SW Test Workshop
Semiconductor Wafer Test Workshop

CNT-Based Microspring Probe Design – Towards small pitch (<50 µm) applications

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UNIVERSITY OF SURREY

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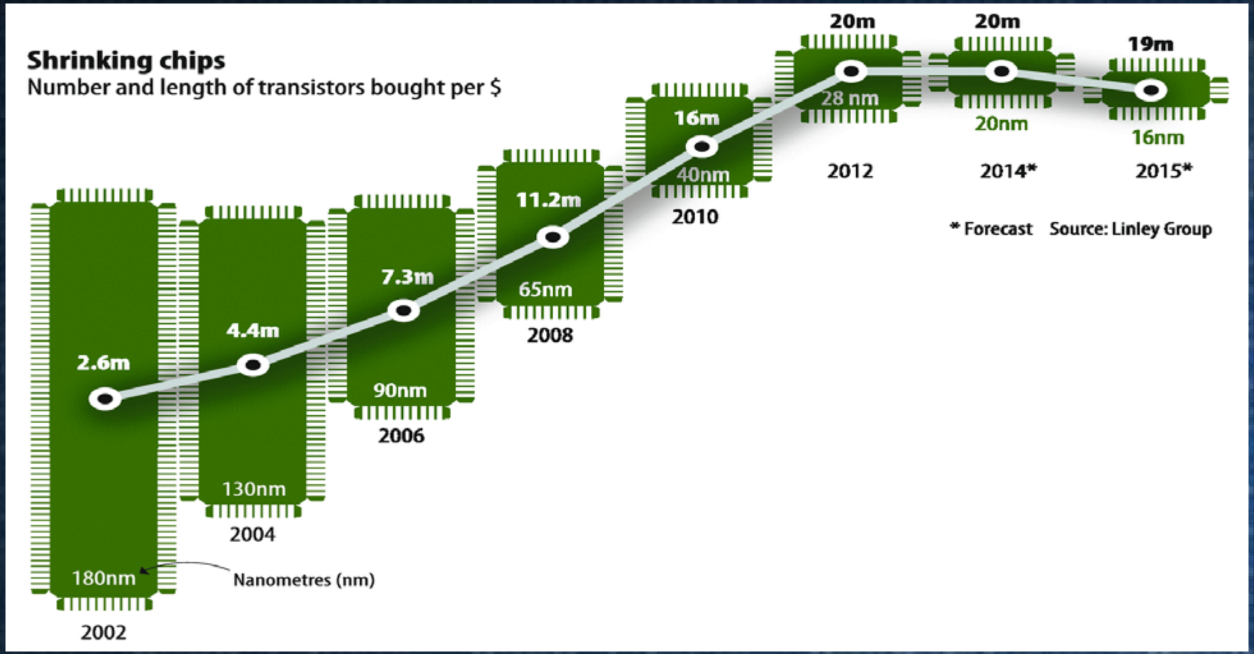
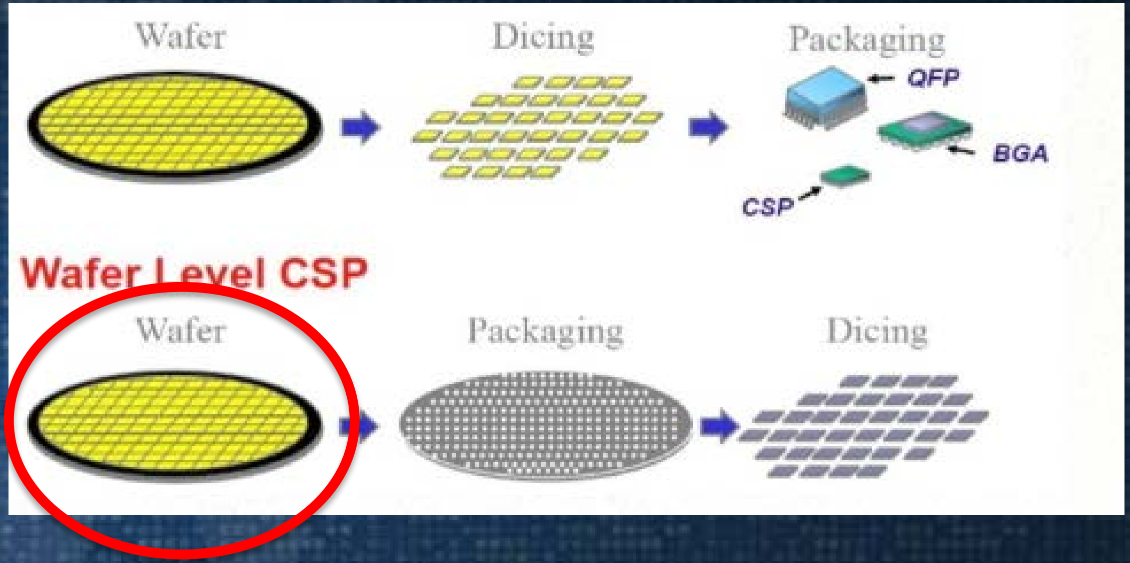
Overview

- Motivation
- Why Carbon Nanotubes?
- Photo-thermal CVD Deposition and Characterisation of CNTs
- Functionalisation of CNTs
- Contacting Carbon/Electromechanical Testing
- Conclusions
- Future work

Motivation



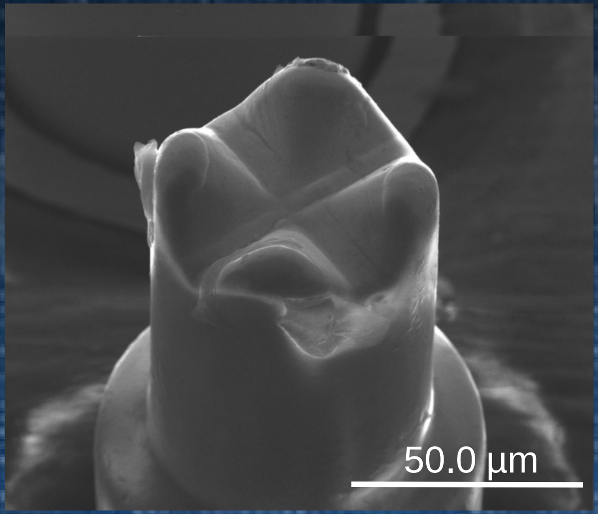


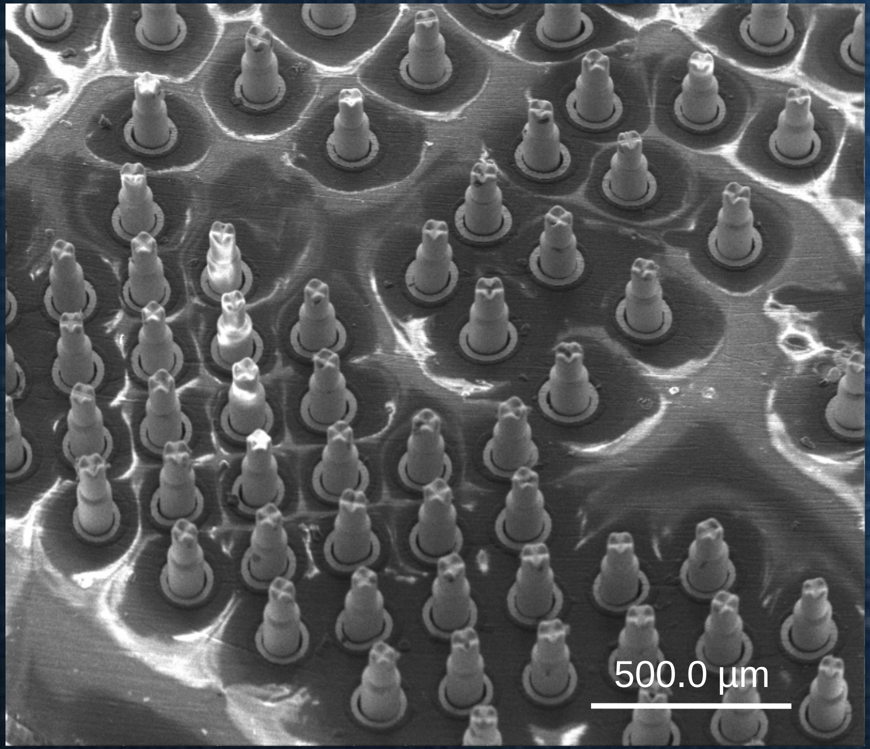
https://www.nytimes.com/2015/09/27/technology/smaller-faster-cheaper-over-the-future-of-computer-chips.html

https://www.prnewswire.com/news-releases/microprocessor-and-gpu-market-expected-to-be-worth-usd-8369-billion-by-2022-300466716.html

