Carbon Nanotube Composite Surfaces for Electrical Contact Interfaces

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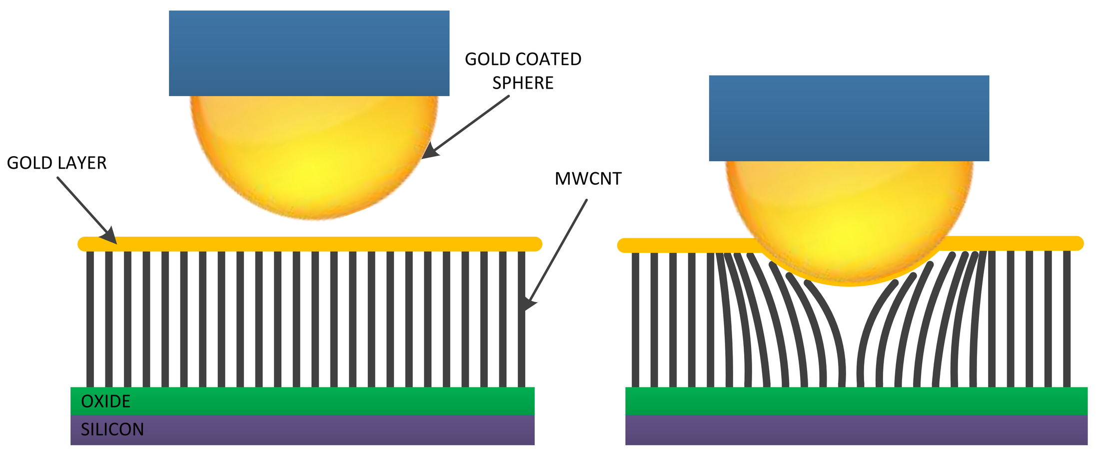
Problem Outline, Aims and Motivation

Material transfer between switching contact surfaces in MEMS relay switches causes device failure.

- Investigate CNT composite surfaces and develop robust mathematical models describing the contact and impact mechanics, contact resistance and switching performance of the surfaces.
- Develop CNT composite surfaces for integration into a MEMS relay device.
- Deliver prototype MEMS relay capable of switching over 10^8 cycles (with load conditions: 4 V >10 mA).



Schematic illustrating switching mechanism between gold coated sphere and gold coated carbon nanotube composite surface. Electrical conduction is through the gold film; the MWCNT-forest is used for its mechanical properties.

Modelling and Investigations

Aims of Modelling

- Characterise and analyse the mechanics of the CNT array
- Characterise failure mechanisms of CNT array
- Create model for contact of and material transfer of Au-Au/MWCNT and Au/MWCTN-Au/MWCNT
- Predict lifetimes of Au/MWCNT contact surfaces

Fine Transfer Mechanism

Melting voltage:

$$\theta_m = \frac{V_c}{2\sqrt{L}} = 3200 V_c\ (°K)$$

Material transfer:

$$\Delta v = \frac{A_r t}{N}$$

Accounting for switching bouncing:

$$\Delta v = \frac{A_r t}{N \times n}$$

Considerations

- Existing models exist in the forms of 1-D spring arrays, which do not describe buckling.
- Equation of motion for beams with damping:

$$\frac{\partial^2 u}{\partial t^2} + \frac{EI}{\varrho A}\frac{\partial^4 u}{\partial x^4} - \frac{S}{\varrho A}\frac{\partial^2 u}{\partial x^2} + \sigma(u) + 2\left(\alpha_0 \frac{\partial u}{\partial t} - \alpha_1 \frac{\partial^3 u}{\partial t\, \partial x^2} + \alpha_2 \frac{\partial^5 u}{\partial t\, \partial x^4}\right) = 0.$$

Plan

- Advance Euler's beam analysis to include CNT-CNT interactions and statistical model for entanglement.
  - Statistical model required for the distribution and deformation of CNTs.

Modelling roughness of surface profile

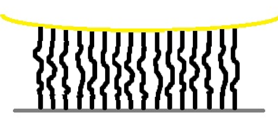
- Au/MWCNT have increased surface roughness compared to Au contacts.
- Weierstrass' function is frequently used to describe surfaces (top line).
- Adding an additional term to the function (middle line) which describes the Gaussian nature of the height and width distributions of the CNT array creates an improved model.

Phase 1: Small Deformations: Elastic

- Elastic deformations
- Can be treated as array of 1-D springs or mass/springs
- Model required to fit force profile, which has hysteretic properties to describe foam-like nature of compression.

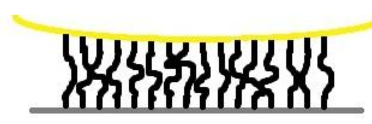
Phase 2: Medium CNT Deformation: Interaction

- CNTs begin to deform.
- CNTs begin to interact with each other.
- Modelled as Euler's beam or a foam.



