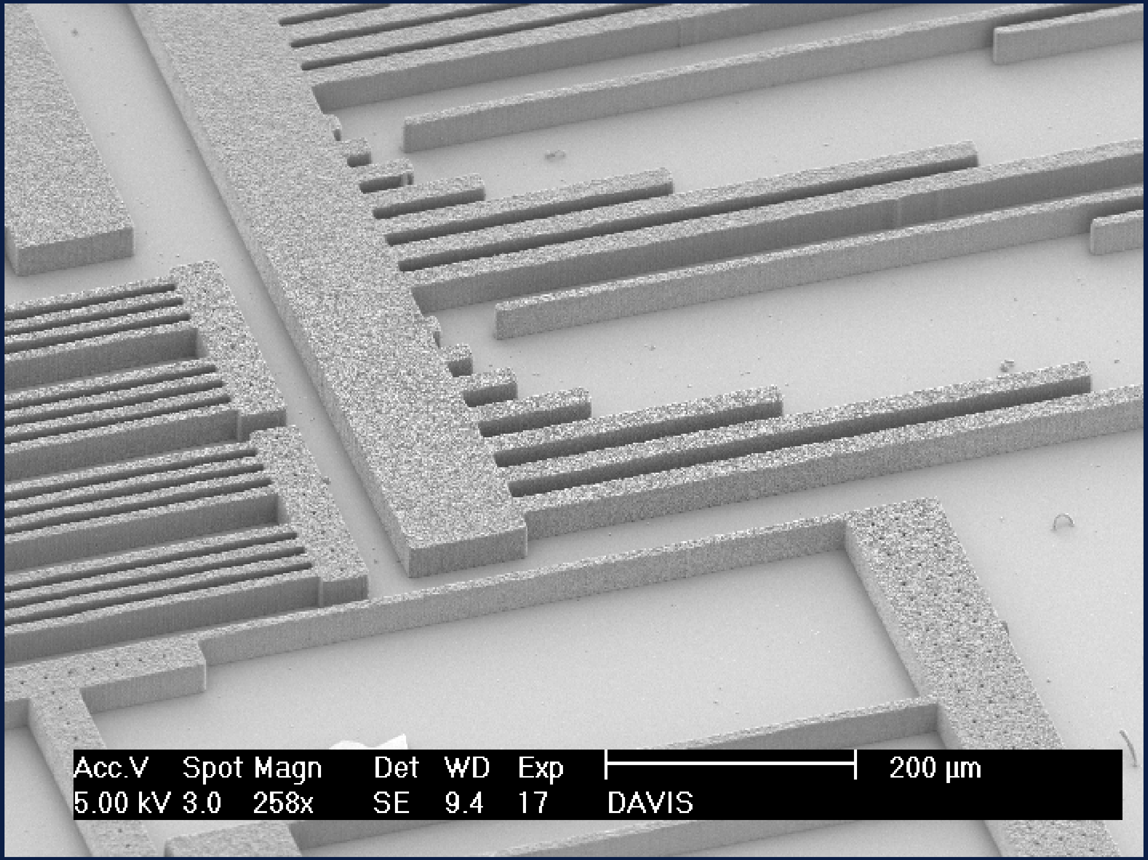




$\rho_{forest} \sim 4\ \Omega\text{-cm}$

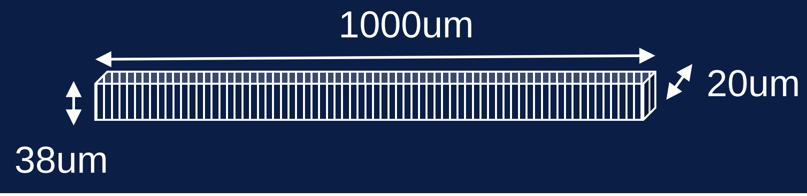
Approximately the same resistivity as previously reported for other CNT-composites

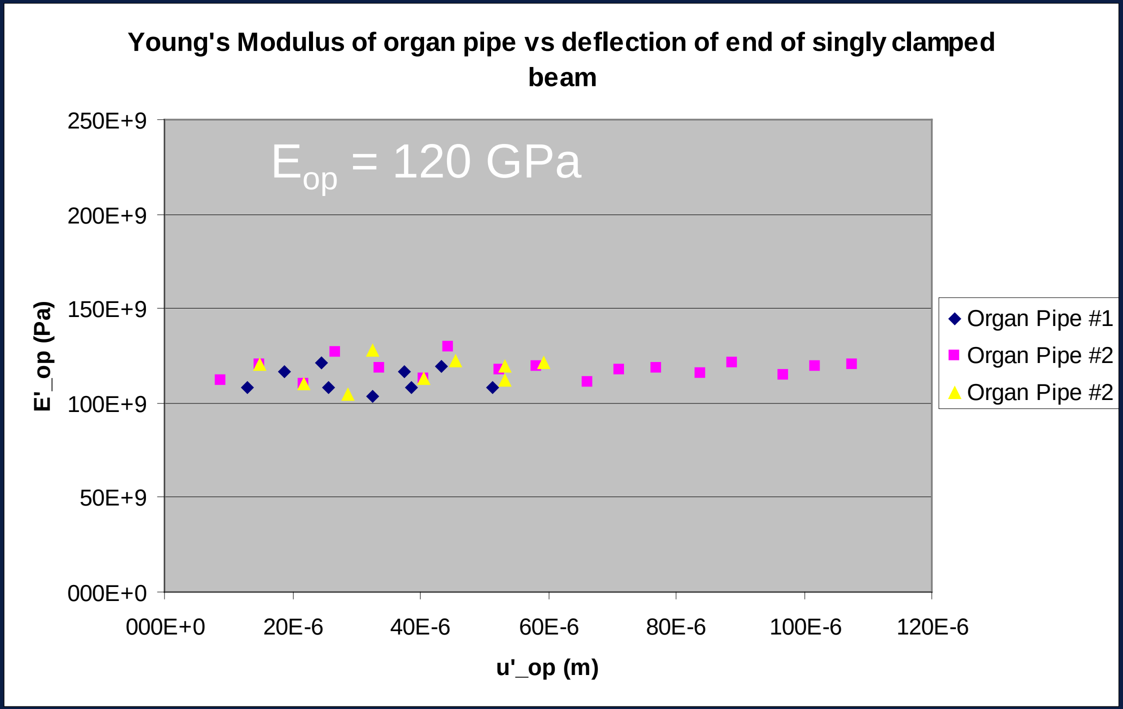
Mechanical Characterization



Filled forests are solid and well adhered (can withstand the scotch tape test)