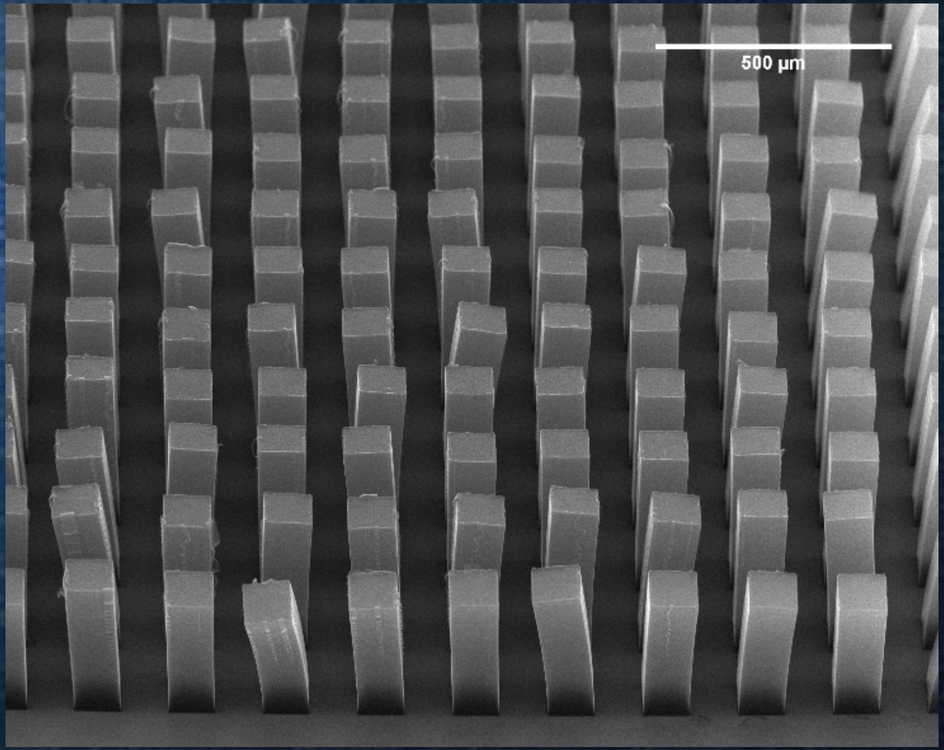
Motivation

- 200 µm pitch microspring probes





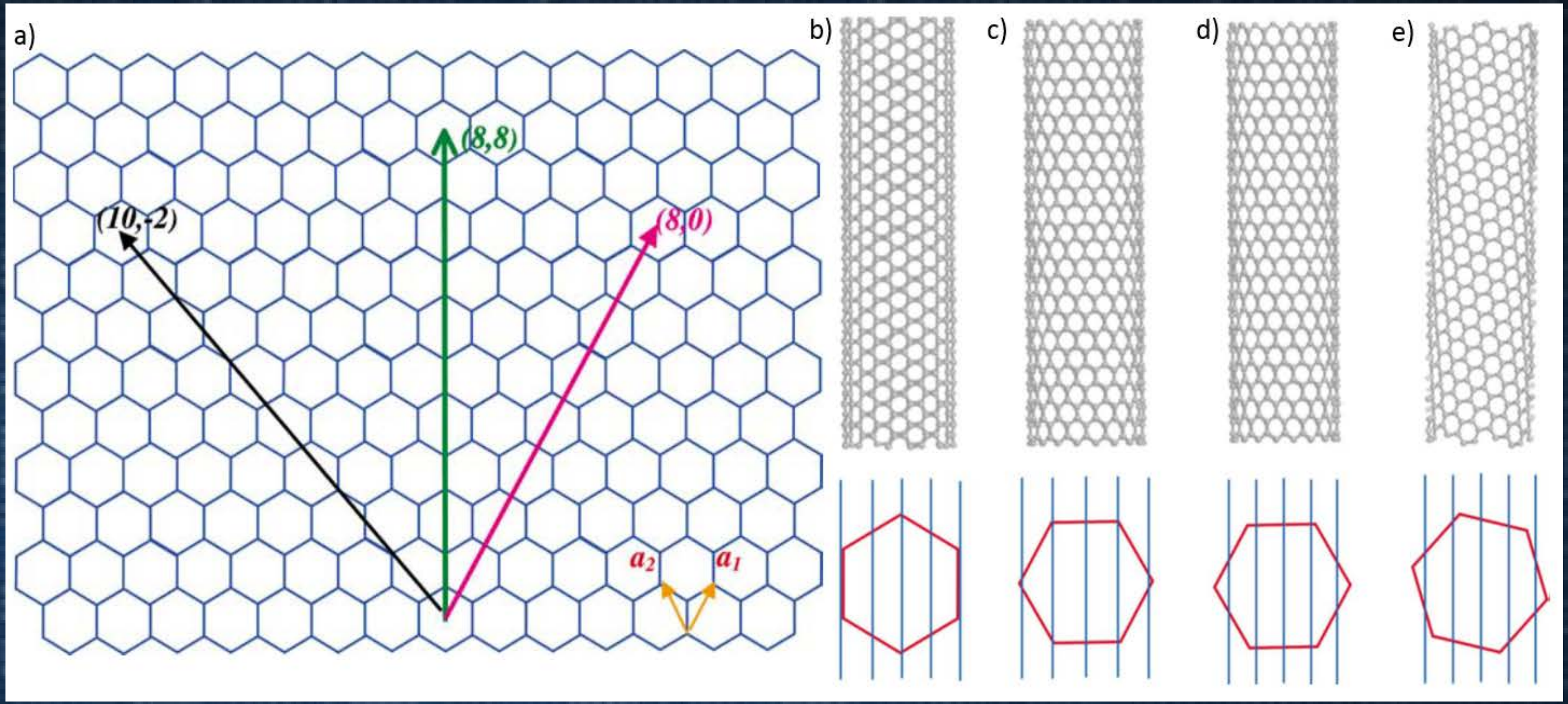
Can we replace these with CNTs?



Carbon Nanotubes (CNTs)

Overview and types of CNTs

- A SWCNT is a graphene sheet rolled over into a cylinder.
- The nature of the wrapping (chirality) and the diameter of the tubes gives different electrical properties
- Metallic $E_g = 0$, semi-metallic $E_g < 100\text{mV}$ and semiconducting $E_g = 0.7\ \text{eV}/d_t$
- Synthesis of CNTs can be done by different methods but the main deposition method is catalytic CVD method.



Dai H 2002 Carbon nanotubes: Opportunities and challenges Surf. Sci. 500 218–41

Carbon Nanotubes (CNTs)

- **Quantised Electrical Conductance of CNTs**

G_o, ($\sim \frac{1}{12.9} K\Omega^{-1}$) is the quantum conductance of a one-dimensional channel

$$G_o = \frac{2e^2}{h}$$

General formula for conductance, Landauer formula $G = \underbrace{G_o T}\underbrace{M(\mu)}$ where T is the transmission probability per channel and $M(\mu)$ is the # of conducting channels

For SWCNTs with **perfect metal contacts** (T = 1), the resistance value can be found to be 6.45 KΩ

Depends on the chirality and the diameter of the tube

Classical Contact resistance in CNTs

$$R = \underbrace{R_{contacts}} + \underbrace{R_{tube}}$$

$R_{contacts} \geq h/4\,e^2$

Theoretical limit, no scattering at the interface

Ballistic conduction

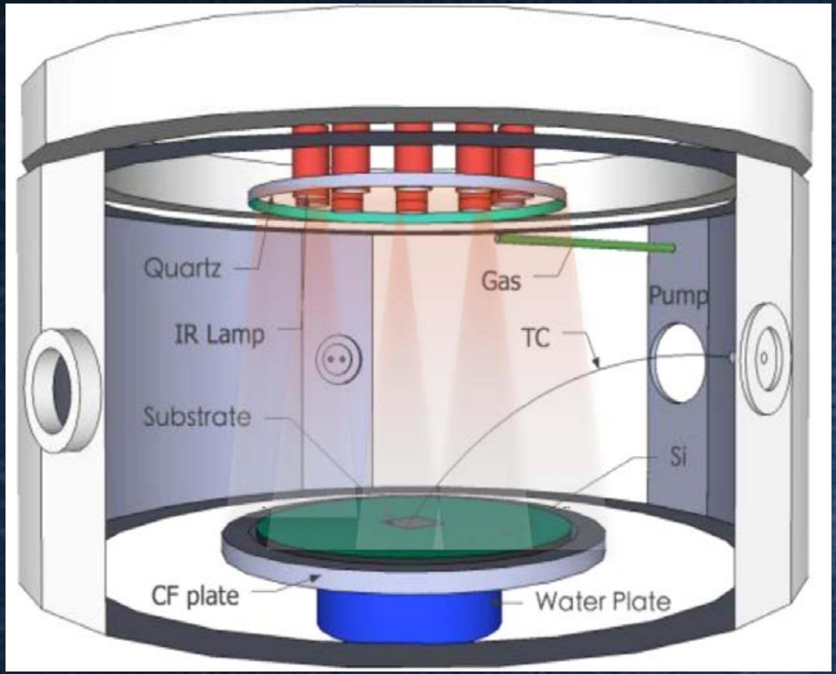
$R_{tube} = (h/4\,e^2)(L/l)$

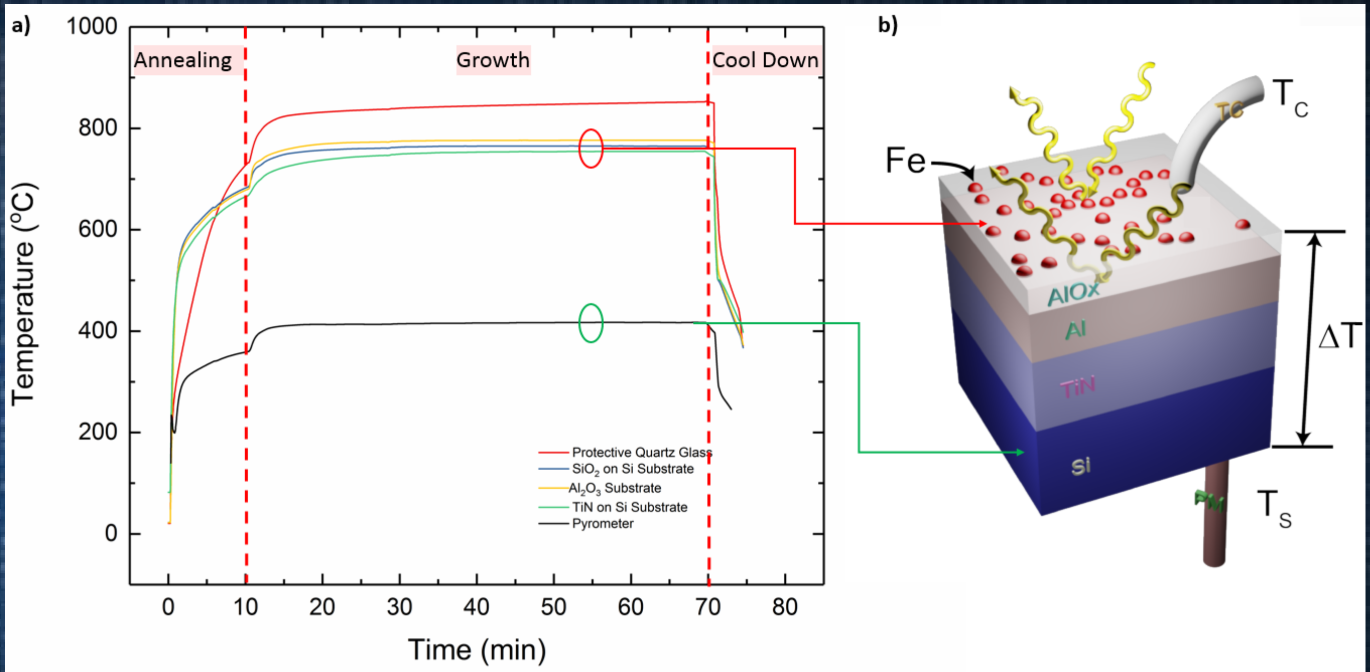
L is the tube length, l is the mean free path

When $L \gg l$; the resistance deviates from ballistic and becomes more length dependent.