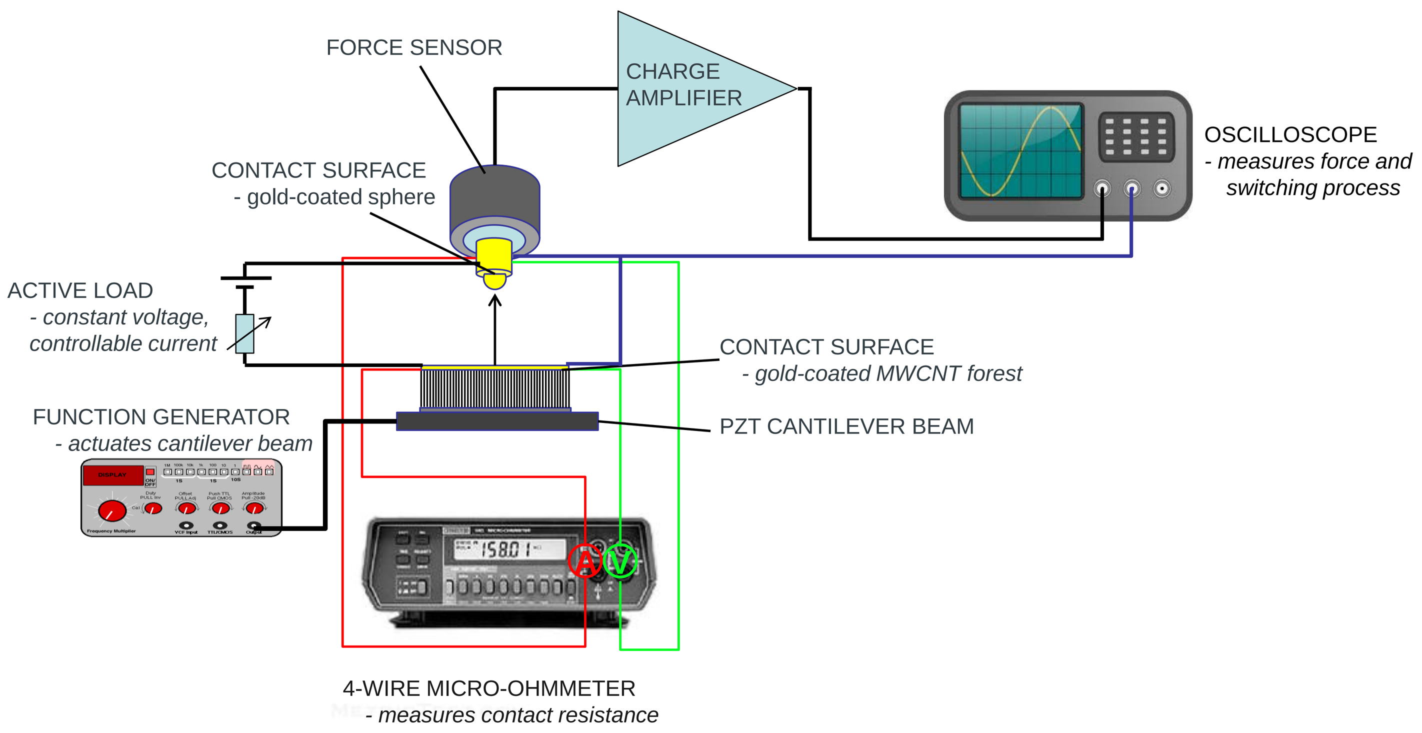
Phase 3: Large CNT Deformation: Entanglement

- Requires additional terms to equation of motion to describe CNT-CNT interactions.
- Permanent deformation due to entanglement.



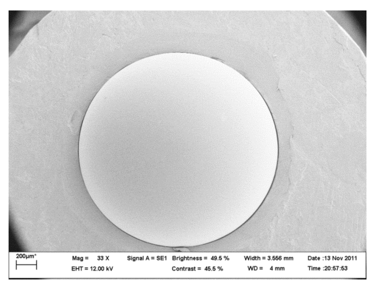
Experimental Work

Test Rig Setup



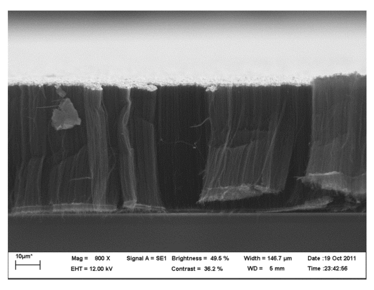
Schematic of experimental setup. A piezoelectric cantilever, on which a Au/MWCNT contact is mounted, is actuated by a function generator. The force applied is measured by a force sensor. The contact resistance is measured with a 4-wire ohmmeter. The voltage across the switching contacts is 4 V and the current is varied from 10 mA to 50 mA.

