Fabrication and Characterization of Carbon Nanotubes as r.f Interconnects

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Introduction:

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- The unique properties of carbon nanotubes (CNTs) have been extensively studied over the past 20 years.

- Much work on the low frequency electrical transport properties but little on the high frequency transport.

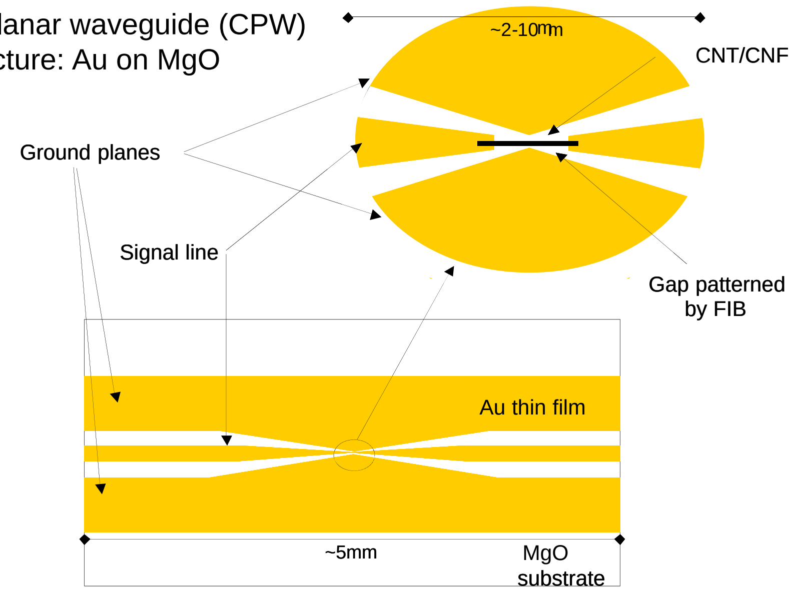
- Here we report ESA sponsored work on using CNTs as high frequency interconnects to 50 GHz.

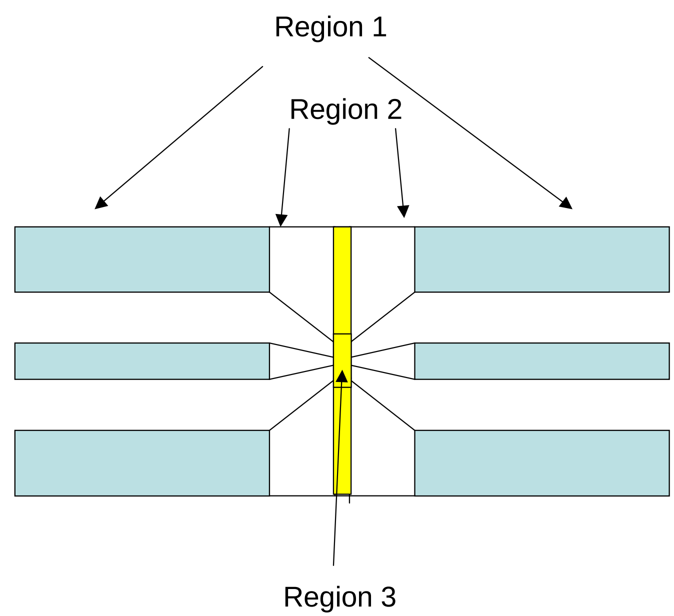
- Outline of the talk
  - Co-planar waveguide (CPW) design
  - Mask design and photolithography
  - Choice of substrate and wiring materials
  - CNT quality assessment and tube selection
  - FIB milling and micromanipulation
  - Microwave response of CNT interconnects
  - Correlation between d.c. and r.f response
  - Conclusions and future work

CPW design and fabrication

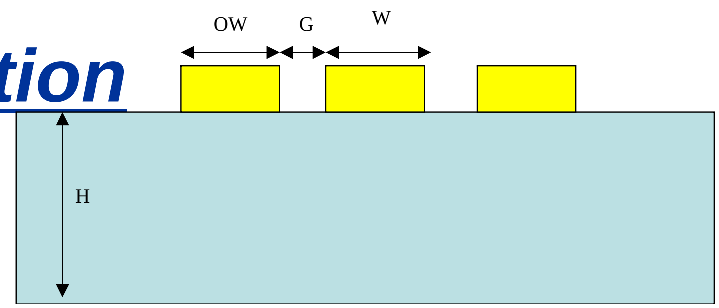
- **CPW (Co-planar waveguide) modelling & design**
  - Region 1 standard CPW
  - Region 2 taper
  - Region 3 FIBbed region
- **Select substrate and materials**
  - MgO for substrate since it is cubic single crystal which is isotropic
- **Mask design and fabrication for various device geometries and calibration artefacts.**
  - Characterisation of CPW test structures based on measurements with calibrated VNA probe station for on-wafer components using standard TRL [Through, Reflect, Line] method
- **Deposition and photolithography of relatively thick gold film on MgO substrates.**
  - The substrate is 500 µm thick MgO
  - Au film is 500nm thick

Coplanar waveguide (CPW) structure: Au on MgO

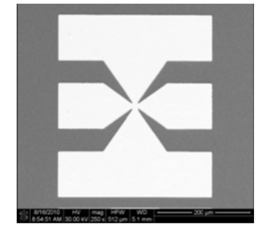




CPW design and fabrication

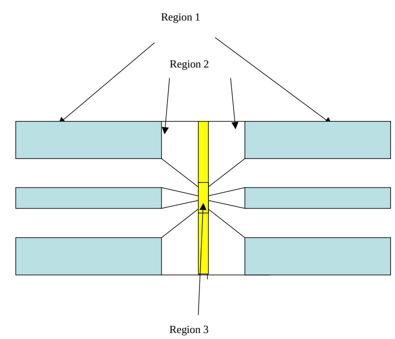


CPW:

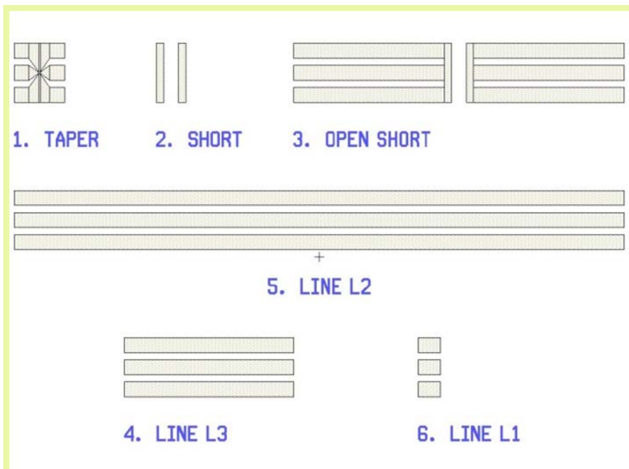


Detailed Mask design and fabrication for *various device geometries and calibration artefacts*.