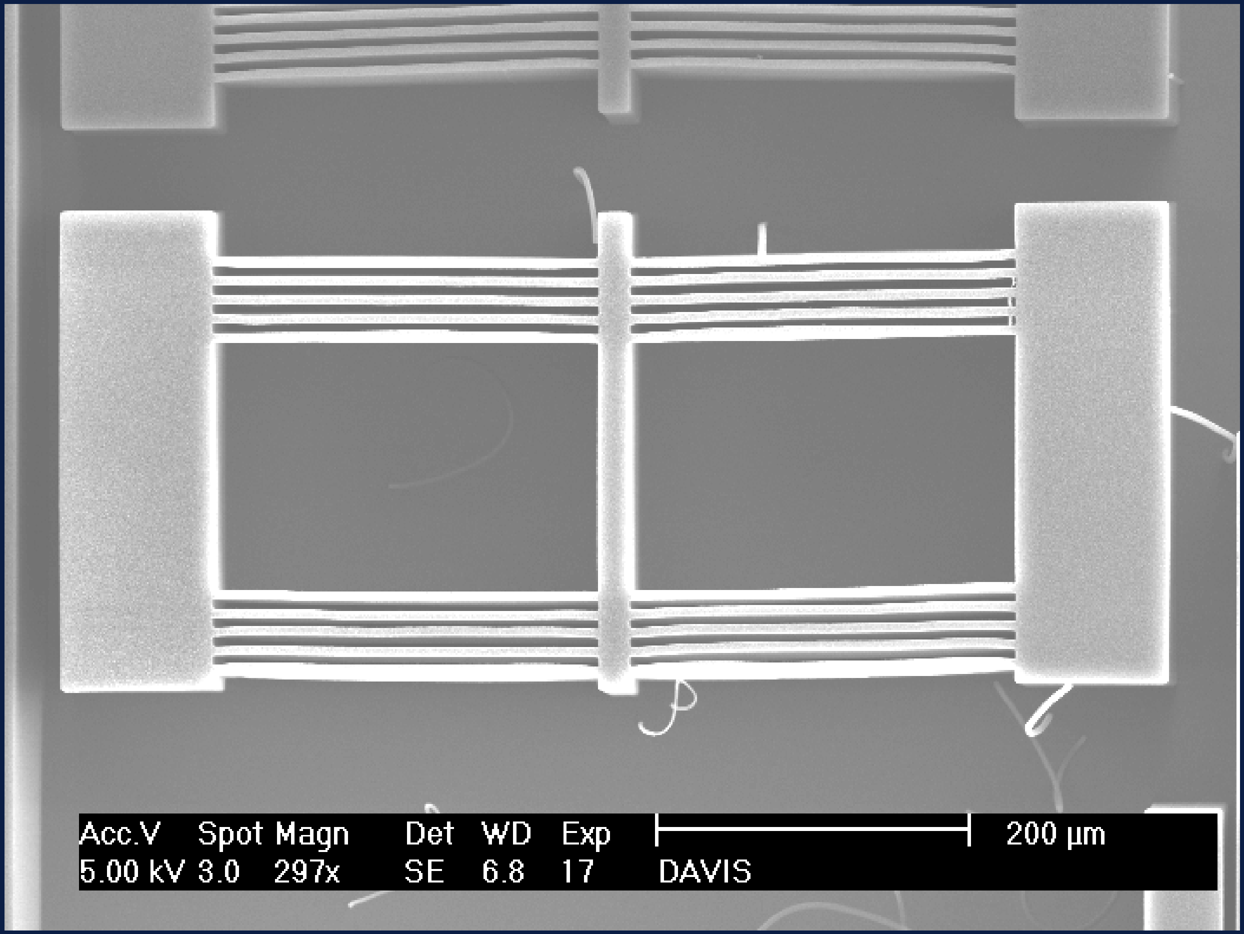
Beam Bending Measurement of Elastic Modulus





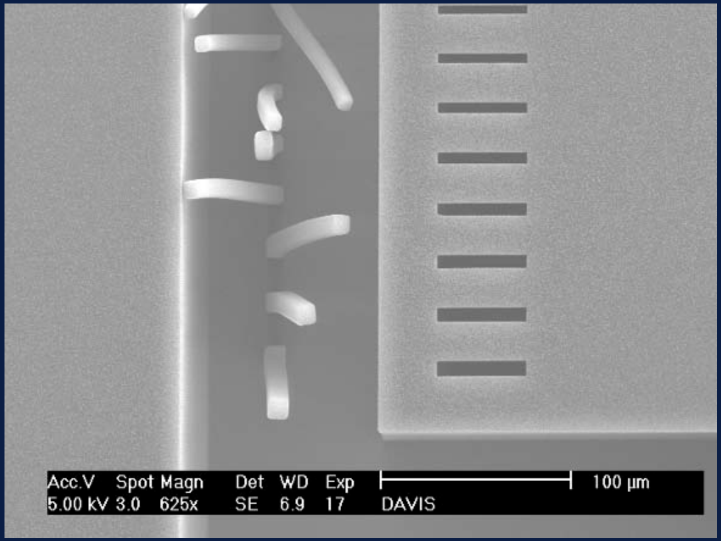
Reported bulk polySi modulus ~ 140-210 GPa, dependent on deposition conditions

Actuated device: thermomechanical in-plane microactuator (TIM)

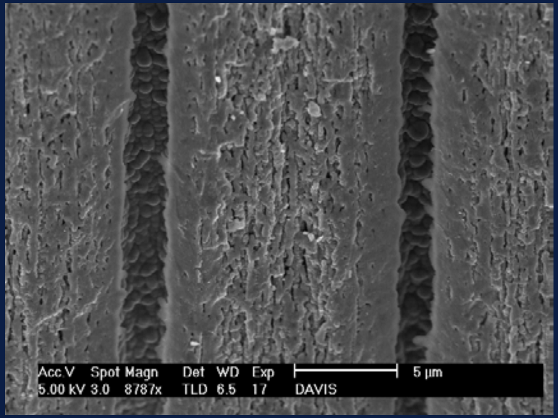


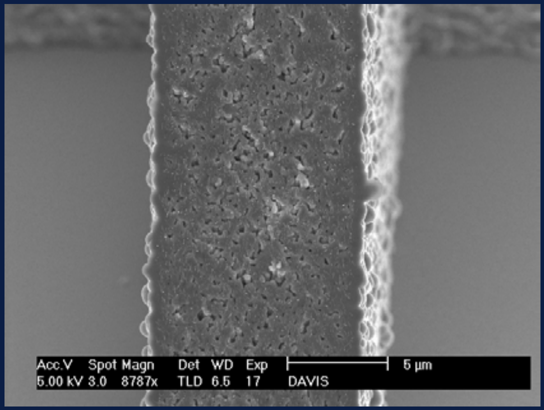
Developing Engineering Design Rules

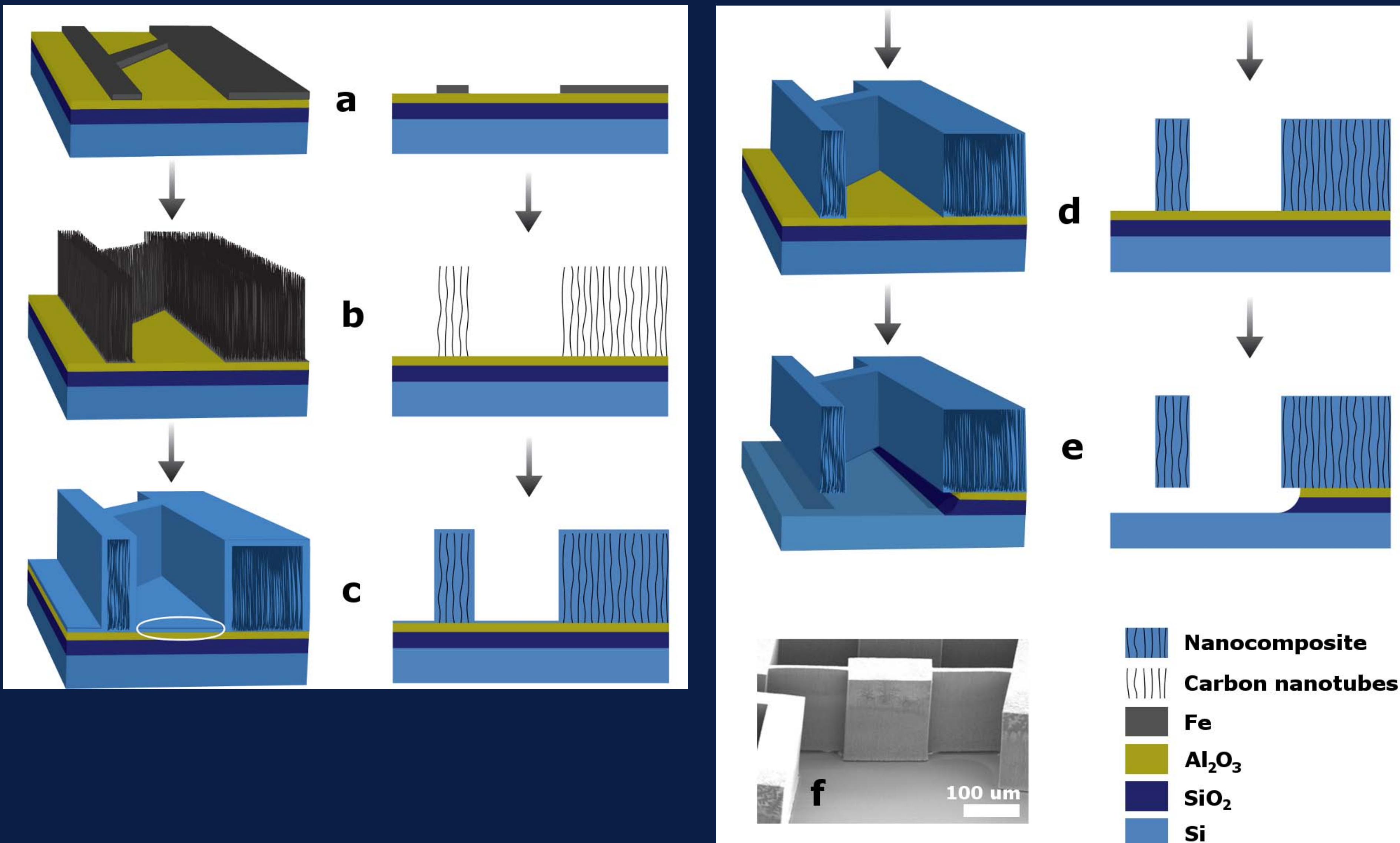
- Height to width ratio for dimensional stability