Photo-Thermal CVD Deposition of CNTs

- **Synthesis of Vertically-Aligned CNTs**



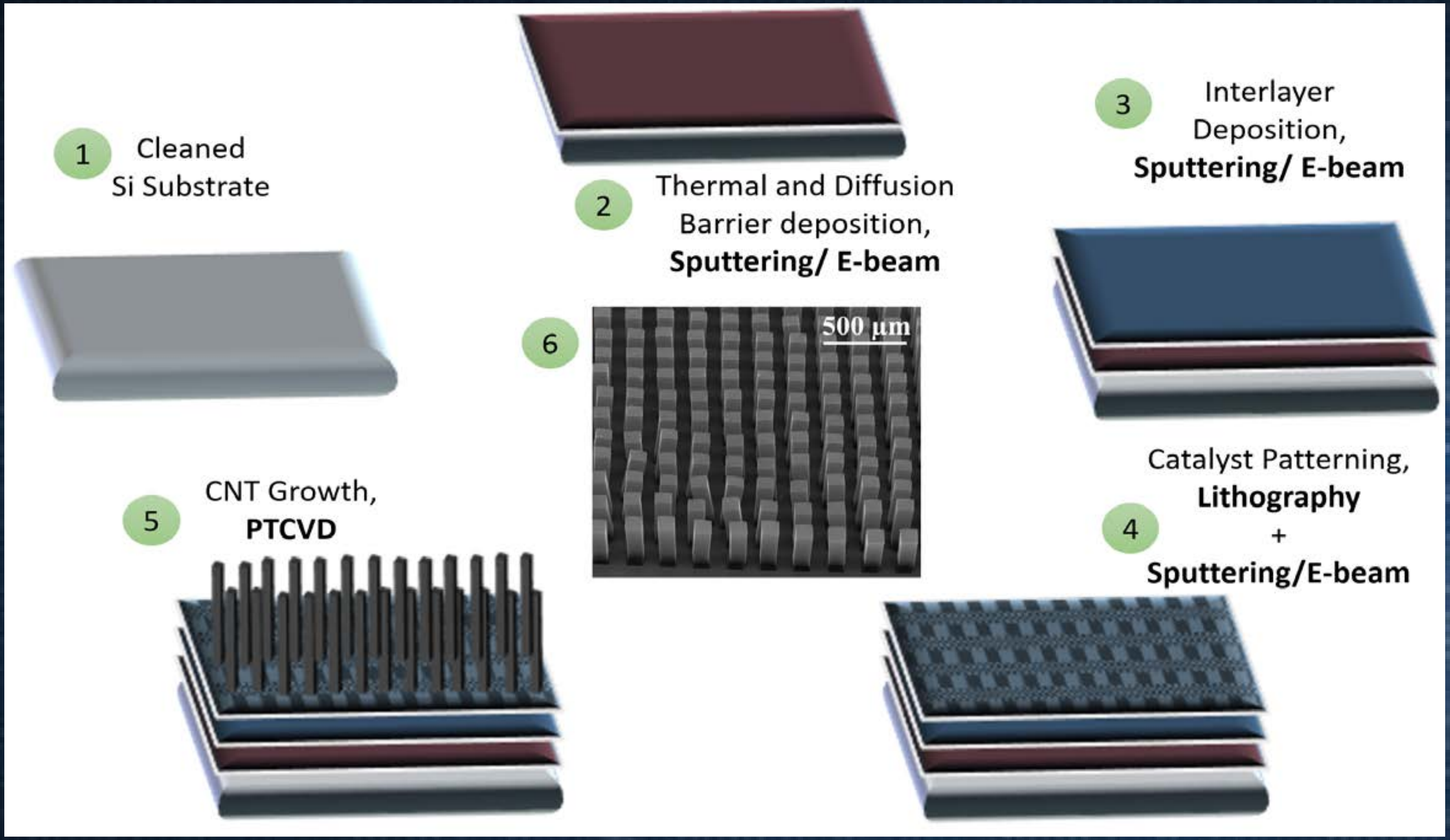


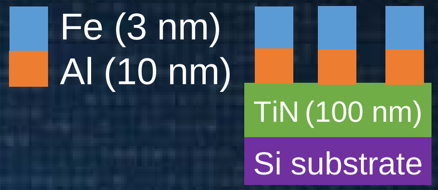
The PTCVD system consists of :

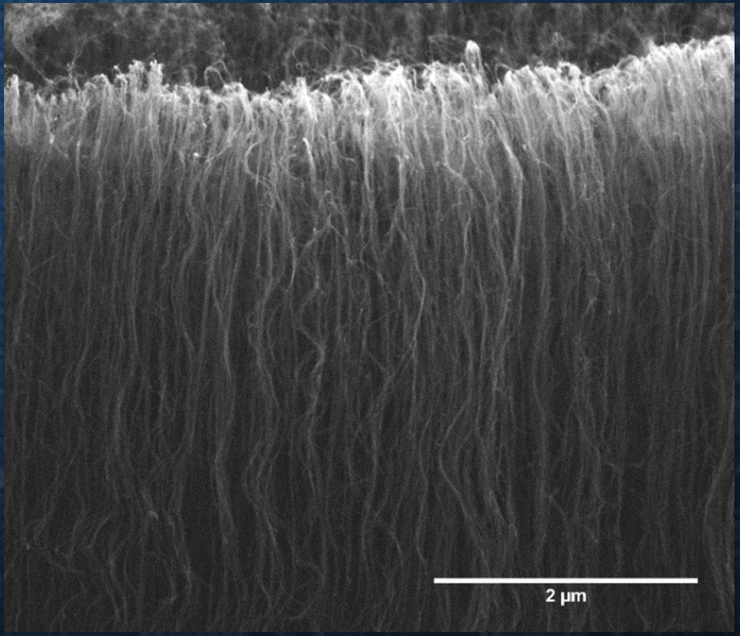
- An optical head as the source of optical energy applied from the top
- A substrate holder cooled from the bottom to keep substrate temperature below 450 °C

Fe (3 nm)	Fe (3 nm)	Fe (3 nm)	Fe (3 nm)
Al (10 nm)	Al (10 nm)	Al (10 nm)	Al (10 nm)
SiO_2 (250 nm)	Al_2O_3 (250 nm)	TiN (100 nm)	Al_2O_3 Substrate
Si substrate	Si substrate	Si substrate	

Fabrication of CNT probe structures

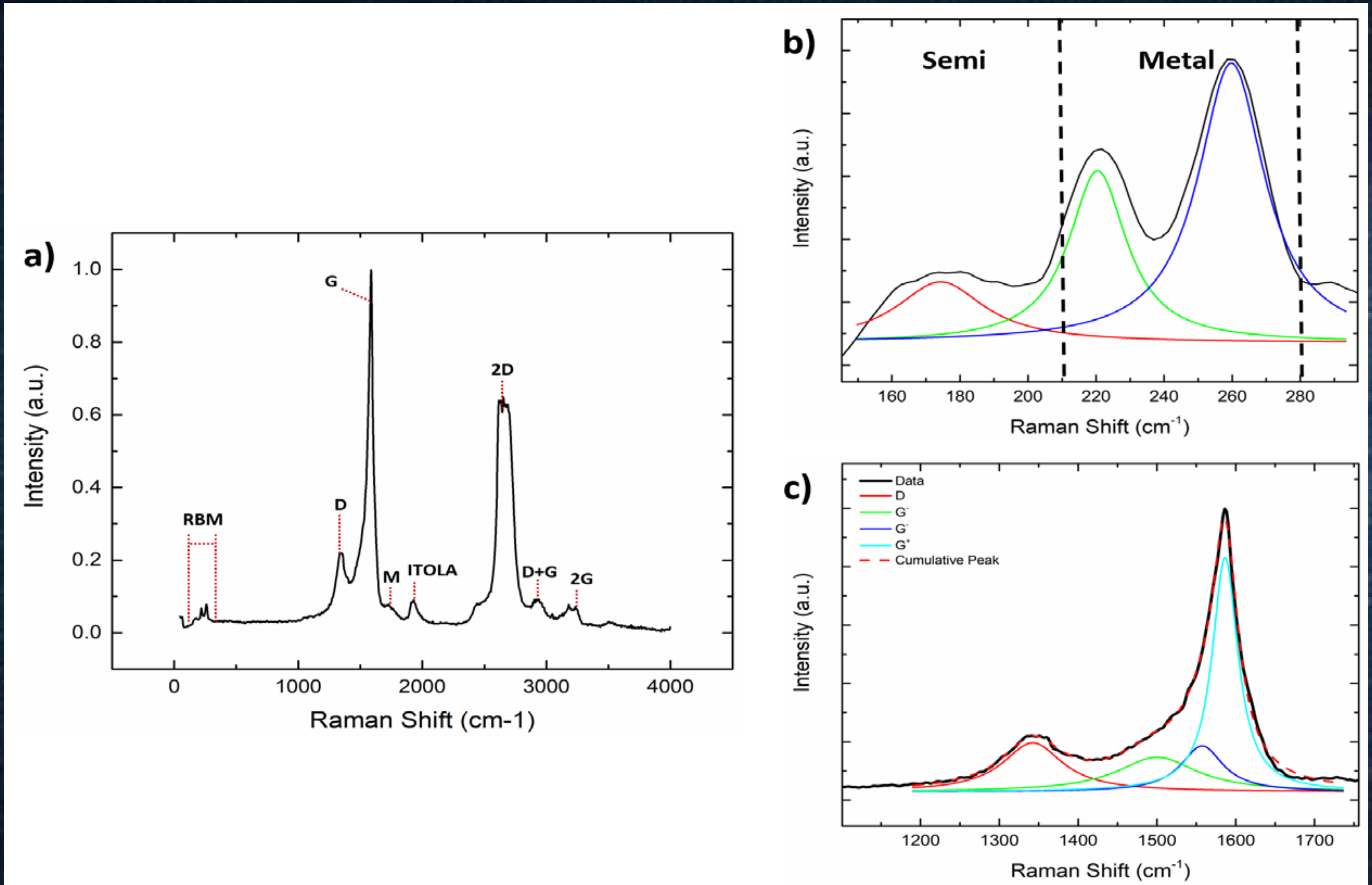






- Selective deposition of the catalyst by photolithography
- 2304 as-grown CNT probes with 50 µm pitch in a 2.4 x 2.4 cm area