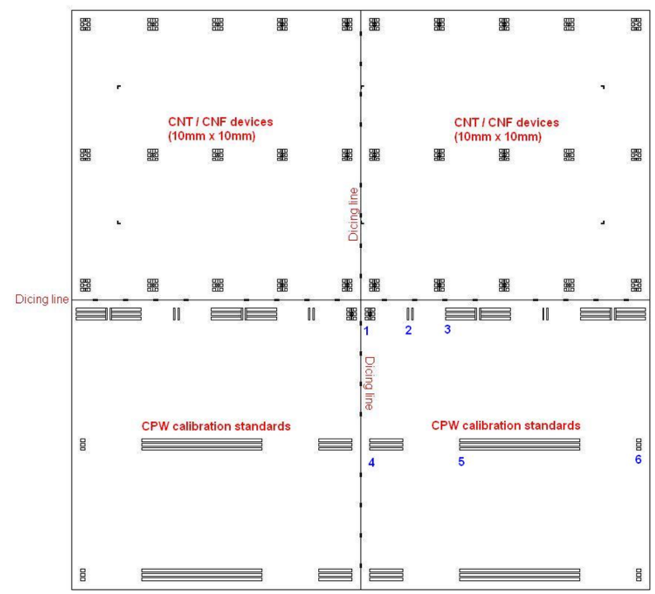
Port Dimensions		
W	100	µm
G	50	µm
OW	100	µm
T	0.5	µm
Taper End Dimensions		
W	8	µm
G	4	µm
OW	192	µm
T	0.5	µm



***Calibration artefacts*:**



Layout of the mask



Calibration Devices		
Short		
W	200	µm
Length	50	µm

Line Lengths		
L1	150	µm
L2	2150	µm
L3	1150	µm
OS1	1025	µm + shorting bar on left
0S2	1025	µm + shorting bar on right

NPL Measurements on Quality of CNT Samples using Dielectric Resonator

- We have previously developed a non-contacting method for measurement of microwave surface impedance of conducting thin film samples.

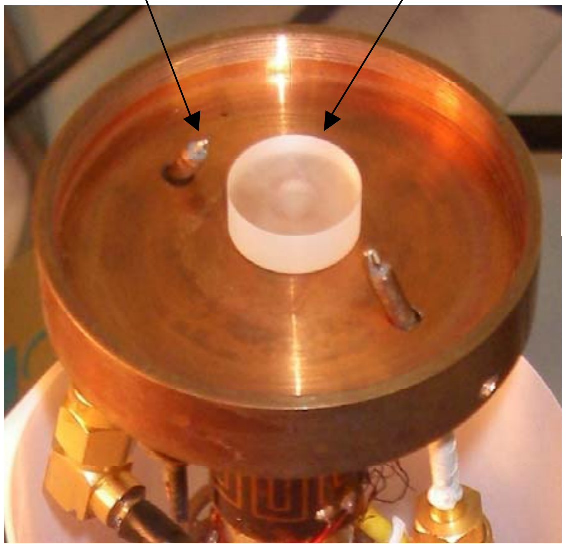
- This uses a high Q dielectric resonator to which the sample is coupled via the external field near the resonator.

- We modified the method to assess quality of various sources of CNTs before using them singly for interconnect experiments.

- A suspension of CNTs on polymer film was used in place of the thin film substrate.

Microwave coupling loops

Sapphire puck



The first samples to be examined were made by chemical vapour deposition (CVD) using the high pressure carbon monoxide (HIPCO) process.

NPL Measurements on Quality of CNT Samples using Dielectric Resonator

- The estimated surface resistance of these nanotubes is some 50 times greater than that of copper at room temperature and 12 GHz.

- This is inline with what has been measured by others for similar material.

- The measured surface reactance is also in line with what may be expected for a ***mat of weakly interacting CNTs***.

$$R_s = 480\pi^2\varepsilon_r\left(\frac{L}{\lambda}\right)^3\frac{1+R}{(1+\varepsilon_r R)FQ_c}$$

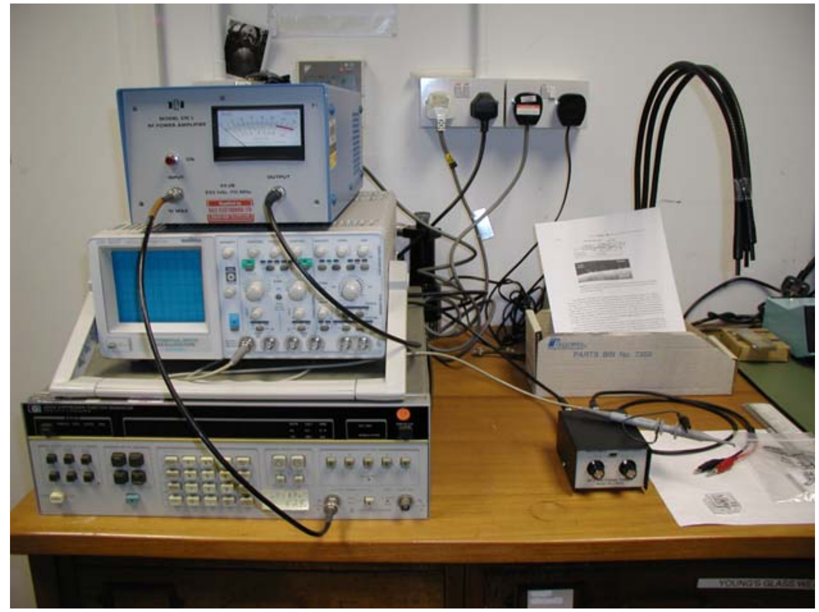
$$X_s = -480\pi^2\varepsilon_r\left(\frac{L}{\lambda}\right)^3\frac{1+R}{(1+\varepsilon_r R)F}\left(\frac{f_0-f_d}{f_d}\right)$$

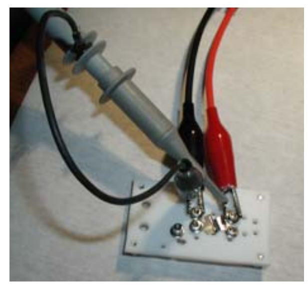
Table 3:

Sample	f_d (GHz)	f_o (GHz)	X_s (Ω)	Q_c	Q_d	R_s (Ω)
3H1	12.16530 (± 0.00001)	12.162359	3.55 (± 1)	1267	14050	**0.55** (± 0.2)

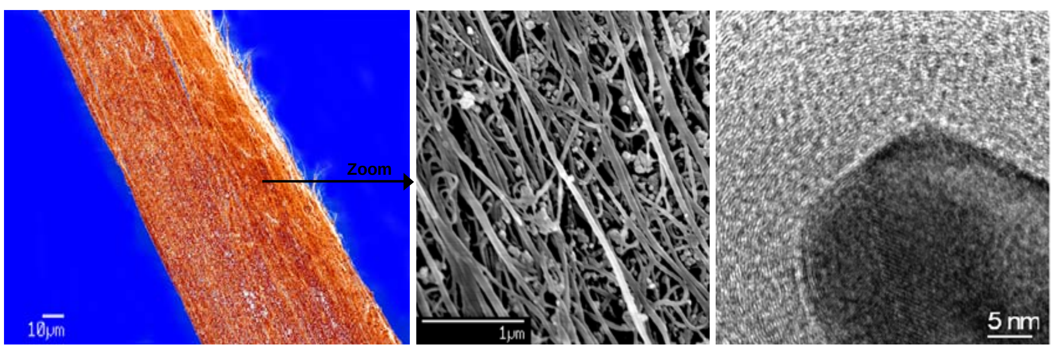
Alignment of CNTs by Electrophoresis

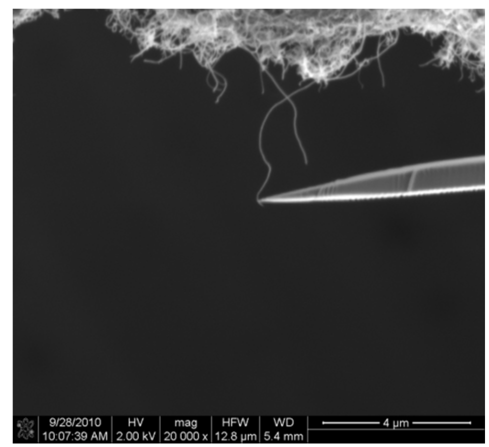
- **Preparation of CNT suspension in liquid**
- **Develop method for orientation and purification of CNT using ac Electrophoresis**
- **Production of the cartridge of purified oriented CNTs**