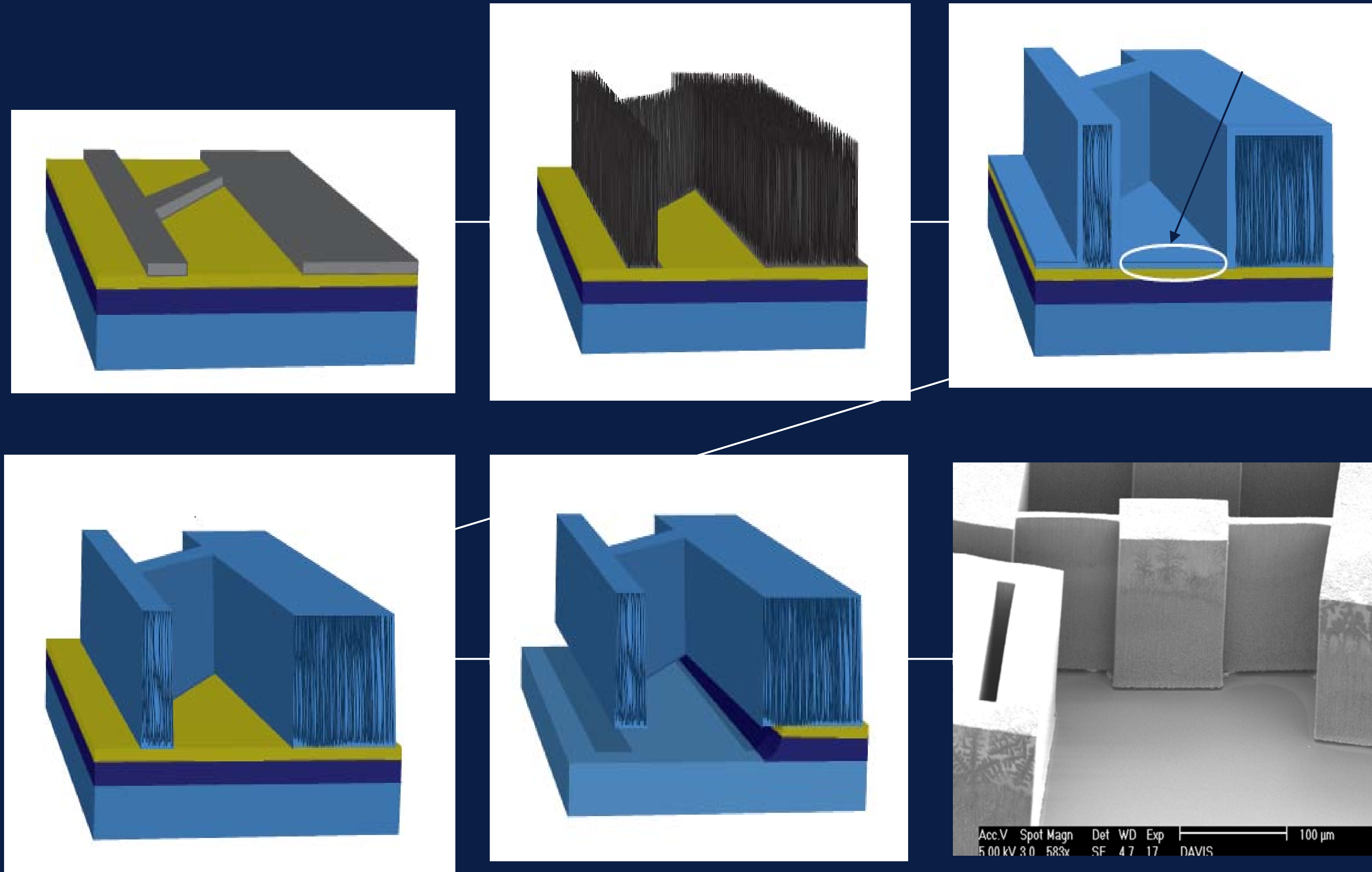
- Maximum feature width for filling of forest interior
- Role of geometry LPCVD fill-factor