Characterisation and Functionalisation of CNT probes



- **RBM:** vibrations in the radial direction

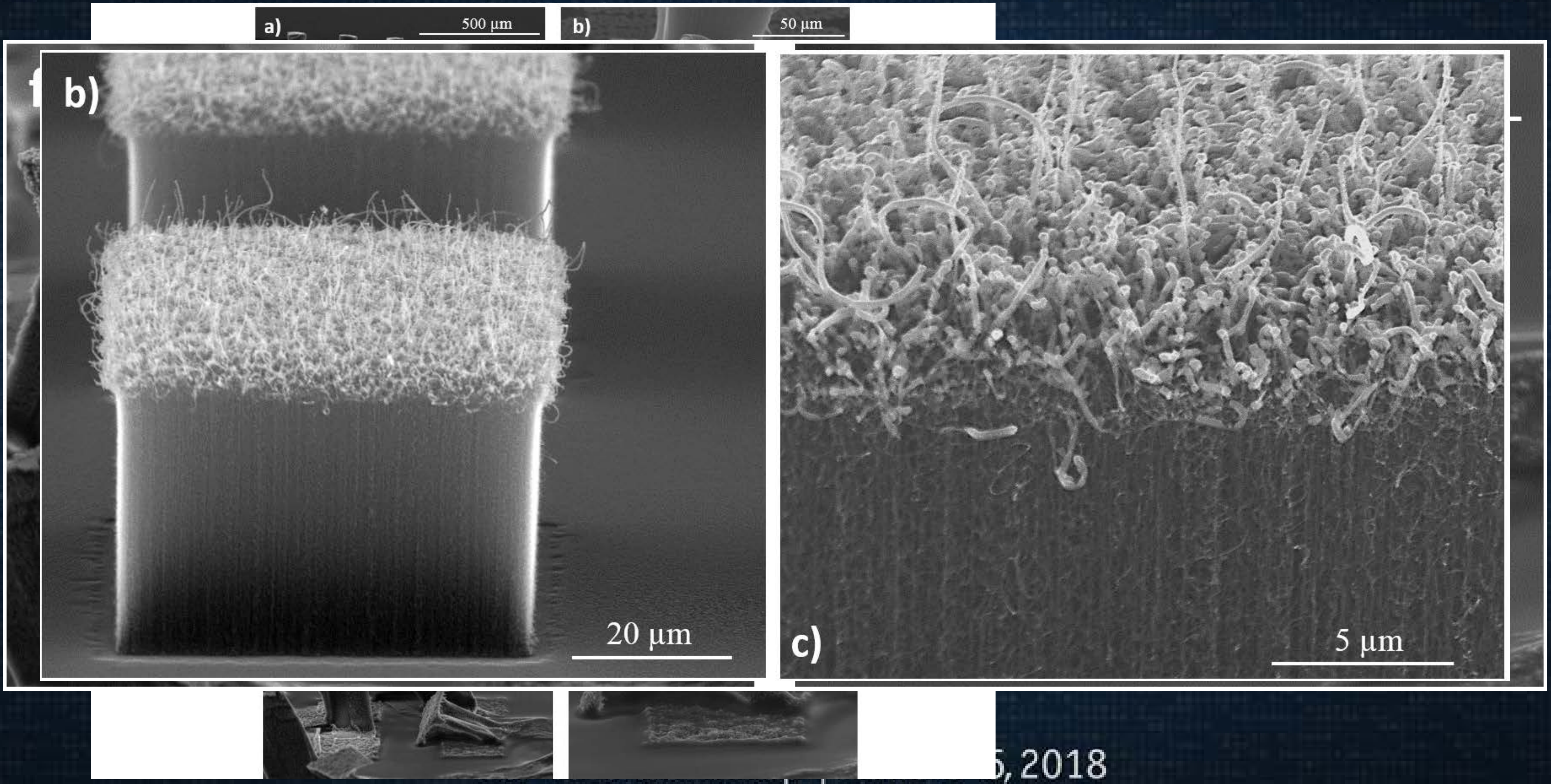
$$w_{RBM} = \frac{A}{d_t} + B$$

the frequency ➡ the diameter

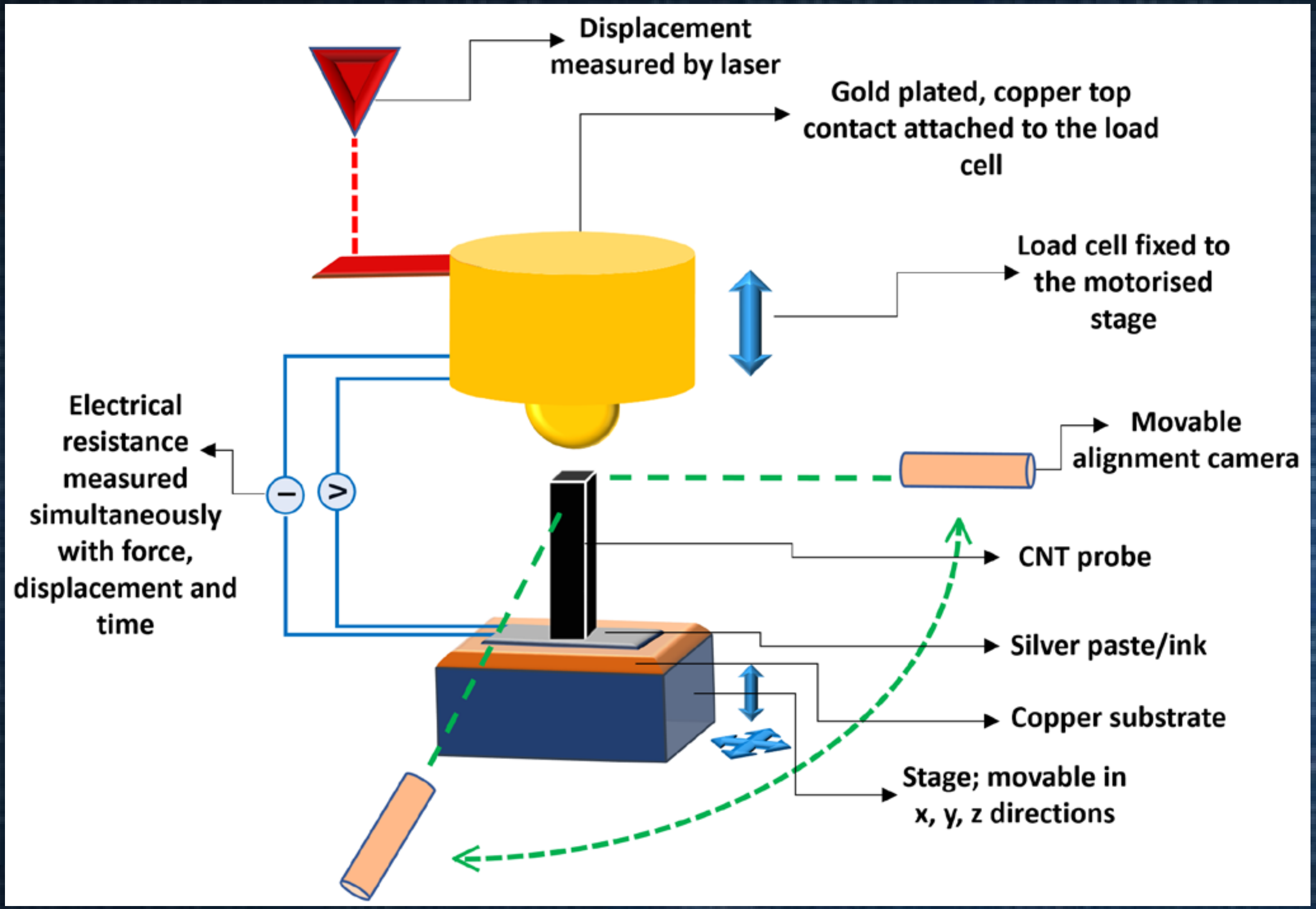
- **D Band:** disorder induced
- **G Band:** longitudinal vibrations, indication of crystallinity
- **2D Band:** Long Range Order

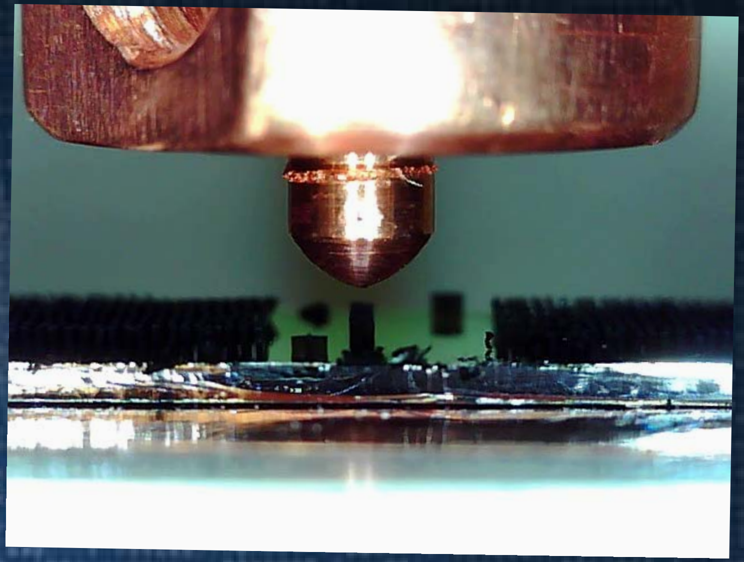
Characterisation and Functionalisation of CNT probes