SEM Images of Contact Before Failure



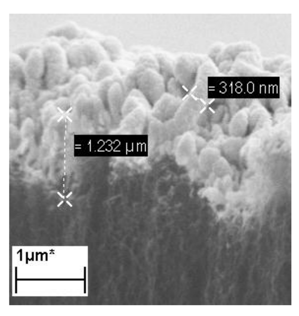
Au-coated Stainless Steel Ball

500 nm of Au is sputtered onto the ball. The resulting surface is smooth.



Angled View of Au-Coated MWCNT Surface

MWCNT forests are grown using thermal CVD. Height varied by altering growth time.

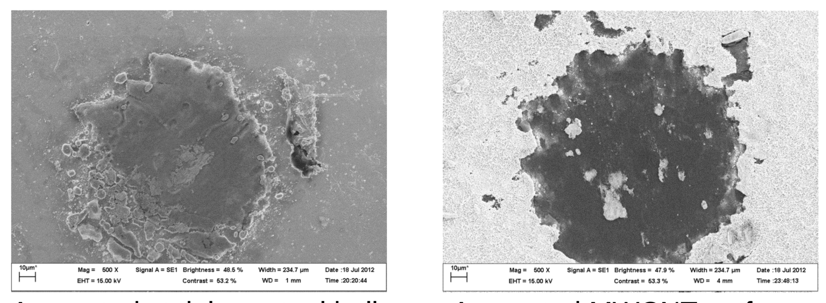


Au-MWCNT Surface

500 nm of Au is sputtered onto the MWCNT forests.

Surface roughness: Ra ≈ 1200 nm

SEM Images of Contact Surfaces After Failure

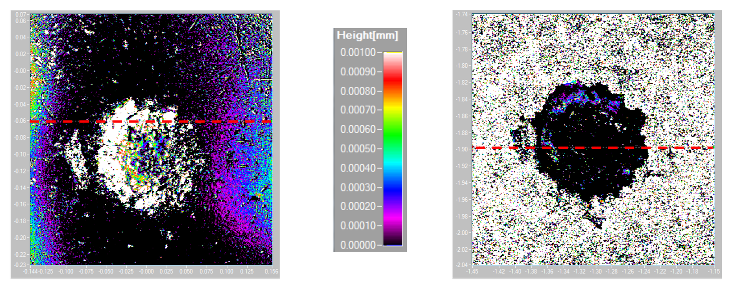


Au-coated stainless steel ball. | Au-coated MWCNT surface.

Load current: 50 mA
Load voltage: 4 V

CNT height: 30 µm.
Cycles to failure: ~10^8

Laser Scan of Contact Surfaces After Failure



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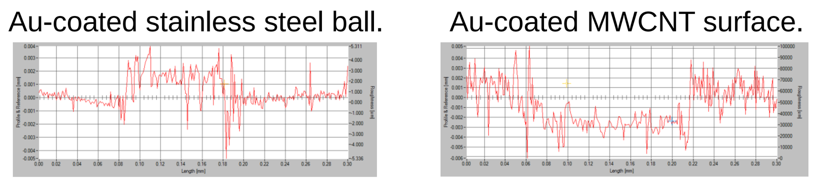
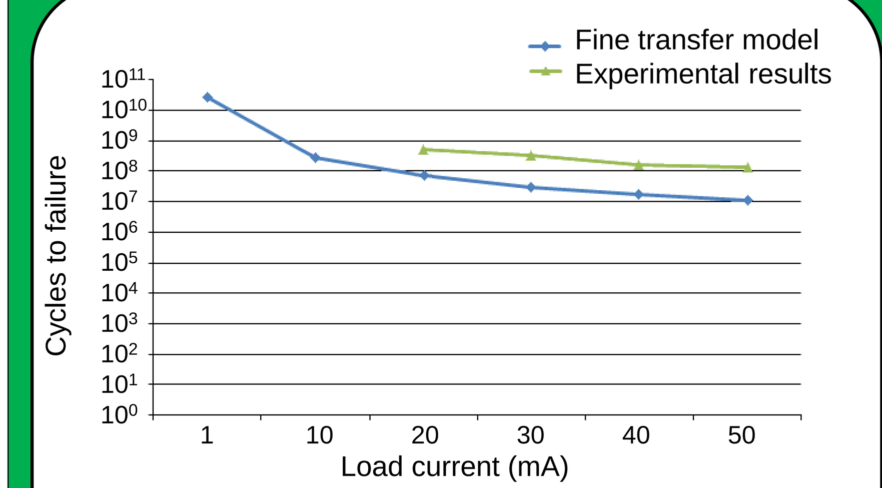
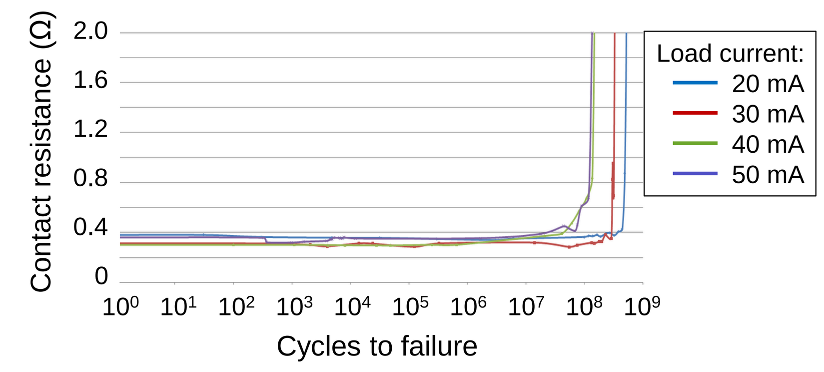