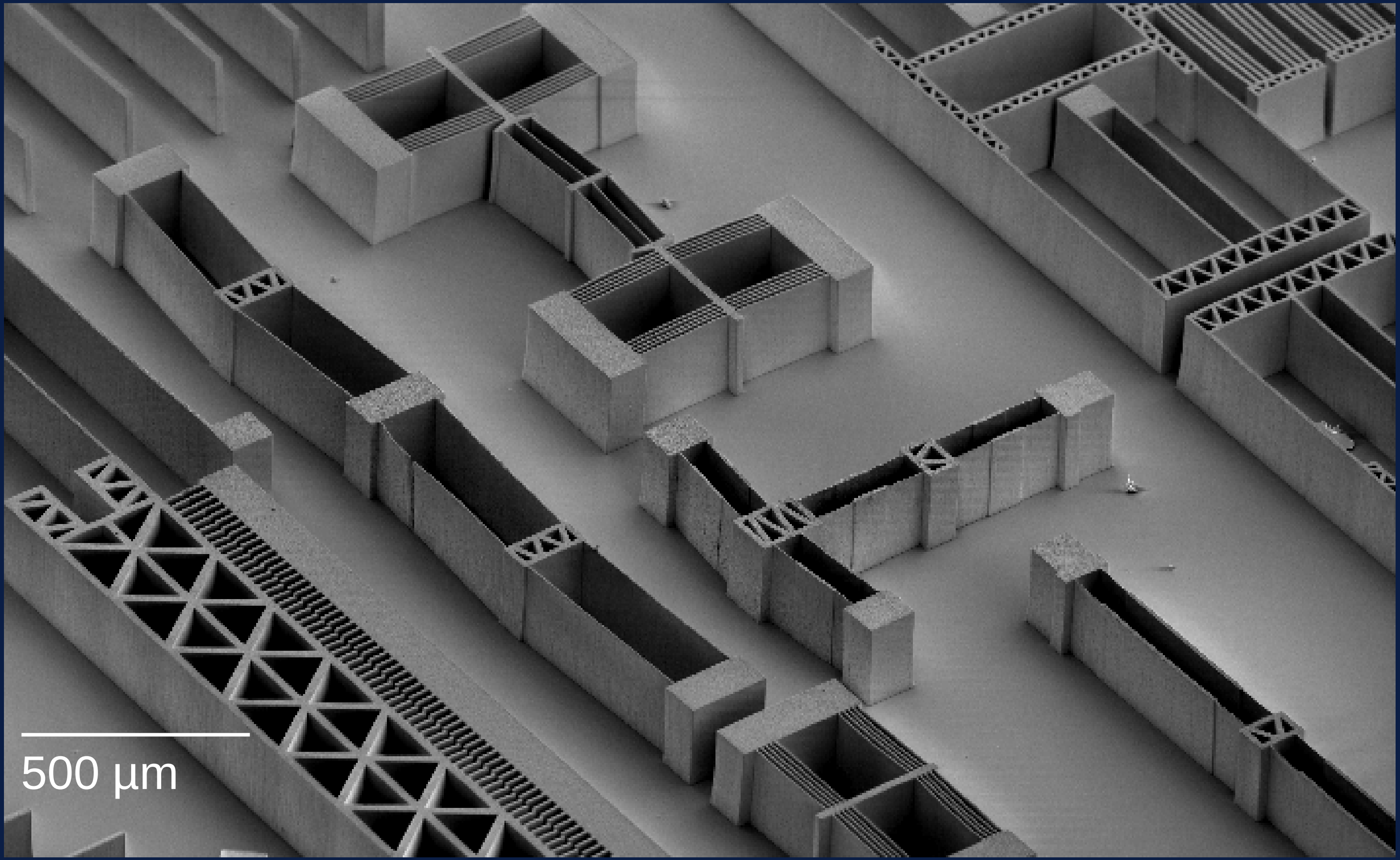



a
b
c
d
e
f
100 um
Nanocomposite
Carbon nanotubes
Fe
Al_2O_3
SiO_2
Si

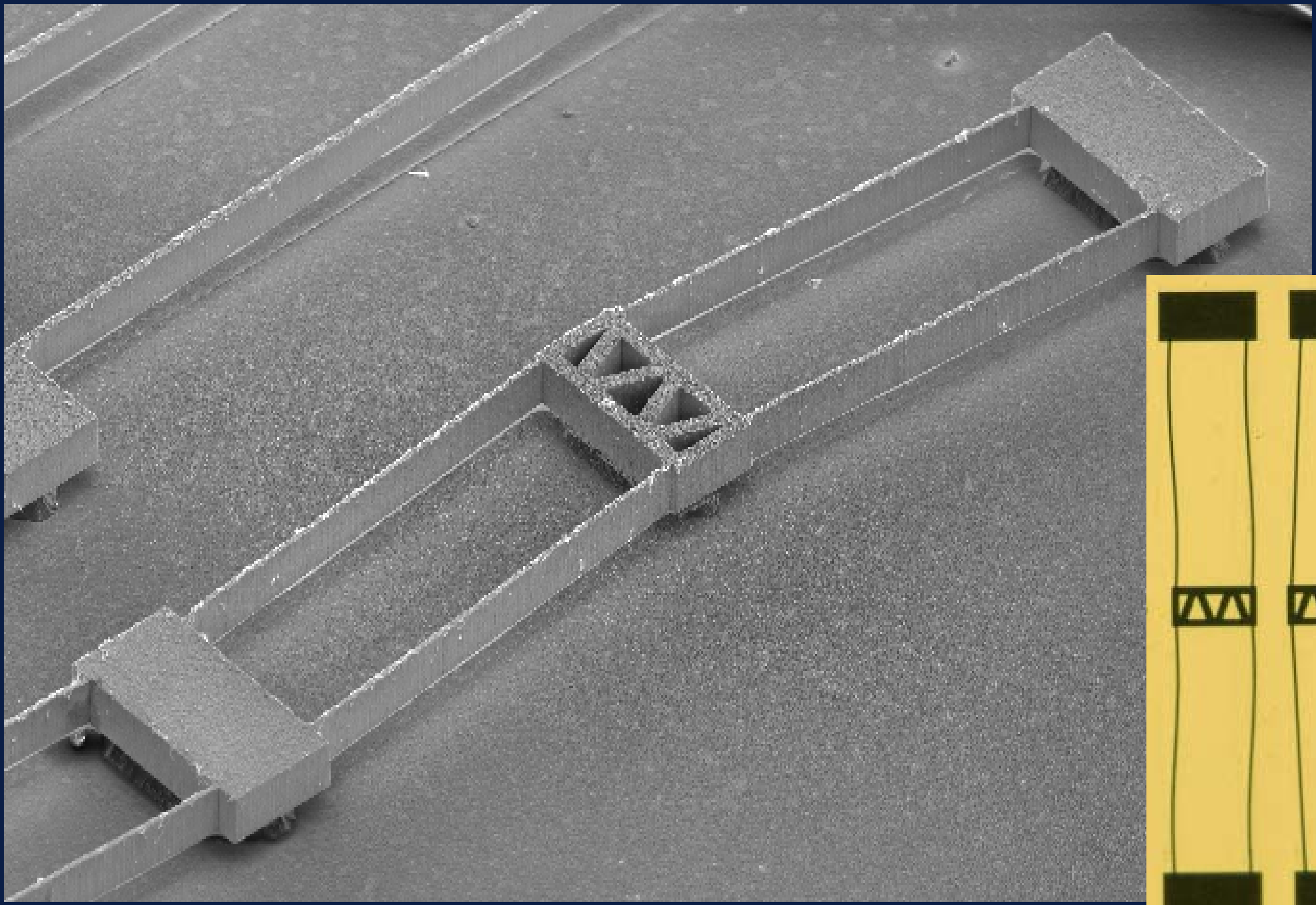
VACNT Composite MEMS Process

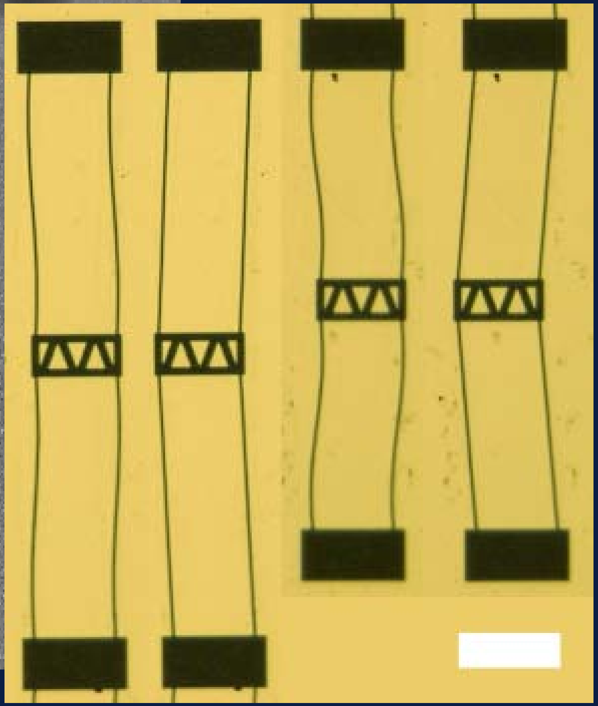


VACNT Templated Microstructures



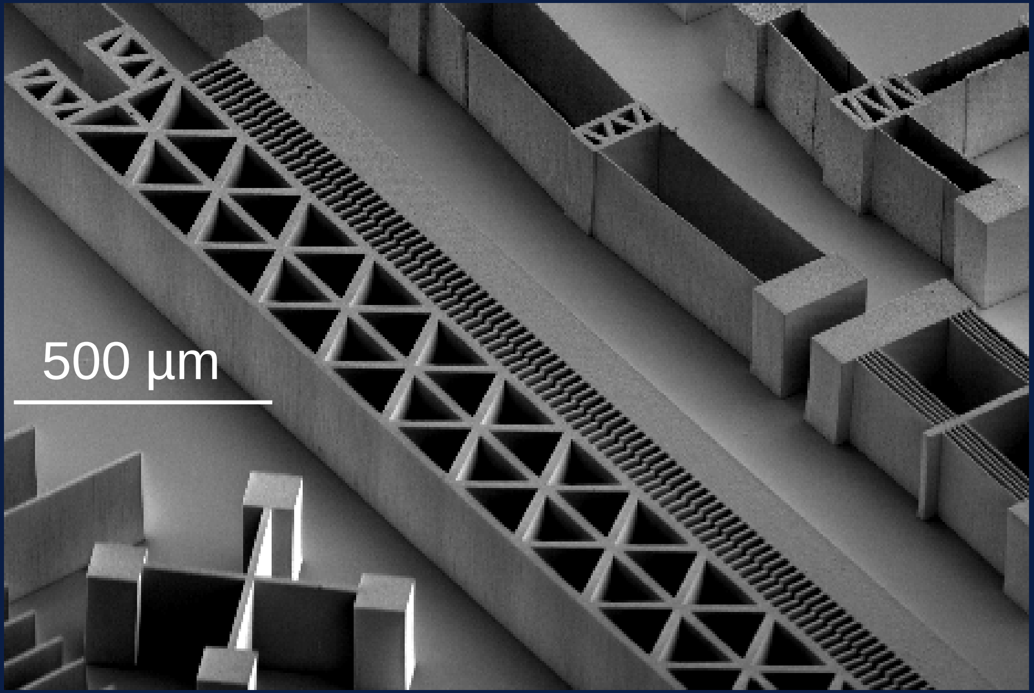
Bi-stable Mechanism

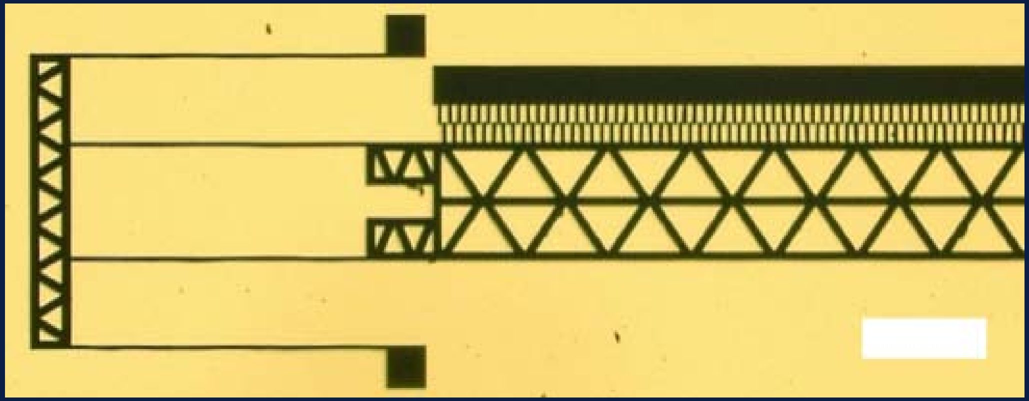