- **Densification**



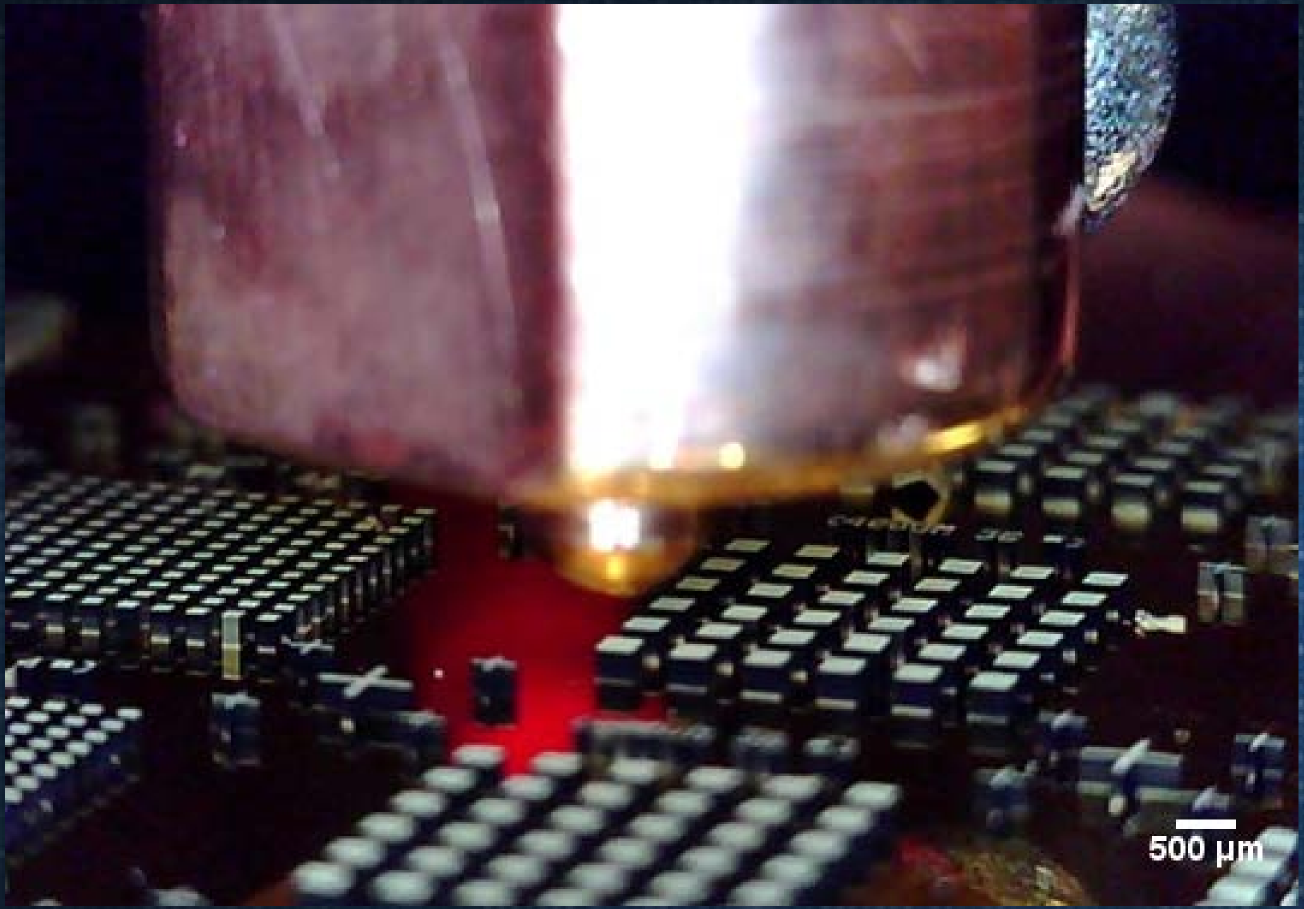
Electromechanical Testing Rig Setup



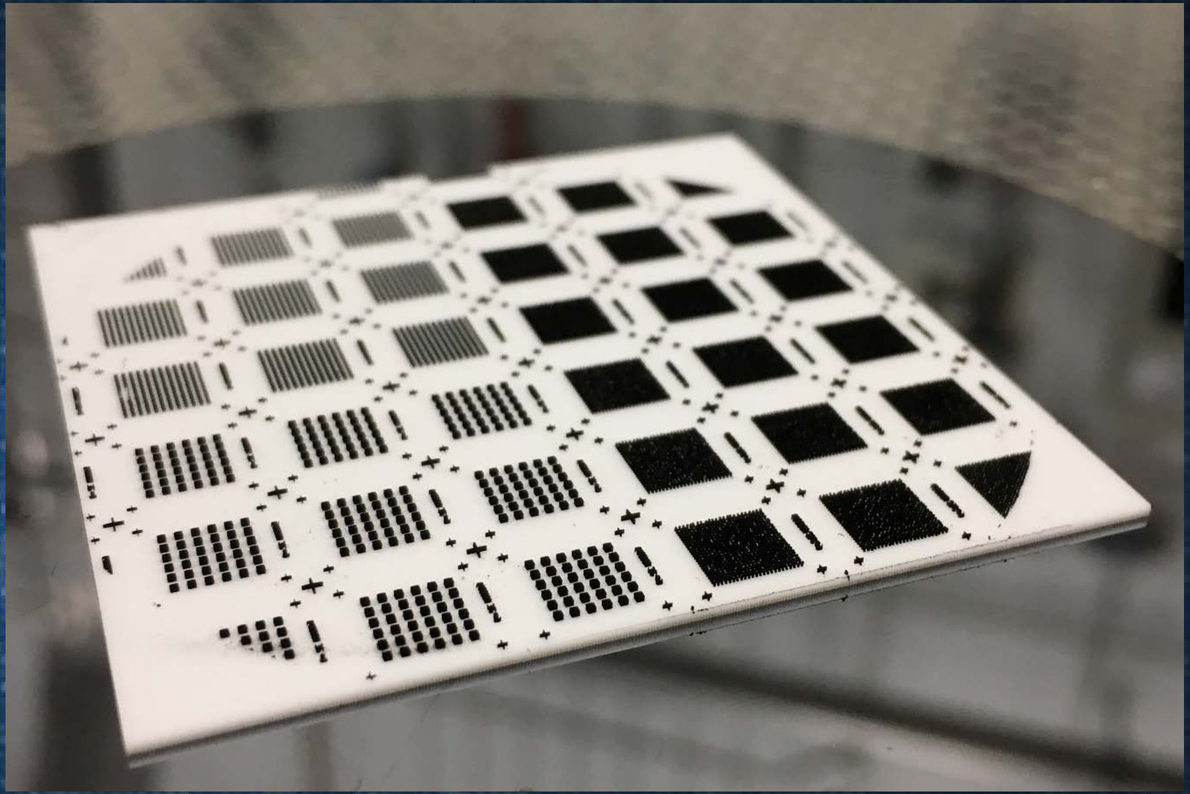


- Load Cell Sensitivity: ± 1 mN
- Max Load: ~3000 mN
- Displacement Laser Measuring Range: ± 5 mm
- Motorised Stage Resolution: ± 1.5 µm

Electromechanical Testing Rig Setup



- Arrays of Au metallised CNT microspring probes with 200 and 400 µm pitches on Si



- As-grown vertically aligned CNT probes on alumina substrate with various pitches
  - Probe lengths up to 750-800 µm

Approach

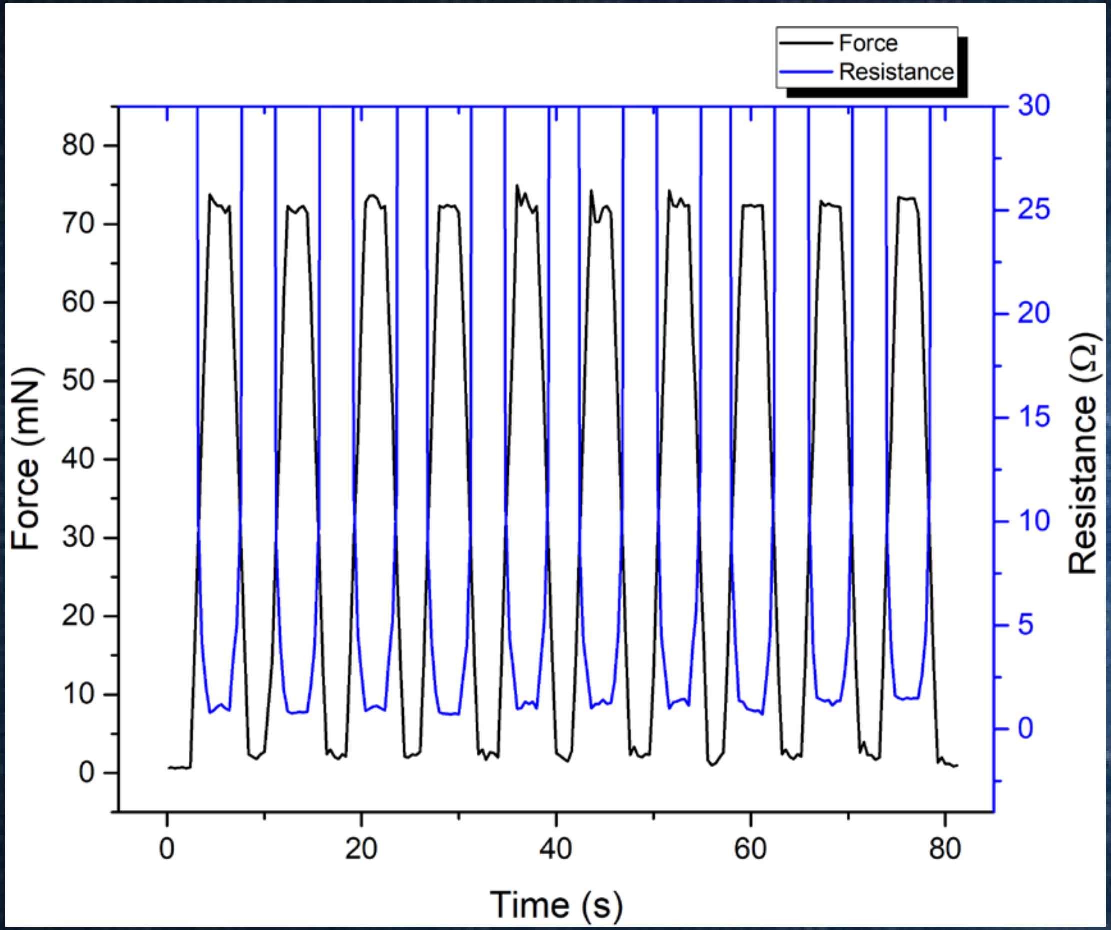
Electromechanical Testing of metal-CNT probes