The electrophoresis set-up



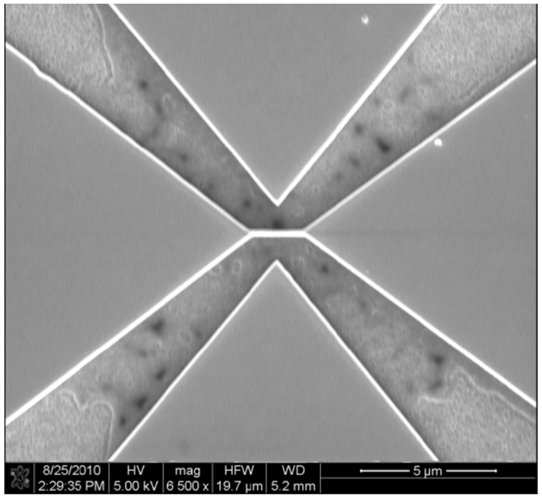


CNT cartridge with micro probe

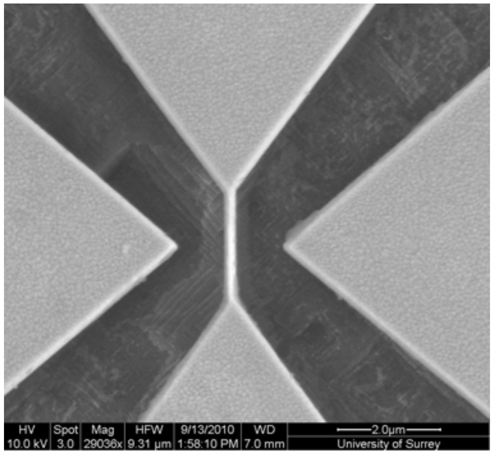
Nano scale patterning and CNT/CNF attachment

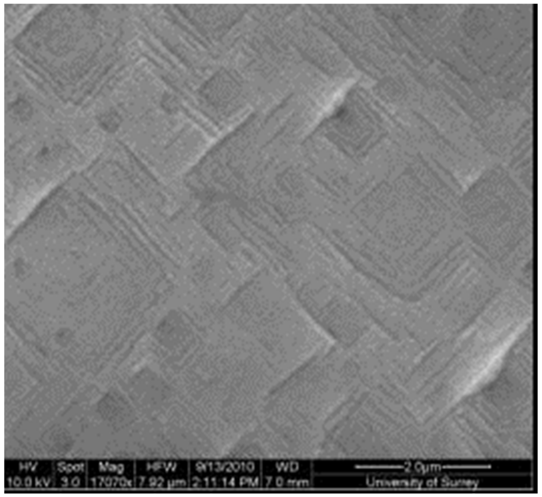
- **Nano scale patterning of test structure using FIB**

- **Solved charging problem for ion milling on MgO substrate**



SEM image of first Au interconnect bridge, following FIB milling, Au nanowire: ***200nm x 2μm***

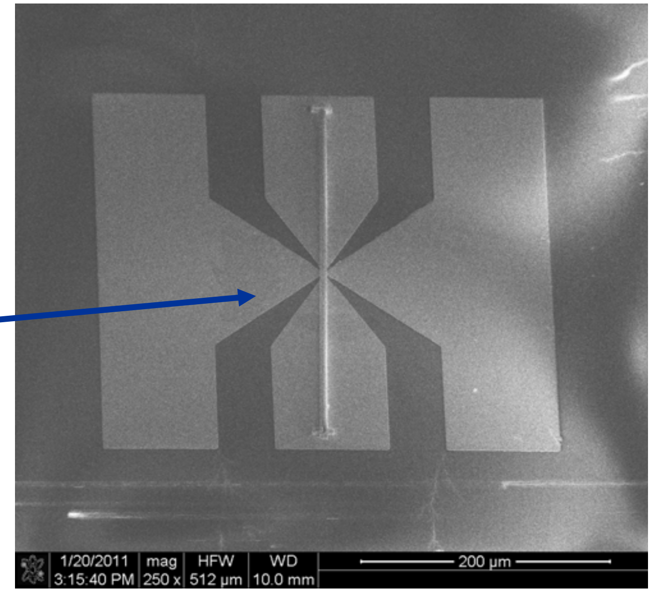


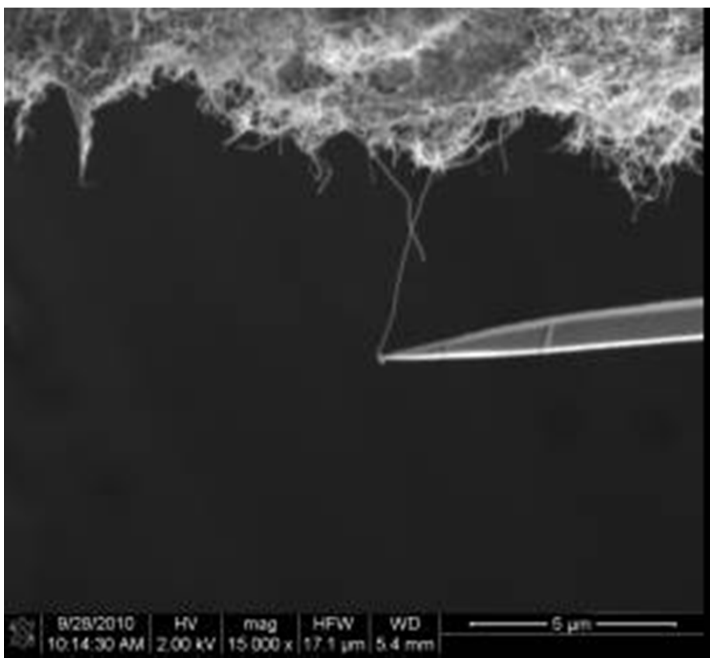


Two images of the devices and substrate following wet chemical removal of the Al layer. The Au device is untouched but the MgO shows some chemical attack.