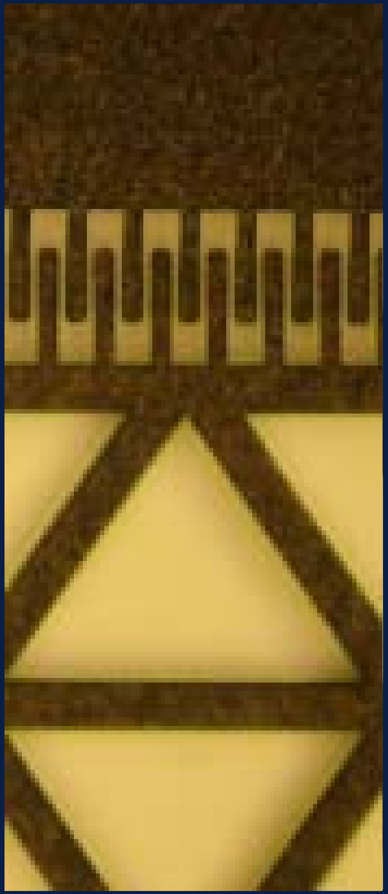


M2U00075.MPG

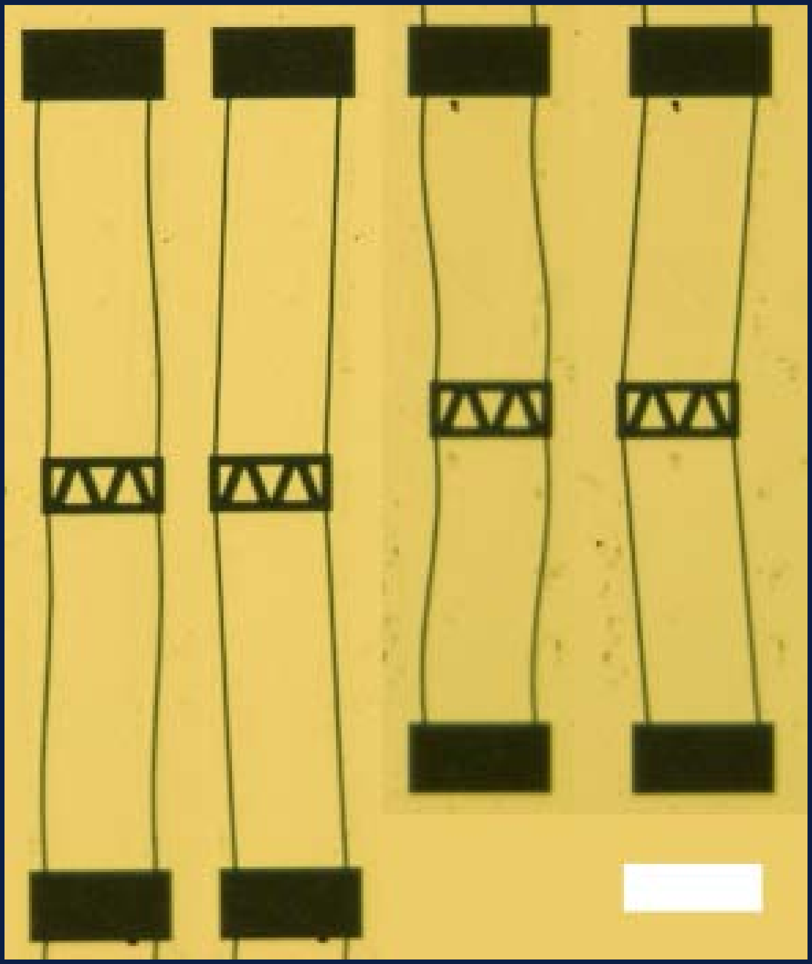
Comb Drive



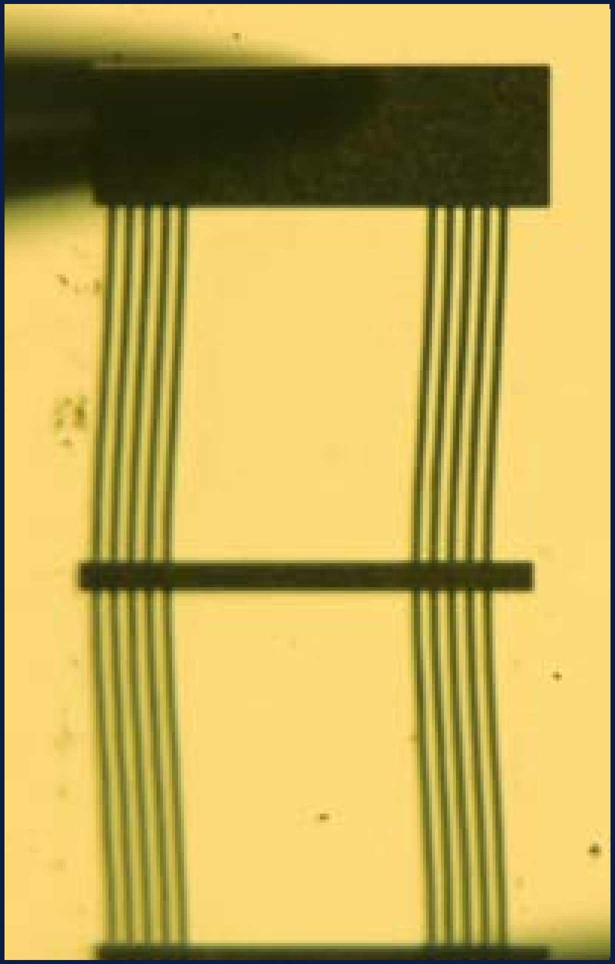




Bistable Mechanisms

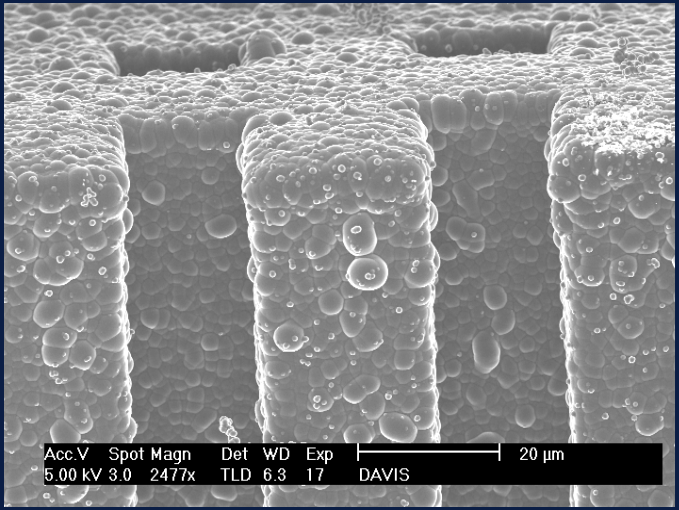


Thermomechanical In-Plane Microactuator (TIM)



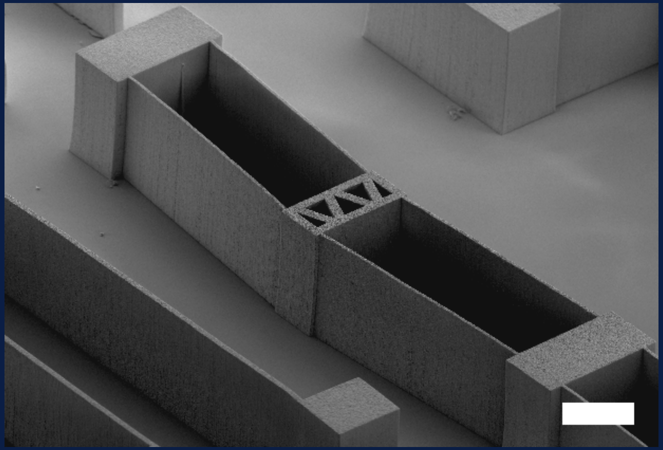
Other infiltration materials

Filled with amorphous C:



Fills most completely

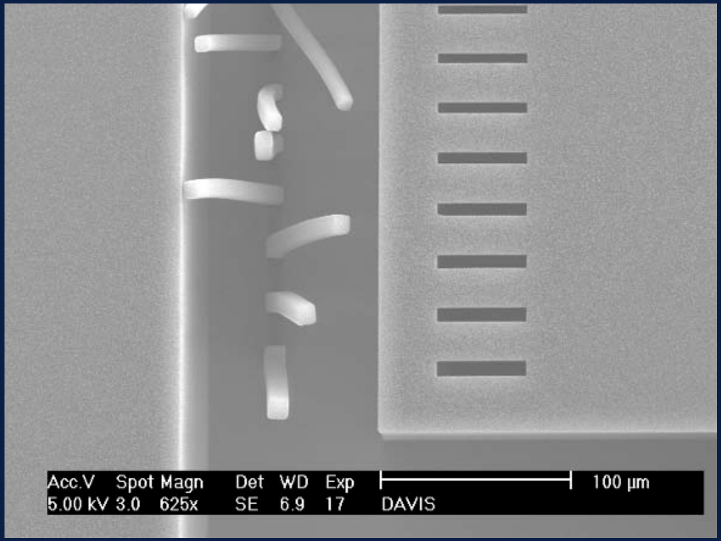
Filled with Silicon nitride:



Forms stable high aspect walls

Developing Design Rules

- Height to width ratio for dimensional stability



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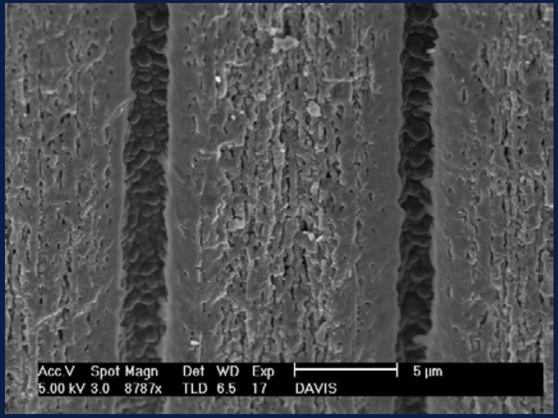
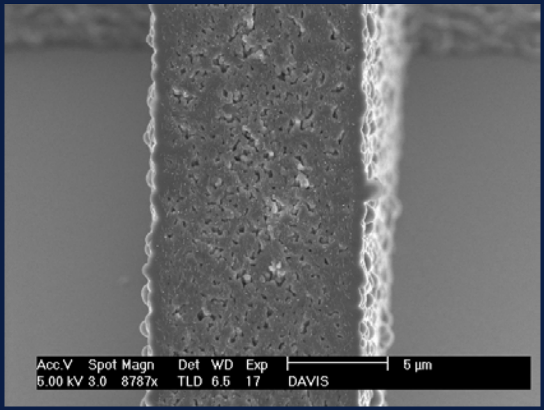
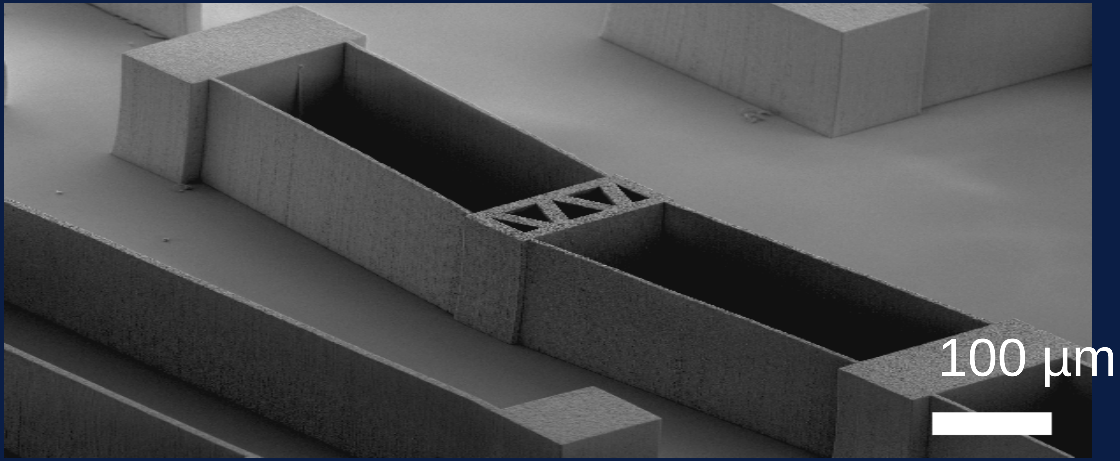