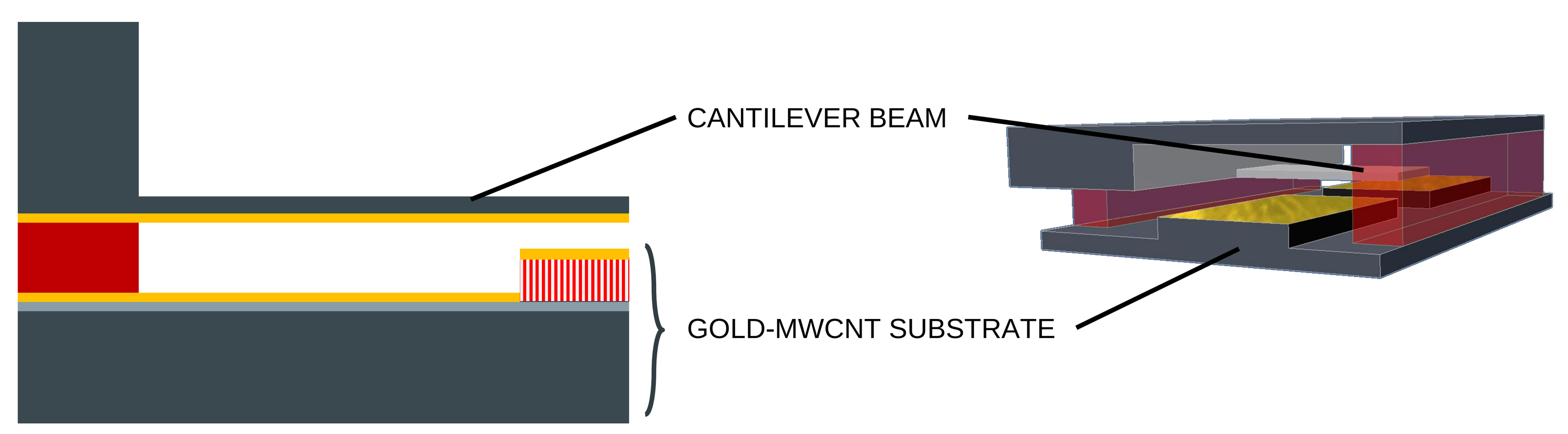




Graphs showing number of cycles until failure. CNT height and load voltage were constant at 30 µm and 4 V respectively. Load current varied.

MEMS Switch

Au-coated cantilever positioned above the Au-MWCNT composite surface, on which a transmission line strip is patterned.



Why MEMS Switches?

Examples of alternative technologies:

PIN diodes, electromechanical relays and field effect transistors

Advantages of MEMS switches:

Very low power-consumption when in off state
Very low on-resistance
Small size
High cut-off frequency
Low insertion loss
} these are particularly important for RF MEMS applications

Further to this, the ability to switch at high frequencies will aid the investigation into the switch failure mechanism.

Conclusions

- The use of Au-MWCNT composite as surfaces for electrical contacts has shown an increase in contact lifetime.
- The fine transfer mechanism which contributes to contact failure has been described.
- Switching lifetimes in excess of 10^8 cycles have been demonstrated for hot switching conditions.
- A MEMS switch has been designed to enable high frequency testing of the Au-MWCNT surface.

Future Work

- Investigate and computationally model the contact failure mechanisms.
- With current test rig evaluate the effect on lifetime of:
  - CNT forest height.
  - Load current.
  - Contact force.
- Fabricate the MEMS switch :
  - To provide experimental data.
  - To show feasibility of incorporating MWCNT into a MEMS switch.

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