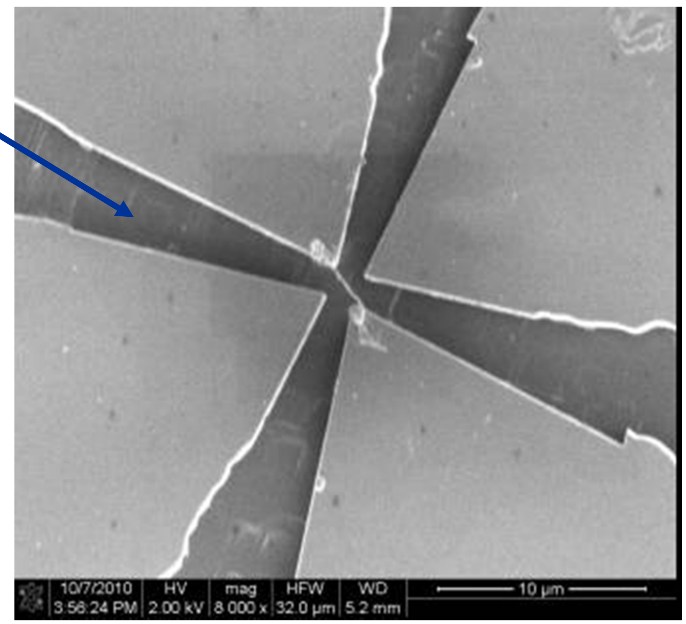
CVD CNT and Carbon NanoFibre (CNF) attachment

- **Image and select the CNT**
- **Attach CNT/CNF**
- **More details below…**





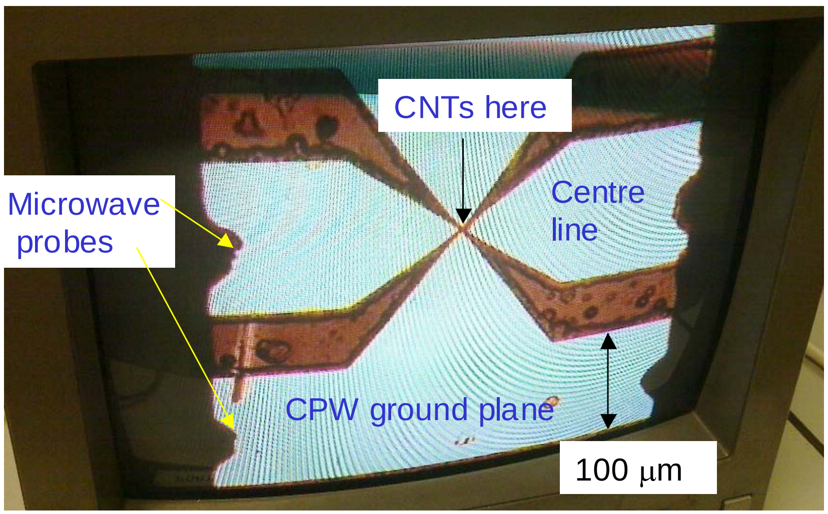
Selection of individual CNTs from electro-phoretic alignment on blade.



SEM images of CNF (top), CNT (bottom) attached to CPW

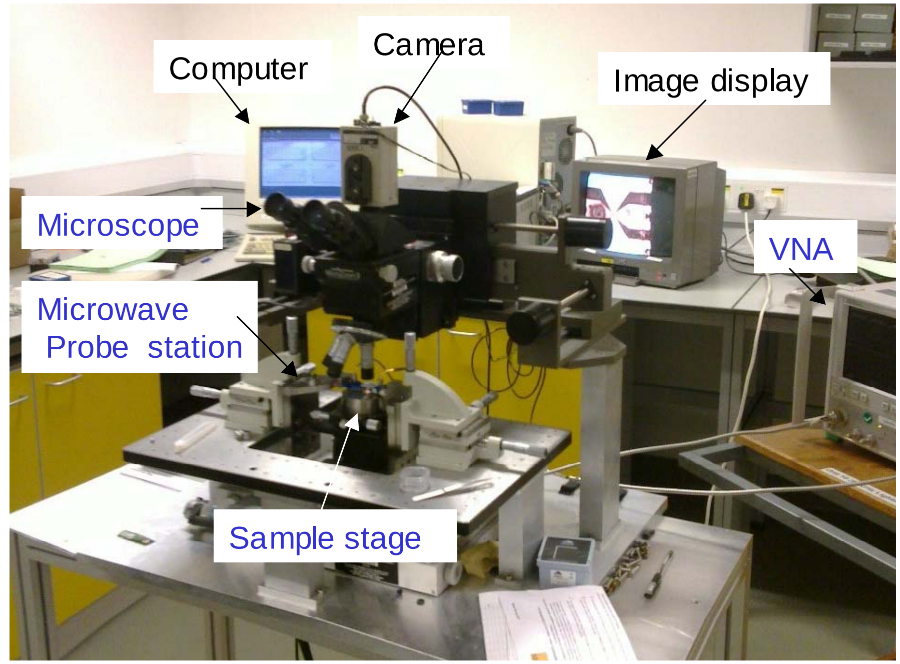
Preparation of the test system

- ***Test Equipment***
- ***Calibration substrates***
- ***Measure the CPW with CNT***

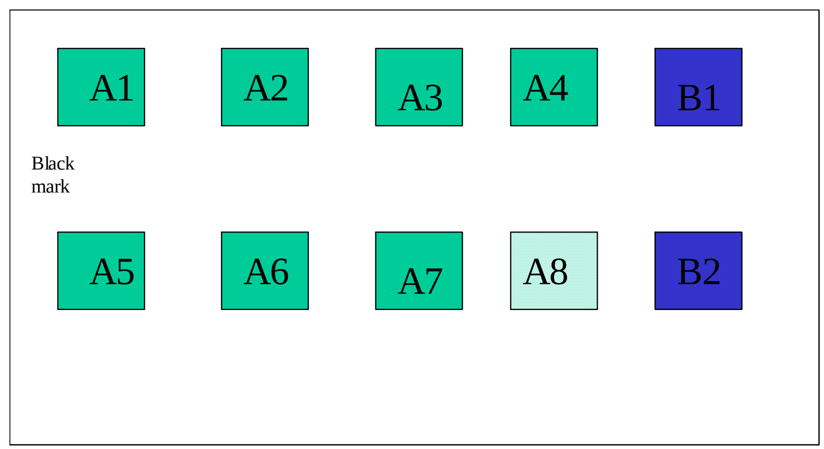


Micrograph of microwave probe landed on RF CPW with CNT sample_ devices-2-A4: the gap is about 200nm.
it is not possible to see the CNT across the gap with this optical microscope.

Microwave probe test system set-up



Device layout



Preliminary Measurement and Modelling Results

- *d.c. measurement*

Device	Description	d.c. resistance Ω
A3	CVD CNT	25.0K
A4	CVD CNT	43.0K
A5	Open circuit	∞
A6	Au line	2.2

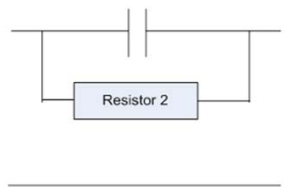
- Simple d.c. measurements of the CNT interconnect resistances showed high values.
- It was not clear if this arose from intrinsic CNT resistance or from high resistance contacts.
- Nevertheless we still measured the high frequency transmission of the devices listed above.