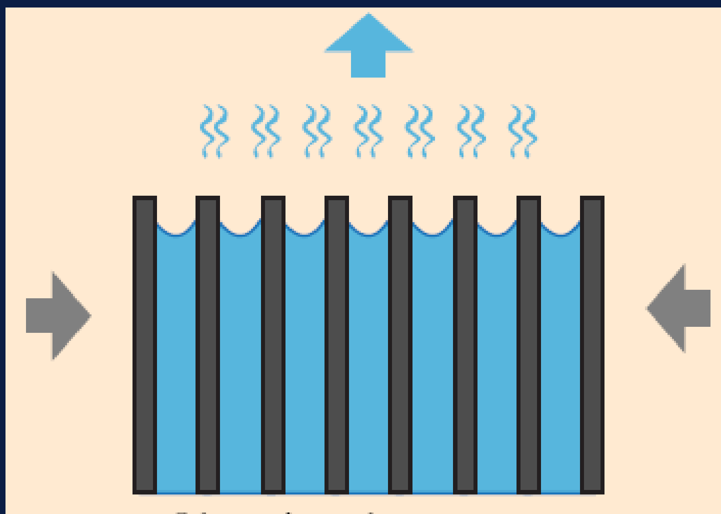
End

Nanostructured Materials as templates for fabrication

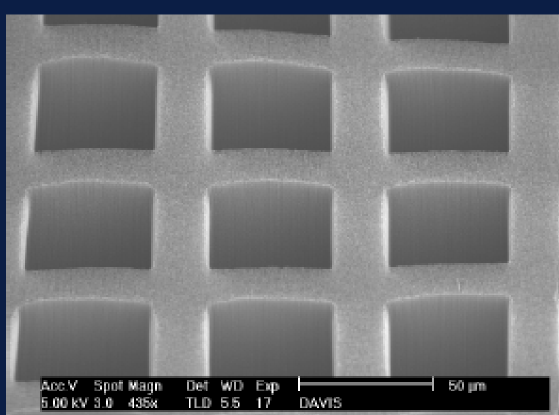


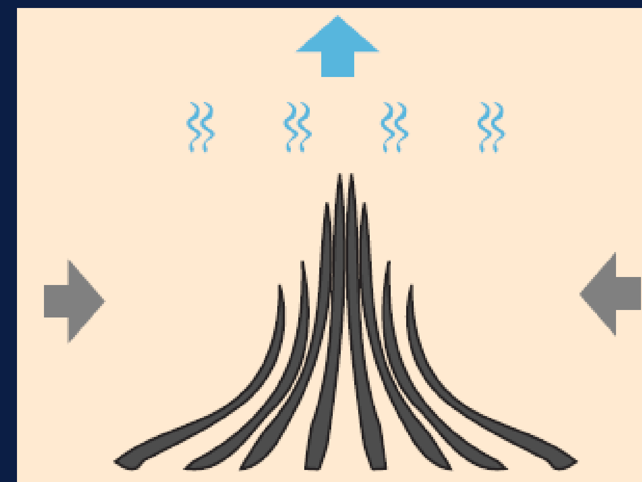
Dense Nanotube Structures

Liquid Induced Densification

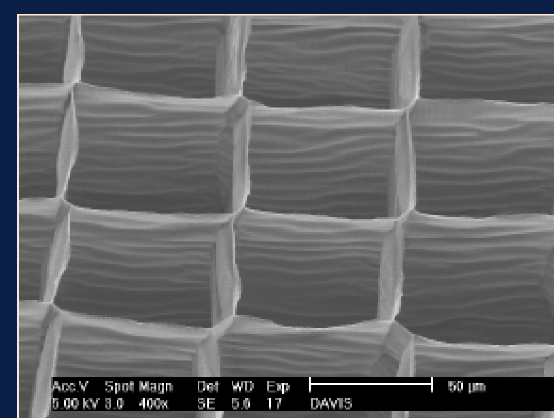


Submerged nanotube structures

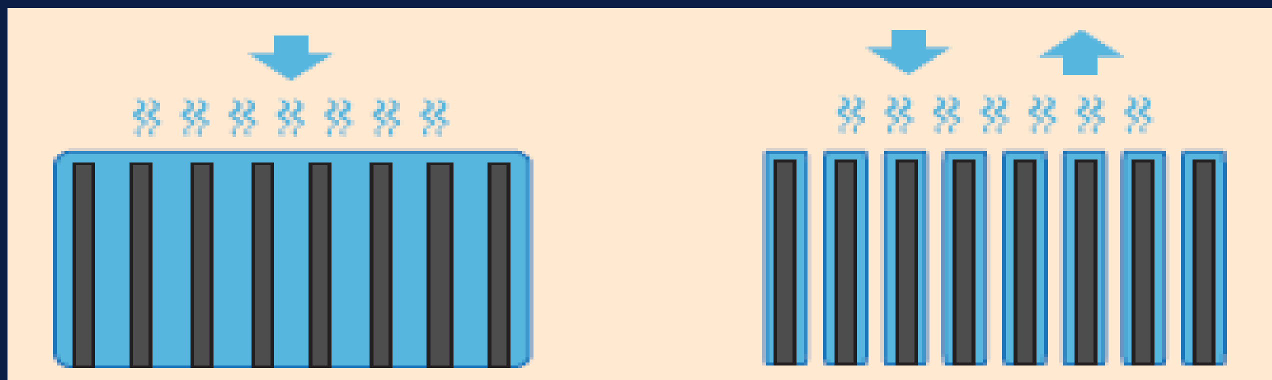




Dried structure

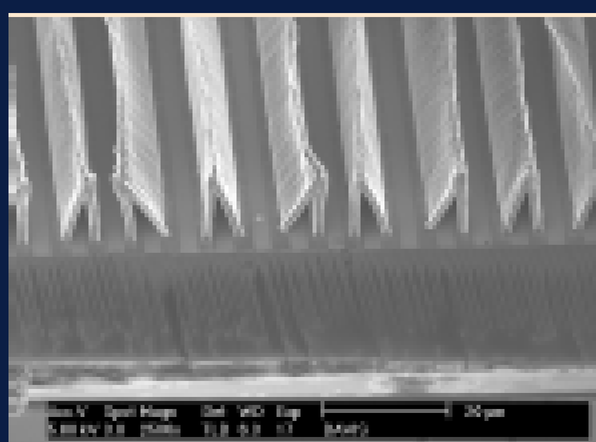


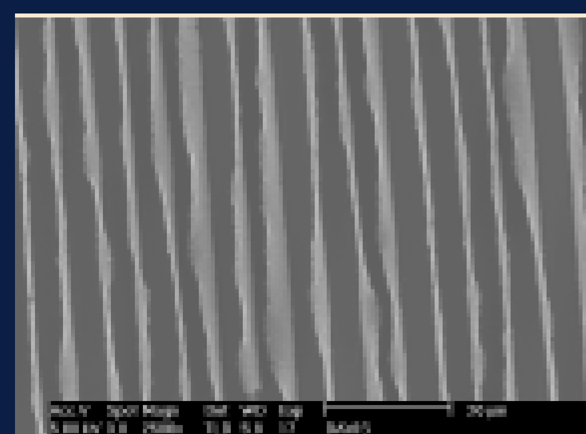
Vapor Condensation Induced Densification -- Lines