Cyclic Loading
- Reproducibility
- Repeatability

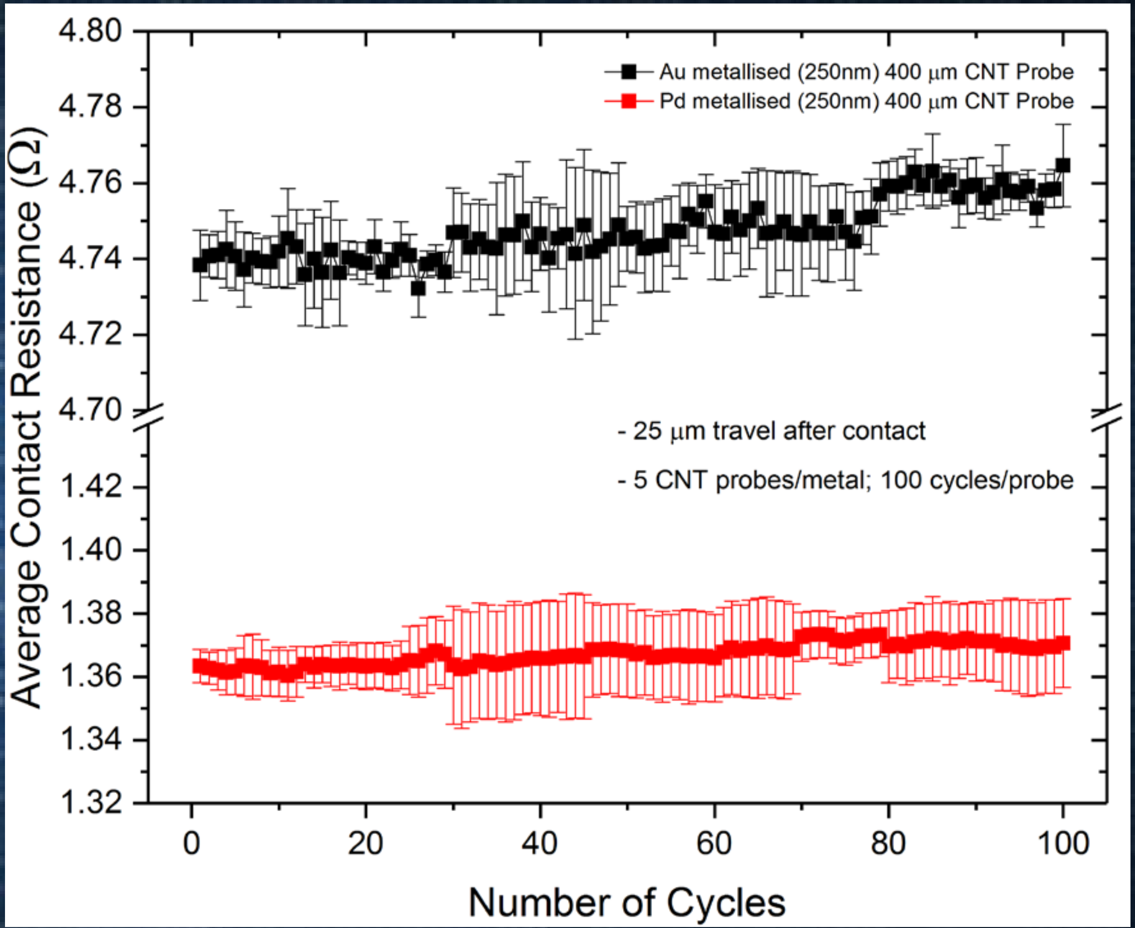
Loading until Failure
- Compliance
- Load/Displacement