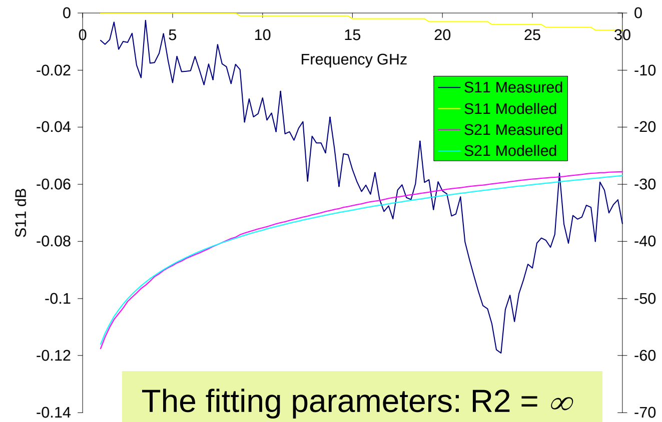
Preliminary Measurement and modelling results

Measured and modelled S-parameters for

- *Open circuit*
- *Au line*
- *CNT*

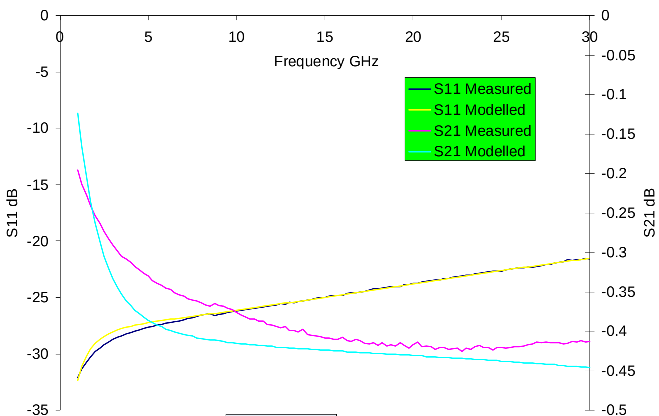
open circuit

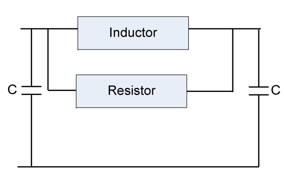




The fitting parameters: R2 = ∞ , C1 = 2.2 e-15F and C2 =0F.

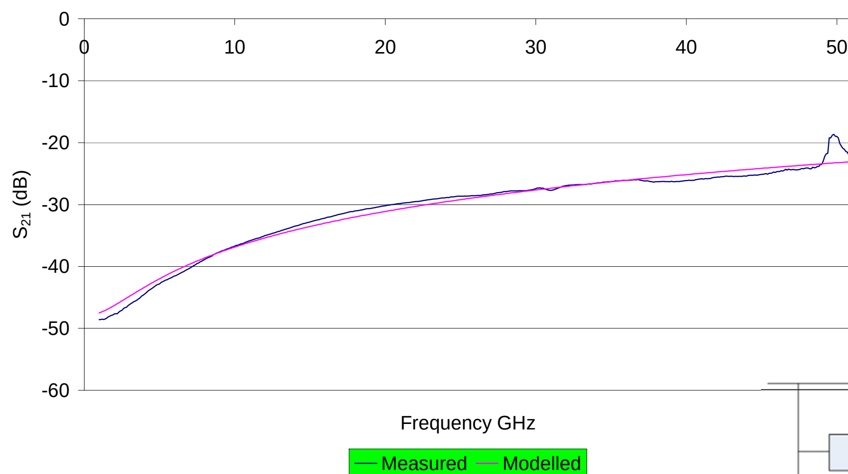
Au line

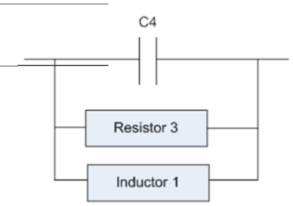




The fitting parameters: R2 = 1.45 ohm C1 = 2.2 e-15F and C2 =5.5e-15F.

CNT device

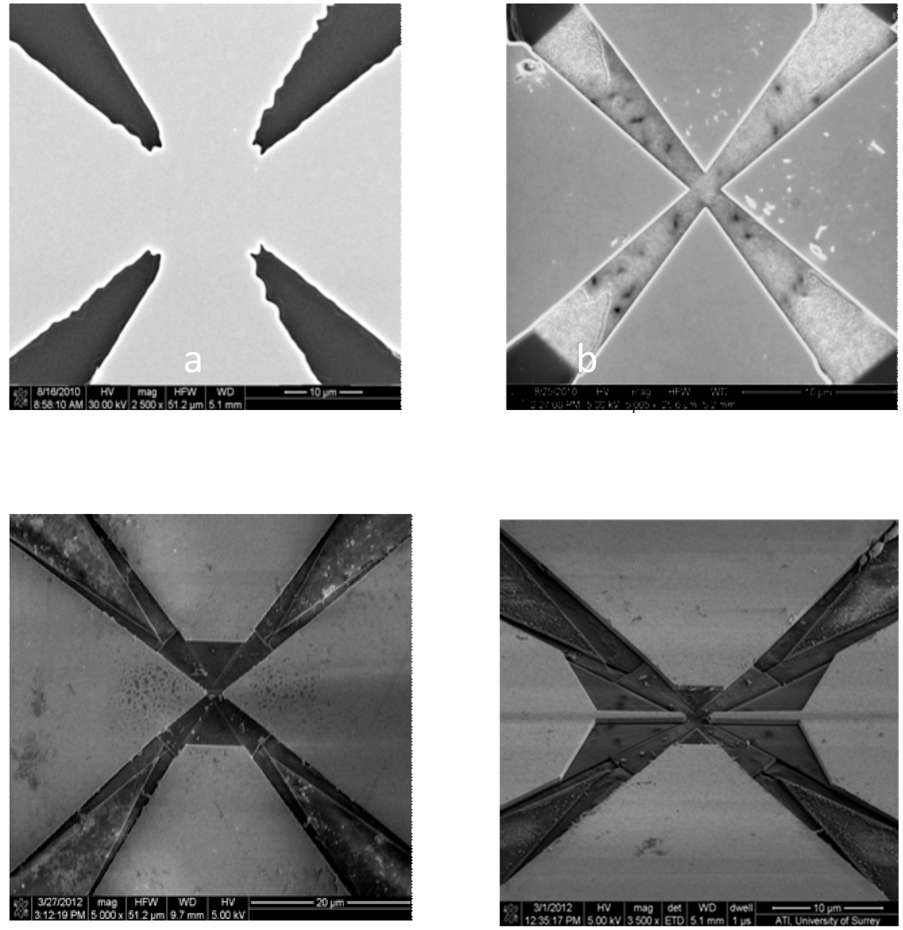




CNT device
Measured and modelled S-parameters for CNT.
The fitting parameters are R2 = 25.0kΩ,C1 = 2.2 e-15F and C2 = 0F