Longer exposure to vapor

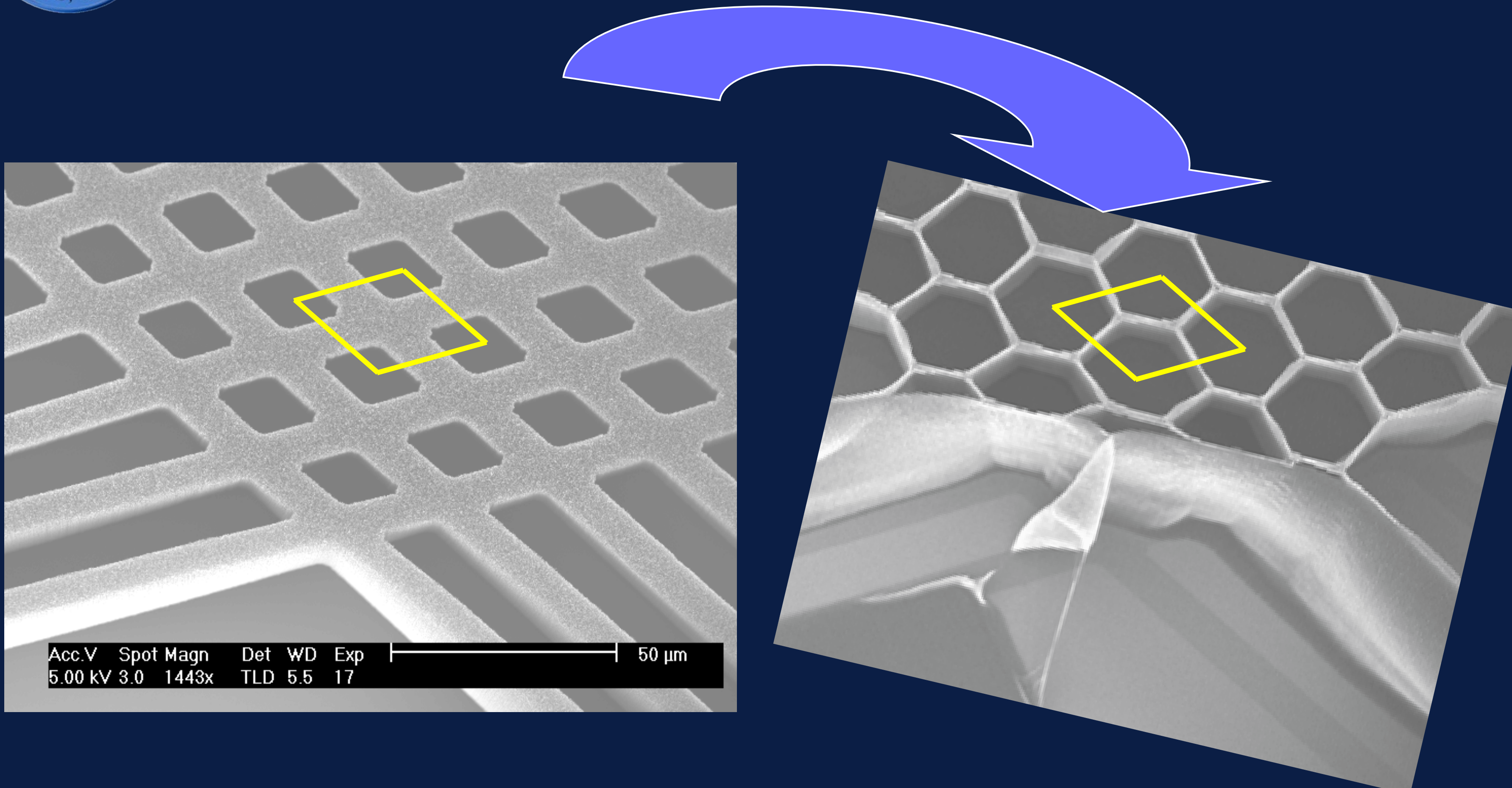
Shorter exposure to vapor





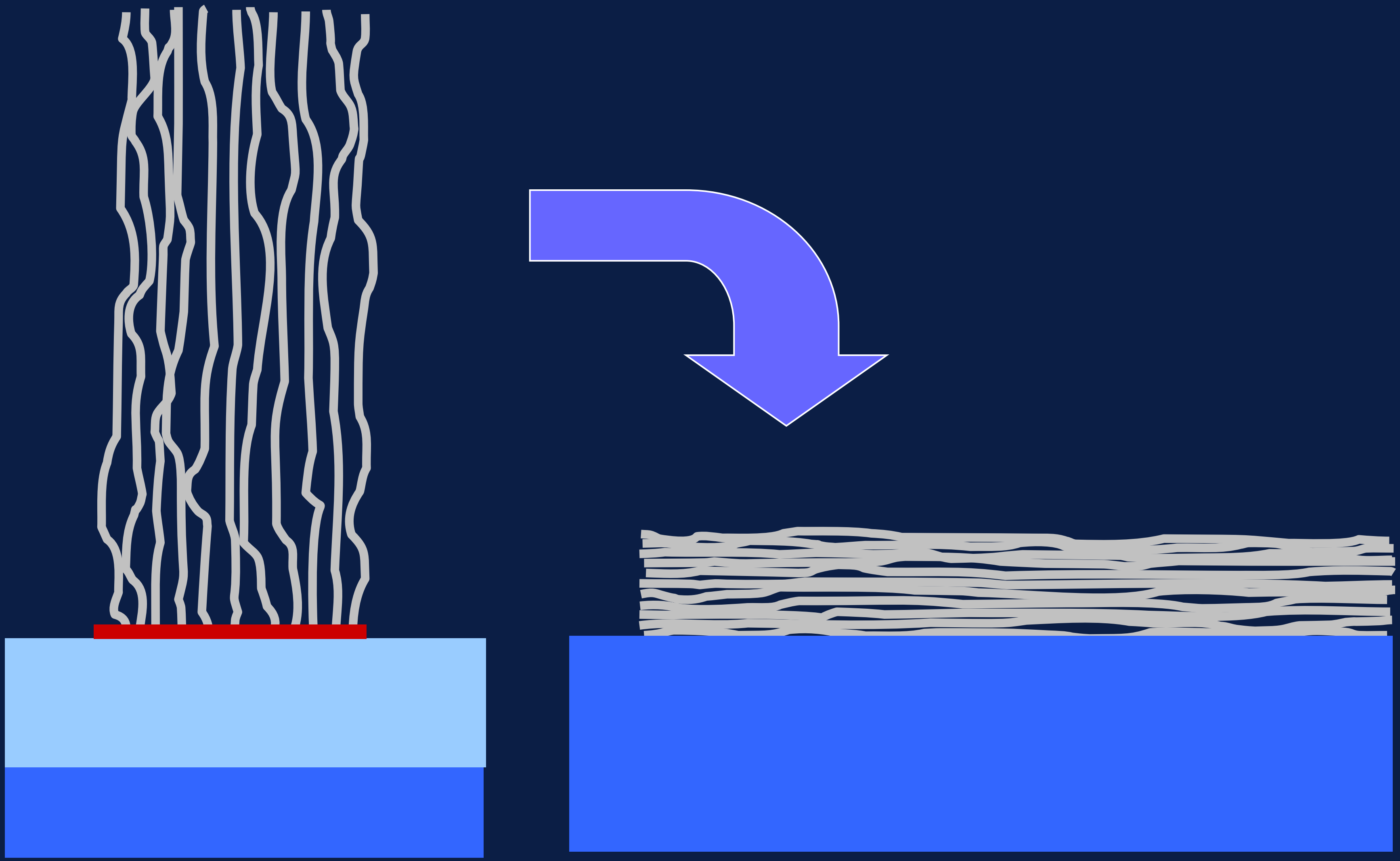
Difficult to control the structure!

Surface forces dominates

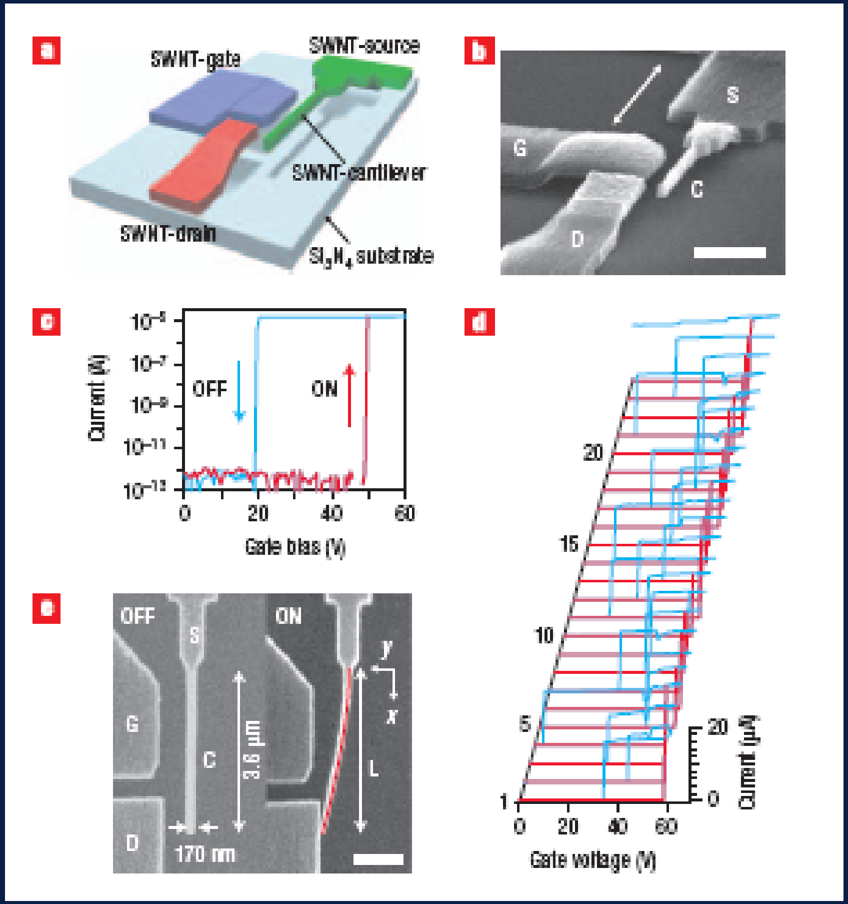


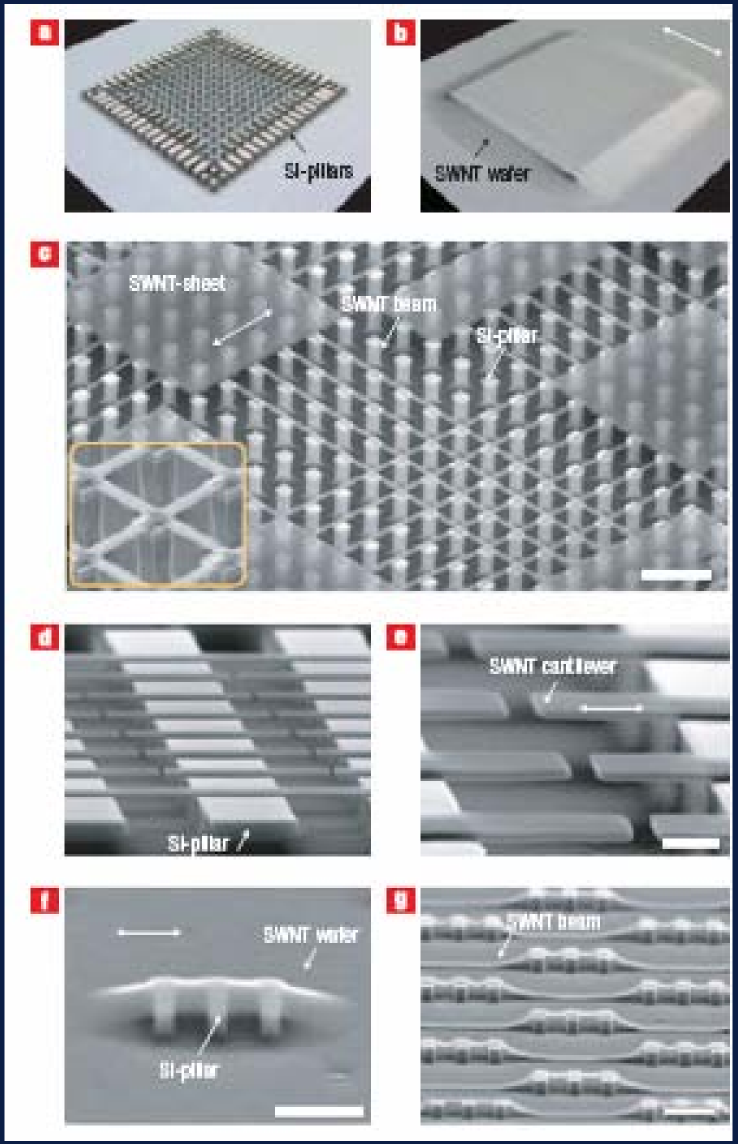
Unequal angles become equal angles.
Final structure depends on initial structure and surface forces

Horizontal Aligned CNT films



AIST Japan group working on in-plane aligned CNT MEMS





Yuhei Hayamizu, Takeo Yamada, Kohei Mizuno, Robert C. Davis, Don N. Futaba, Moto
Yumura, & Kenji Hata **Nature Nanotechnology** 3, 241 (2008).

Complementary logic gate geometry