Constant Loading
- Current Carrying Capability

Results – Cyclic Loading

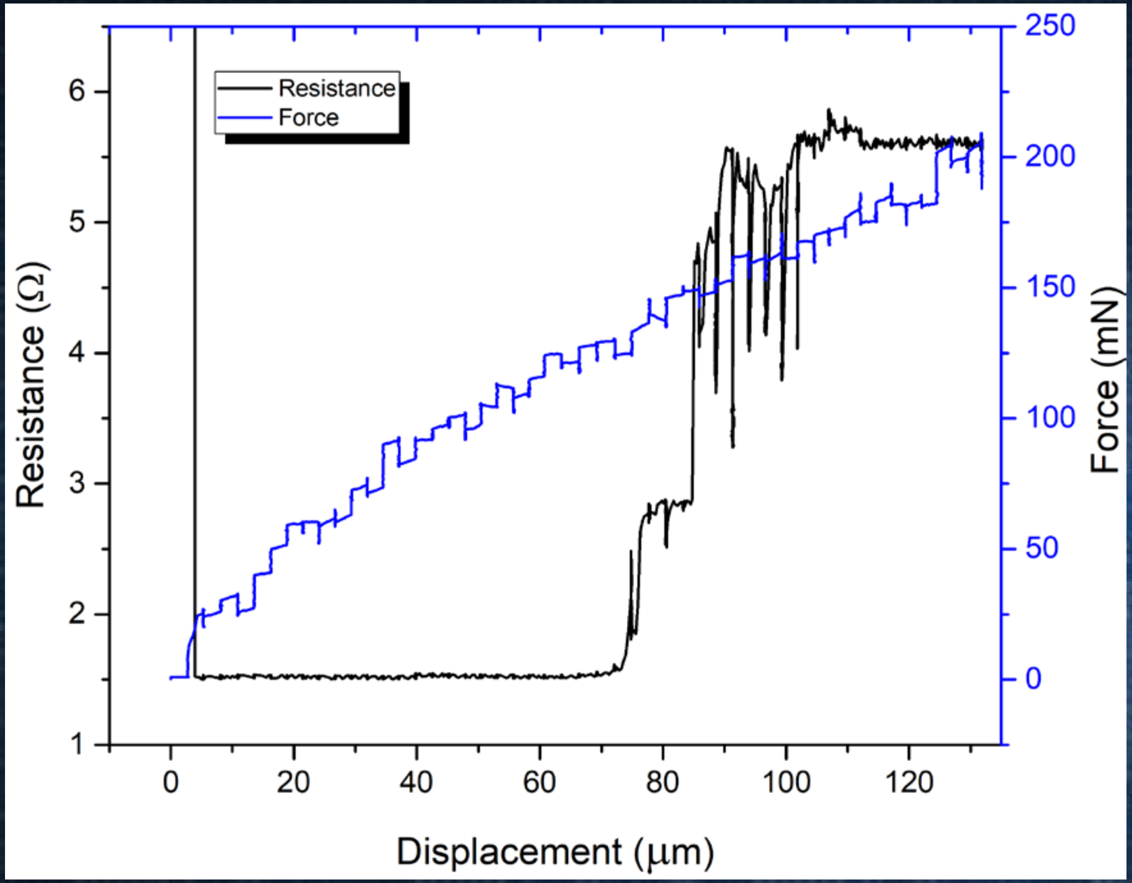


250 nm Pd metallised 400 micron width probe
25 micron travel

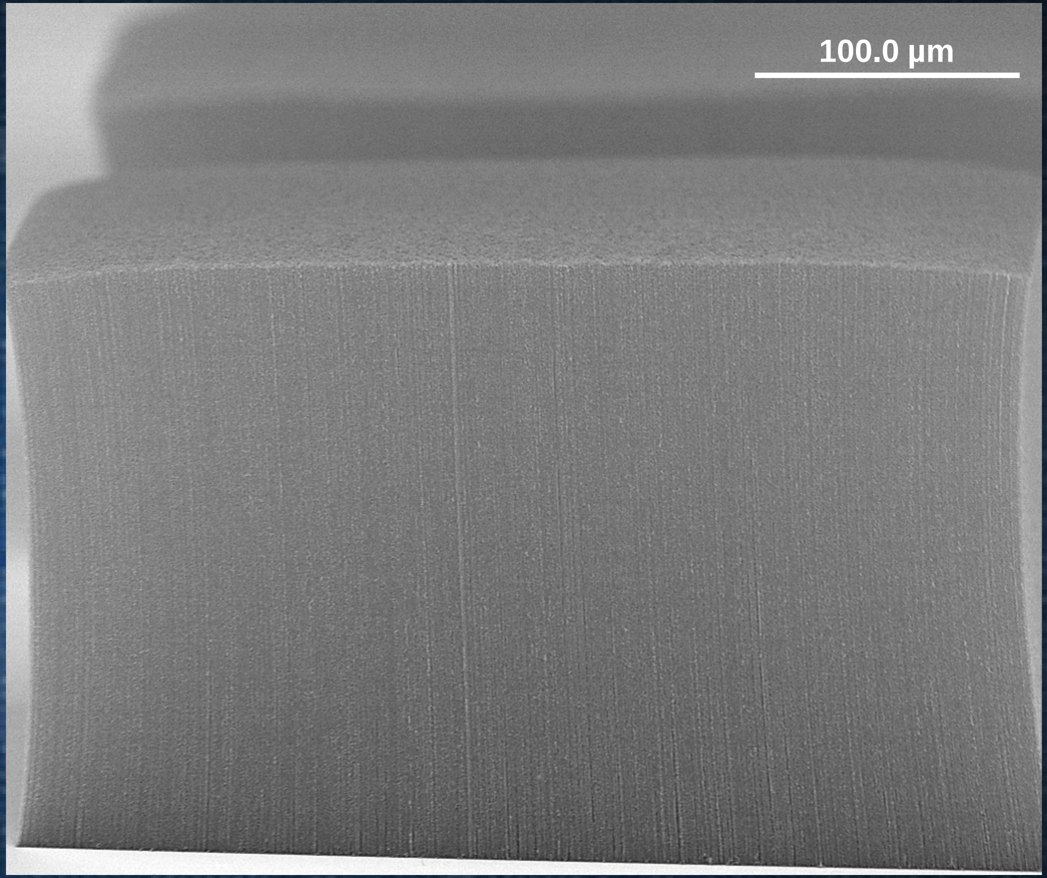


250 nm Pd metallised 400 micron width probe
25 micron travel

Results – Increasing Loading

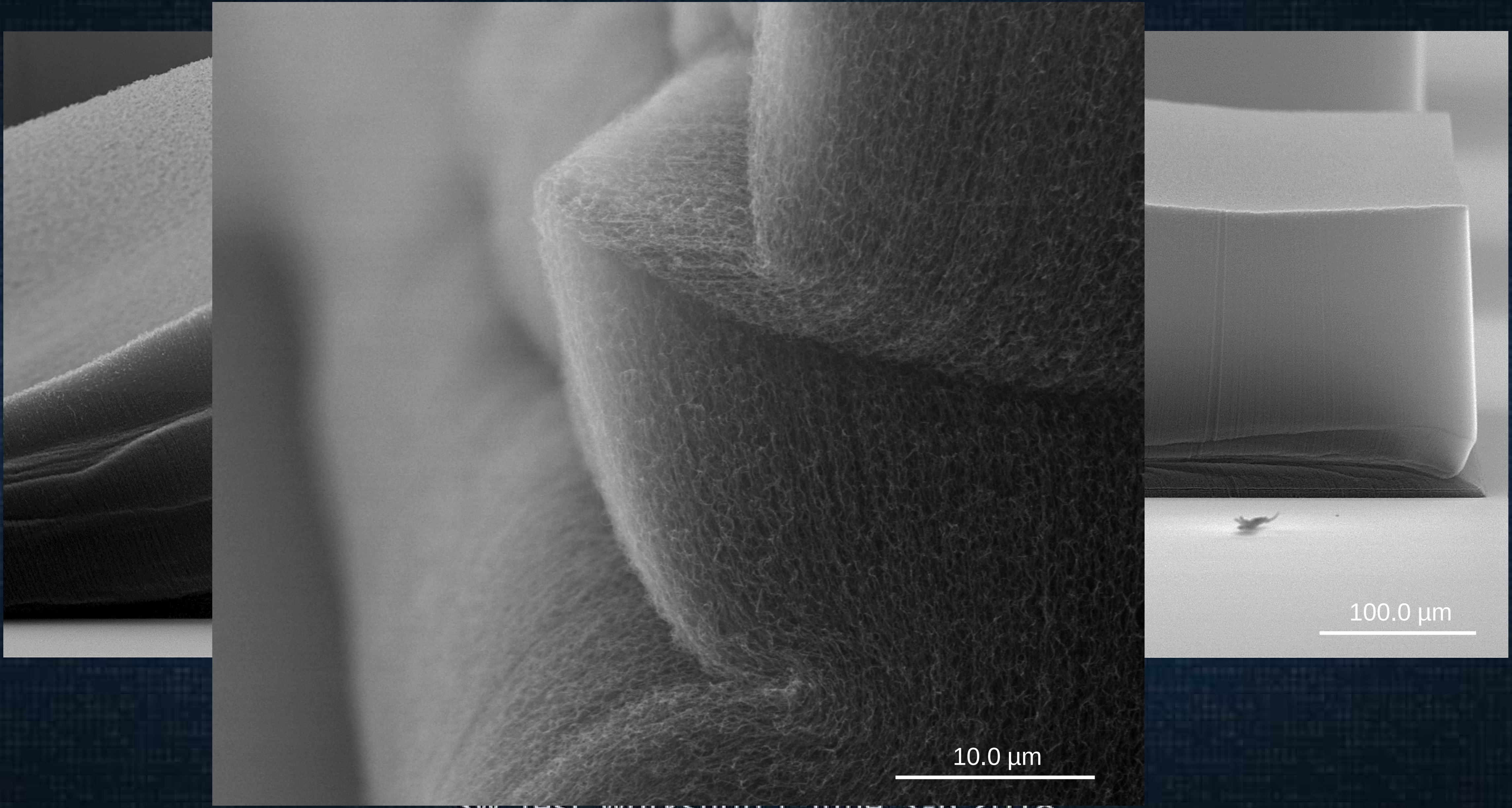


Pd Metallised 400 micron pitch sample
125 micron travel, increasing load – 2.5 µm/travel