Parasitic Capacitance

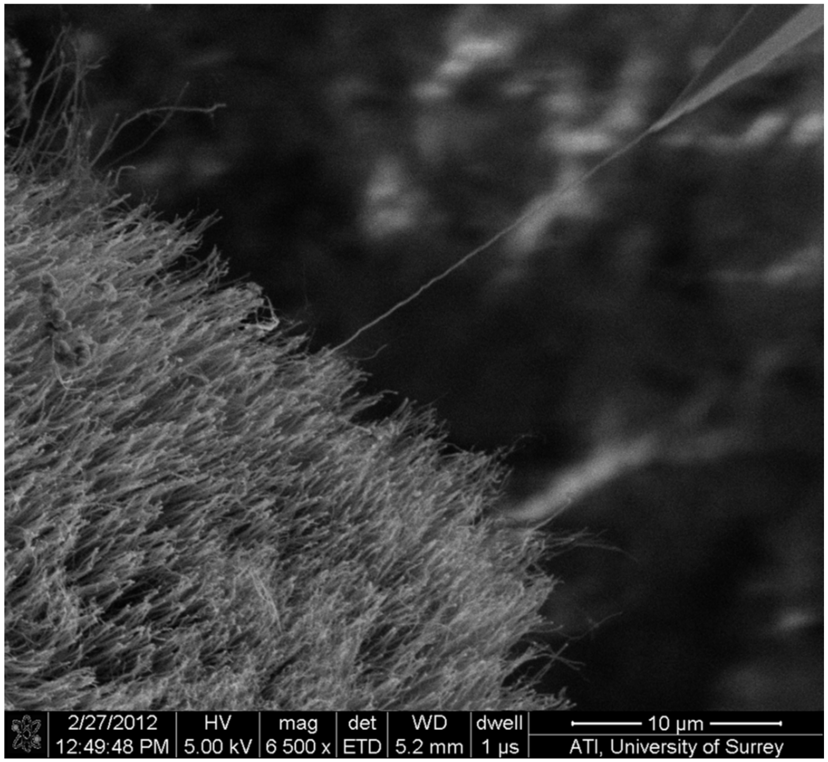
- For high frequency operation it is critical to reduce the parasitic capacitance around the interconnect region.
- This is particularly important when the resistance of the interconnect is relatively high (RC time constant).
- We have therefore used FIB milling to cut back the CPW ground and centre electrodes in the vicinity of the CNT interconnect.



Additional FIB cuts made to the electrode regions of the CPW device structure.

Long straight MWNTs

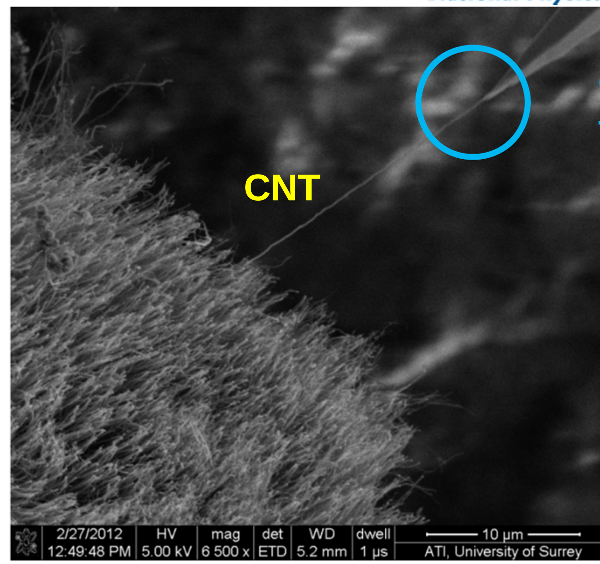
- We acquired a supply of excellent straight MWNTs from TsingHua University (Beijing).
- These are much longer and straighter and therefore much easier to manipulate than the CVD CNTs previously used.
- The image shows individual multiwall carbon nanotube in the process of being extracted from the mat of tubes.
- The tube in this case is in excess of 50μm long.
- Note also the low distribution of tube diameters.



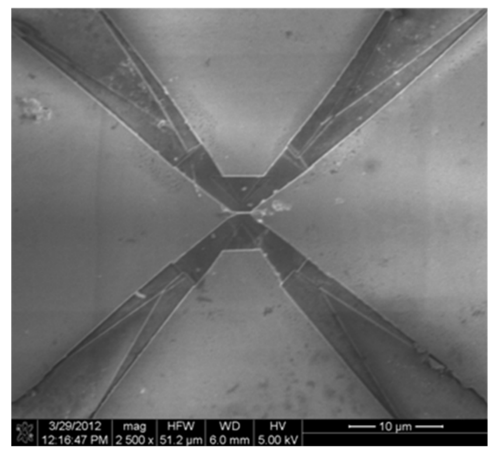
SEM image of the MWNTs

Nanomanipulation & Welding

- A FIB sharpened carbon fibre is manoeuvred to be close to the CNTs and attached to the free end of a single CNT.
- The FIB gas injection system (GIS) injects a small burst of Pt deposition gas while the connection between the fibre and CNT is magnified in the SEM image so that it fills the imaging frame (typically > x100k).
- After a few seconds the GIS is shut off and the beam blanked while the gas dissipates.
- When the tip is reimaged the single tube should be firmly attached to the tip.
- The tip is now withdrawn slowly, carefully pulling the tube from the bundle.
- The tip and tube are now moved in to be close to the CPW structure.



1^{st} step

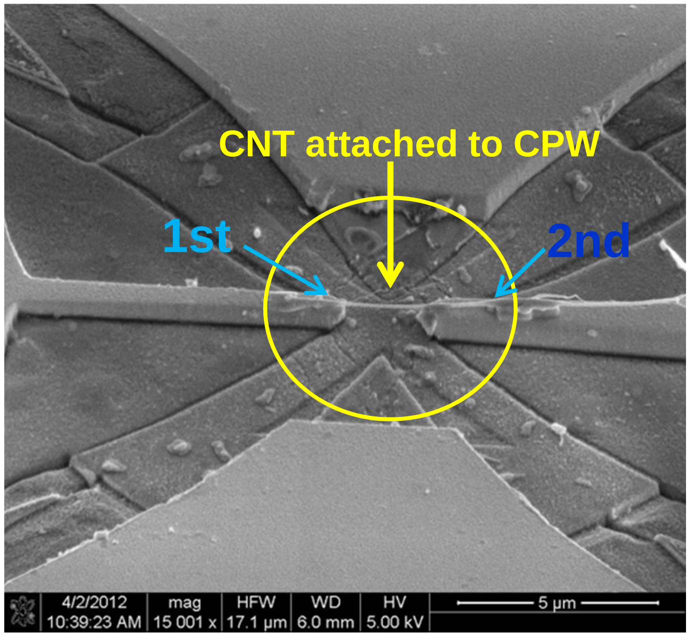


2^{nd} step?

SEM image of the completed device. Note: the image quality is not ideal as it is captured at a high scan rate to minimise exposure of the CNT to the electron beam.

Nanomanipulation & Welding

- A second carbon fibre tip is brought into contact with the CPW to ground it to reduce charge build-up.
- The tube on the tip is brought into contact with the CPW device and manoeuvred into place across the electrodes.
- Once more the Pt GIS is used to attach the free end of the tube to the first electrode.
- With care it is possible to attach the tube more securely to the electrode than to the tip so that the tip can be withdrawn leaving the tube in place.

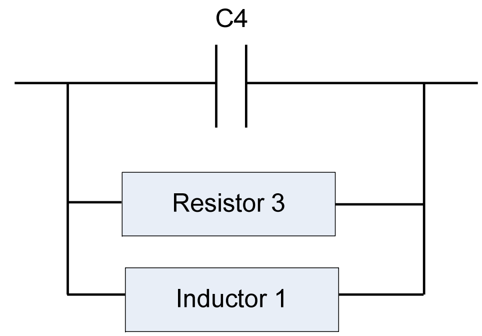


SEM image of one truncated CPW device with attached CNT.

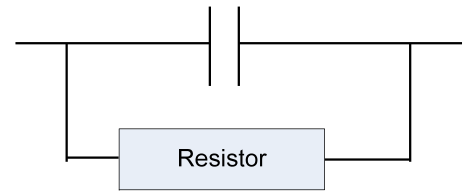
- Next a second short burst of Pt can be used to ensure connection to the second electrode.
- Finally the magnification is greatly reduced and the grounding tip is removed.
- Good images of individual tubes in place are difficult to obtain without damaging the tubes.

Modelling

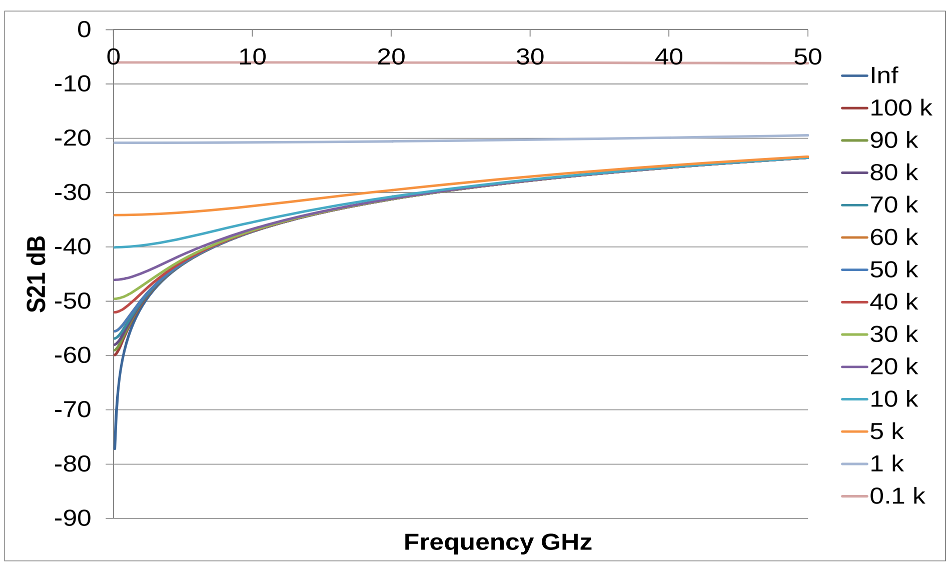
- We have modelled the interconnect as a lumped circuit as shown in the upper figure.
- The inductance required to reproduce the observed frequency dependence of the interconnect transmission is vanishingly small so has been ignored in the second model.
- Below we model S_{21} for a range of interconnect resistances for C=2.2pF whereas we show S_{21} for a range of capacitances, assuming R = ∞.