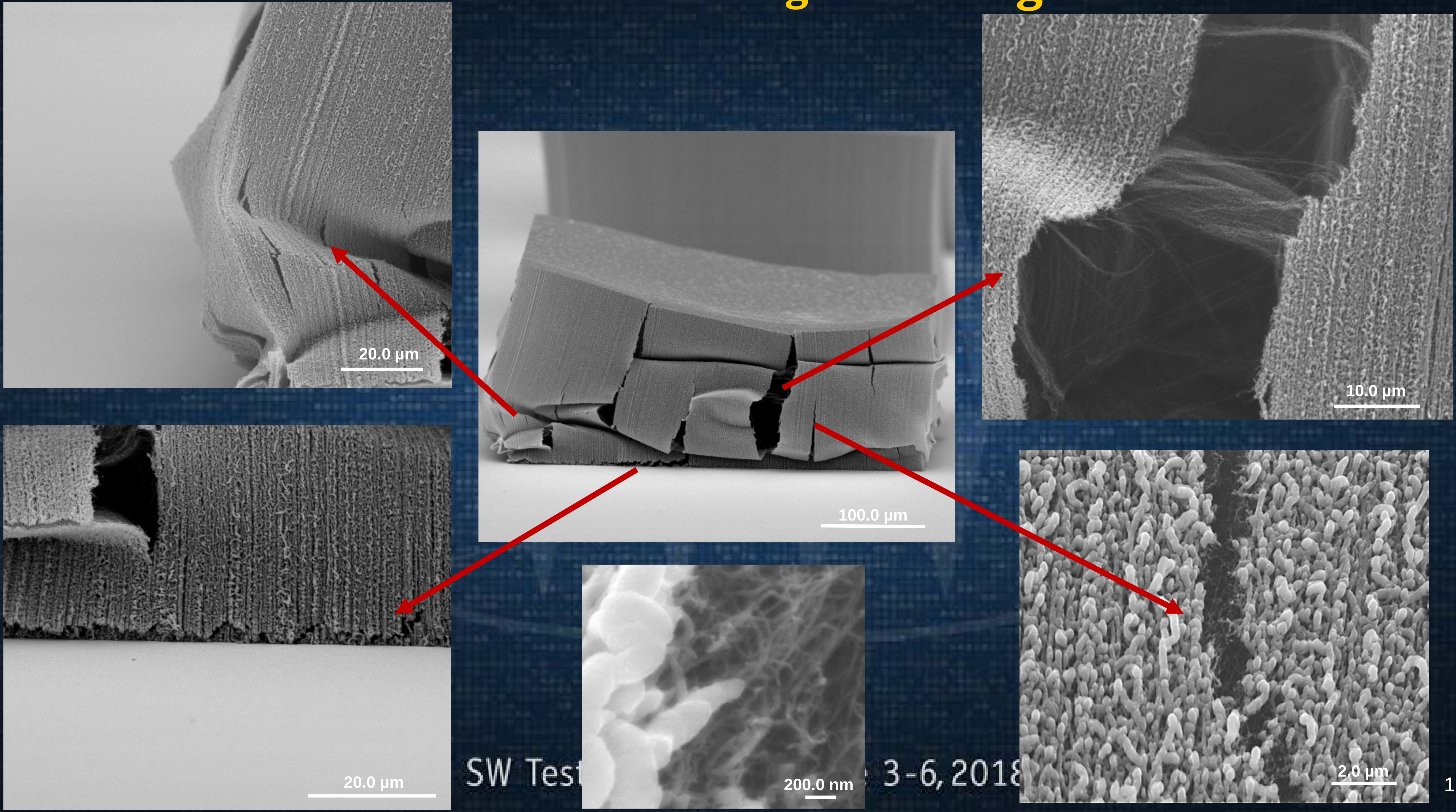


500 cycle - 25 µm travel

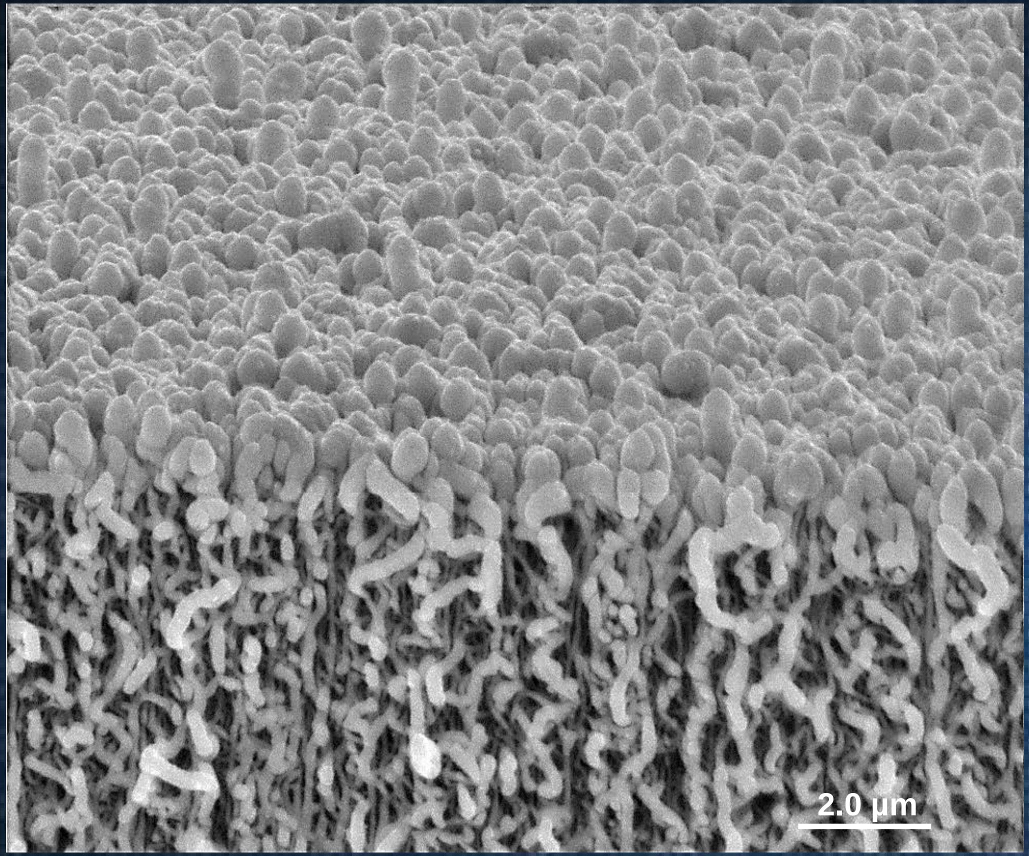
Results – Increasing Loading - Au



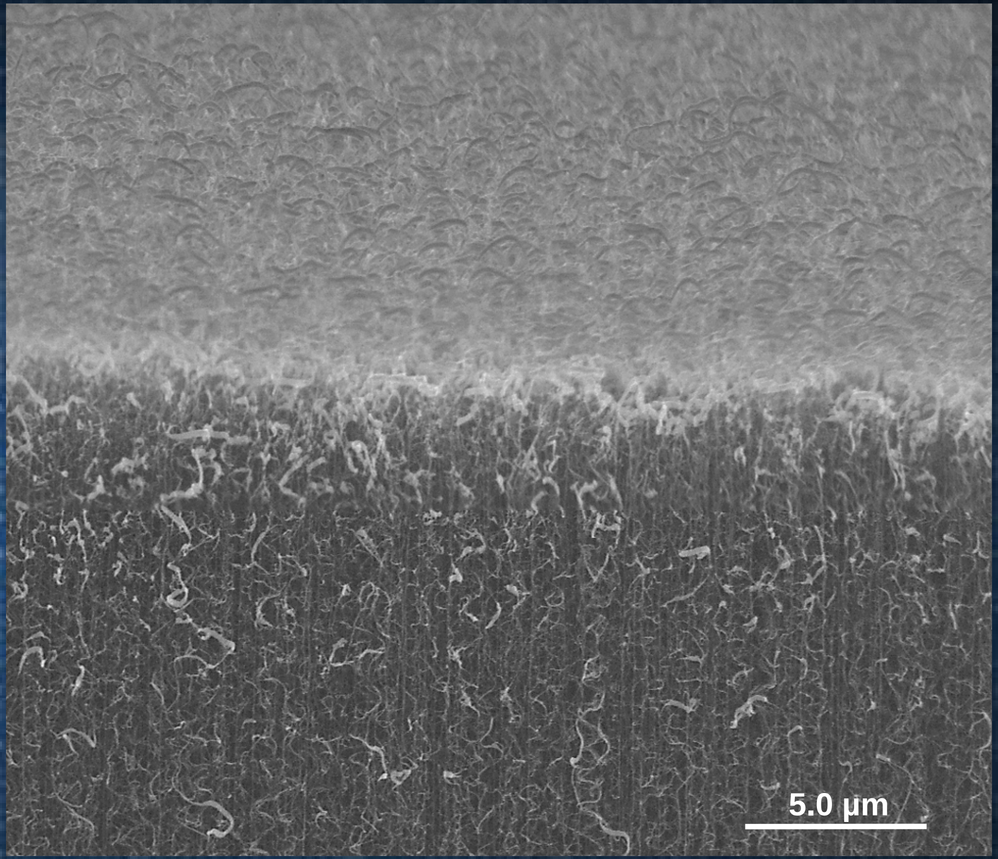
Results – Increasing Loading - Pd



Results – Directional deposition

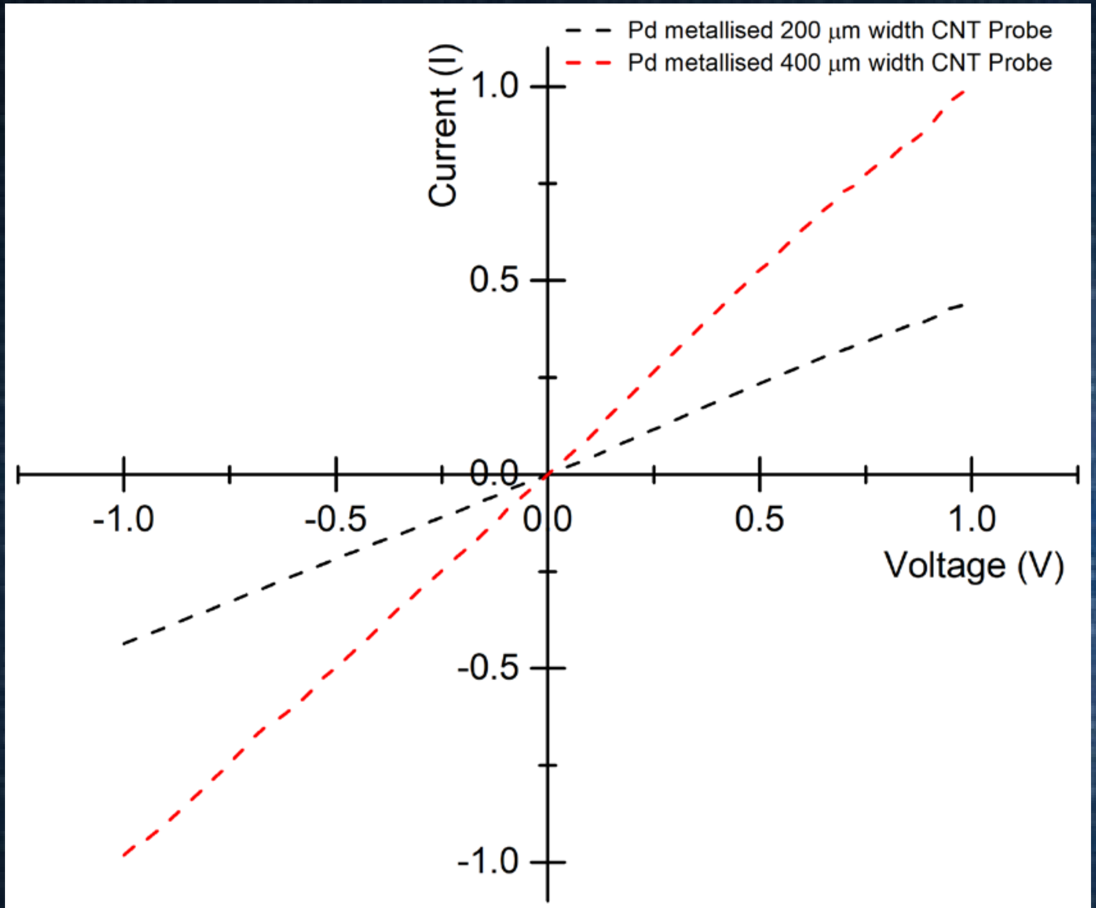


DC - Sputtered Pd

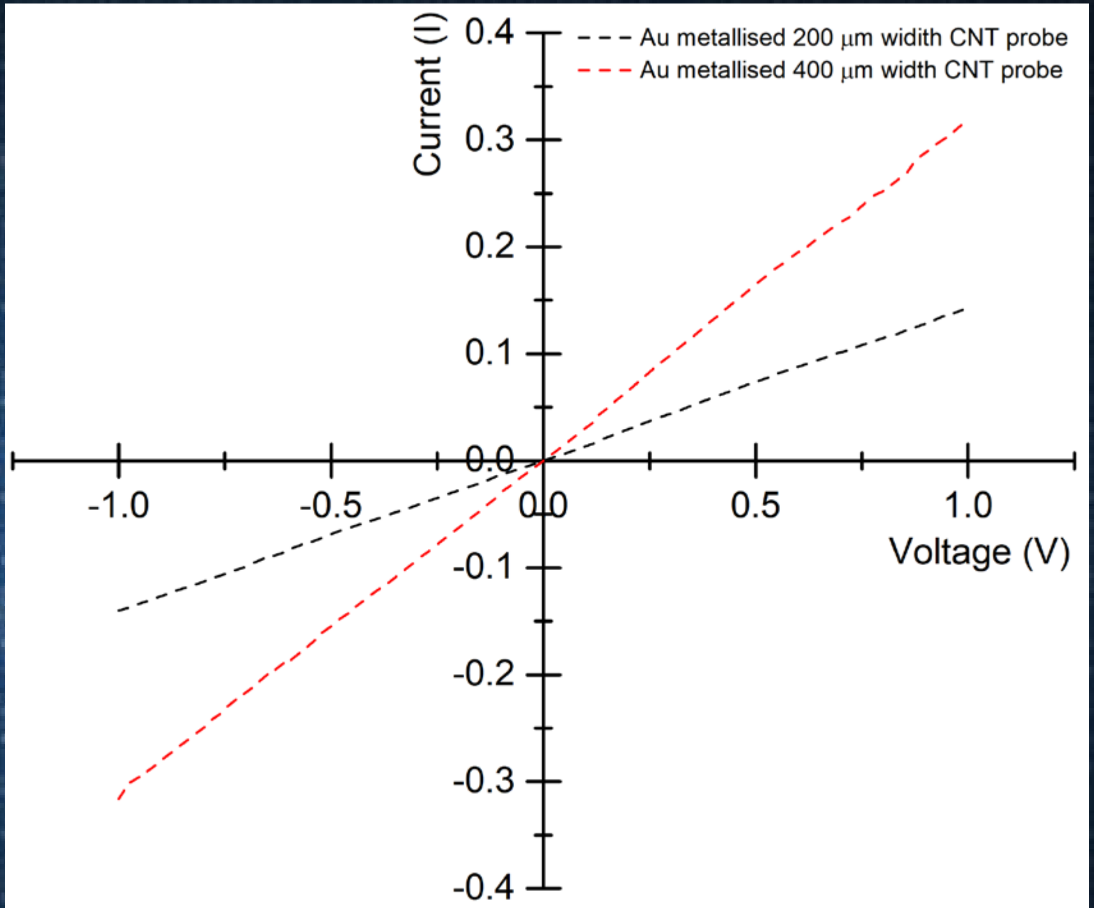


E-beam Evaporated Au

Results – Constant Load



Pd: 400 micron and 200 micron pitch probe



Au: 400 micron and 200 micron pitch probe

Conclusion

- Microspring probe structures (up to 750 µm) based on metallised vertically-aligned CNT are demonstrated
- Pitch can be controlled by selectively patterning the catalyst for CNT deposition
- Reproducible, low contact resistance (<1 Ω) with compliances up to 50µm
- Processes such as; densification, functionalisation allow tunability of the as grown probes

- Higher contact resistance;
  - Work function mismatch
  - Defects and impurities near the interface
  - Poor wetting
  - Resistivity of Carbon

Future work

- Work towards reproducible 100,000 cycles before failure
- Decrease the contact resistance to below 0.2 Ω
- CNT forests as interconnects?
- Transfer printing techniques to form more stable contacts
- High temperature probing applications;
  - CNTs are very stable at high temperatures

Thanks for your attention!

- My supervisors (Vlad Stolojan and Mark Baker)
- Smiths Interconnect for providing funding for this project
- **SWTW Committee for awarding me the IEEE William R. Mann Student Travel Grant**
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- ATI Technical Support Team (Grace Terry, Julian Fletcher, Tony Corless, Jose Anguita, Chris Buxey and Kostis Michelakis
- ATI staff and PhD (Simon King, Laurence Stant)