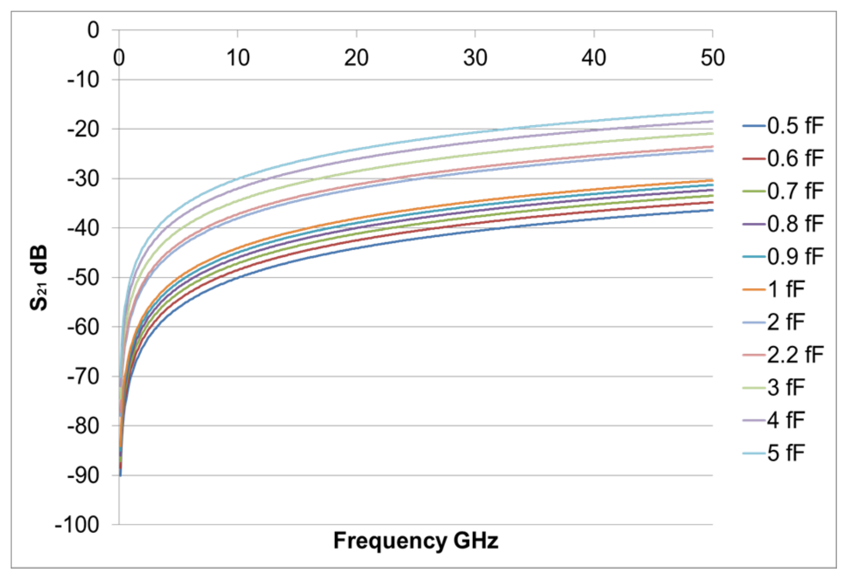
1st Model



2nd Model



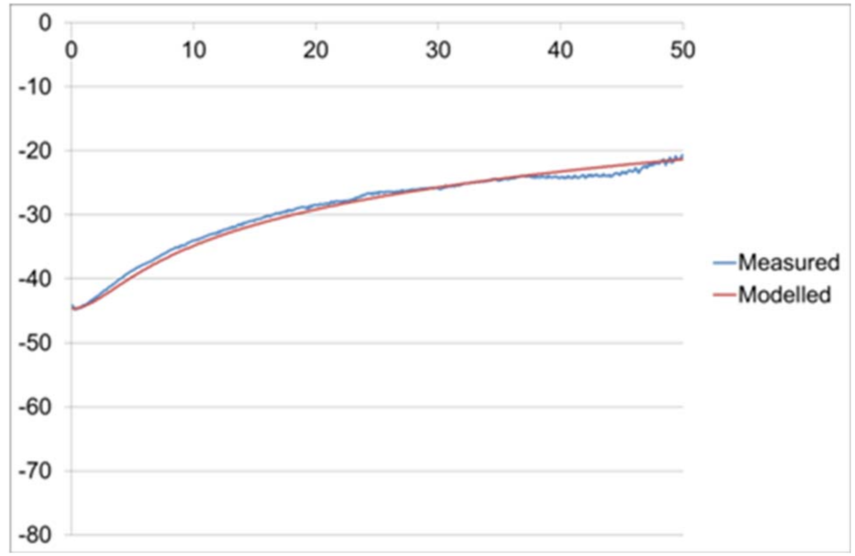
C=2.2pF



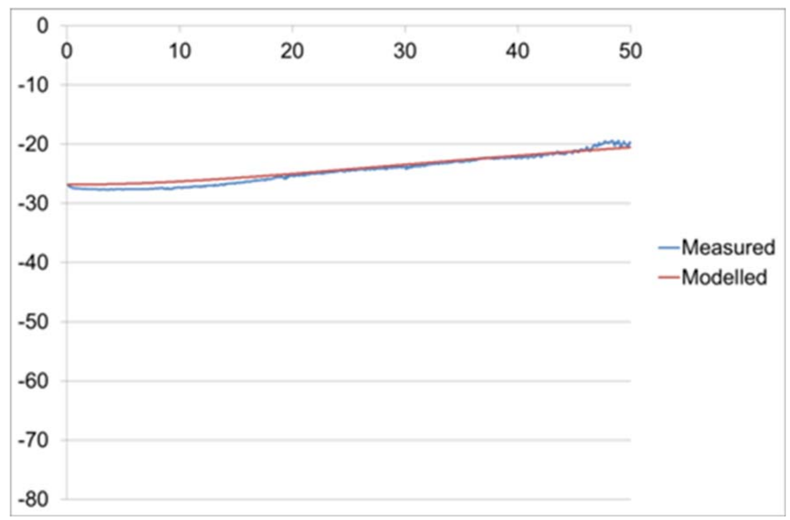
R = ∞

Comparison between Model & Results

- The simple model above gives good agreement with experiment where the d.c. resistance of the interconnect is used for R and C is taken as 2.75pF.
- The upper figure corresponds to R~17kΩ whereas the lower figure has R~2.1kΩ.
- Although lower resistance interconnects would be desirable this requires more specialised CNT production (e.g. MWNTs with more than 20 shells, all of which should be metallic and ballistic).
- This is reasonable to expect but is beyond the scope of this work.
- Note that the input power of the VNA is +10dBm and the interconnect is capable of handling this even though the tube diameter is only 40nm.
- The ultra-high current density capability (5×10^{12} A/m^2) will be of critical importance.



S_{21} vs. f for CNT R1 D2: R_{dc} = 17kΩ, C = 2.75pF



S_{21} vs. f for CNT R1 D3: R_{dc} = 2.1kΩ, C = 2.75pF

Summary

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• We believe the remaining challenges for demonstrator design will arise mainly from the ***reliability, reproducibility and characterisation*** of bonded CNT samples.

• Demonstration of adequate interconnect performance will also depend on *in-situ behaviour* of the CNT samples.

• We will improve understanding of relative importance of contact impedance versus CNT intrinsic impedance.

• The demonstrators will be enhanced versions of the co-planar waveguide (CPW) system already evaluated.

• Enhancements will involve further varying gap dimensions and also the Au CPW centre conductor width in the region of the CNT contacts.

• Outputs from the modelling and measurements will continue to contribute to optimising design.

Conclusion and Longer term vision:

Carbon nanotubes possesses many desirable properties:

- **Extremely high thermal conductivity**
- **High strength & resilience in circuits**
- **Extremely high breakdown current density**

Graphene has these desirable properties of CNTs

However it has a number of advantages over CNTs:

- **Available at wafer scale and may be patterned**
- **No issues of chirality**
- **Very high and gate-tunable mobility**

NPL already has considerable expertise in graphene devices at wafer scale.

NPL and ESA could prove ideal partners to investigate high frequency properties of graphene for interconnects.

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High Frequency CNT Impedance

National Physical Laboratory

Ballistic transport

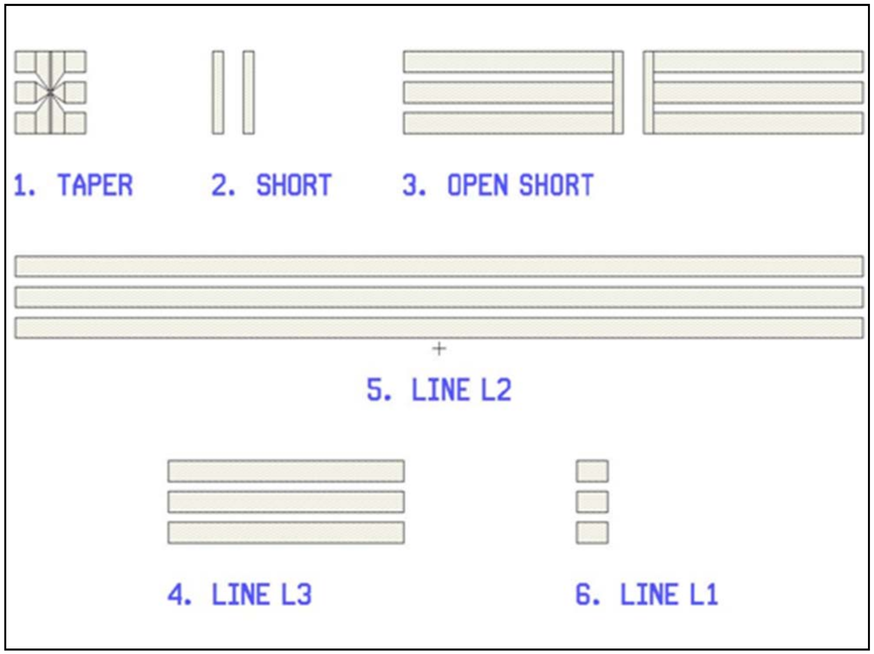
- Ballistic transport occurs when the mean free path for carrier transport, λ , becomes comparable to the length of the sample.

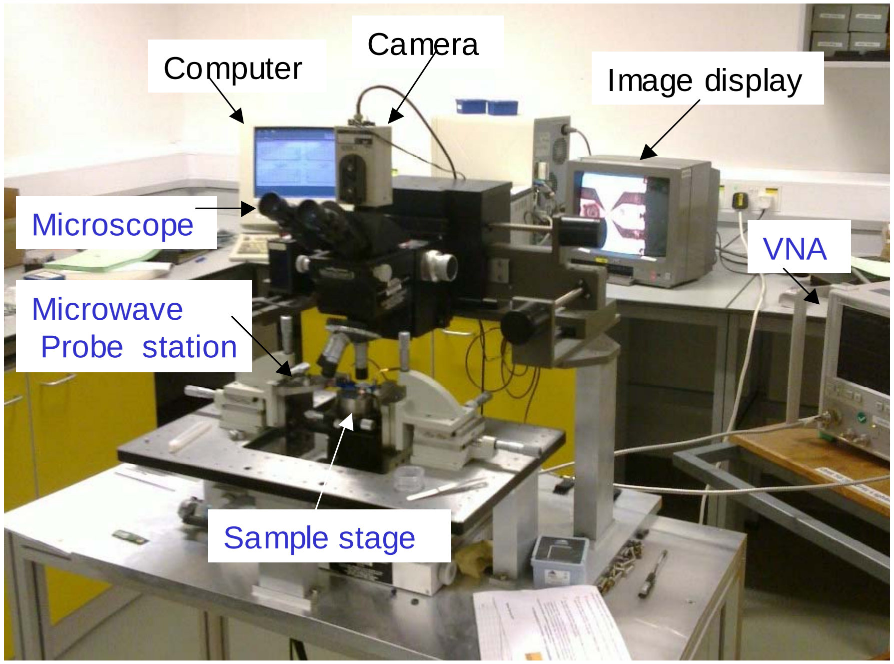
- Recent CNT measurements have demonstrated ballistic transport up to the THz range. The propagation delays suggest the Fermi velocity in a single wall metallic CNT is around 10^6m/s.

- This has practical implications as it implies the Fermi liquid model of independent electron transport in CNTs still applies up to THz frequencies.

VNA Measurements & Calibration

- The figure shows the range of the devices on the chip including the CNT interconnect and TRL artefacts.
- TRL artefacts are necessary for on-chip VNA calibration measurements.





- The chip is mounted on a microwave probe station.
- The probes are carefully landed on the CPW electrodes.
- The Au film may be damaged by repeated contact.