ESA Project: RF potentialities of carbon nanotubes for nanoscale interconnections

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SUMMARY

Introduction:

The final report contains a detailed description of the design and fabrication processes of the carbon nanotube (CNT) demonstrator and reference structures for microwave interconnections and goes on to describe the performance of the CNT interconnects which form the basis of the demonstrators. We finish with conclusions on CNT performance for microwave interconnects and make suggestions for future applications and possible research investigations. Here we extract the key conclusions and propose some future work.

Design and Fabrication:

The basic interconnect structure using CNTs is at the nanoscale whereas the microwave input and output ports are at a scale 10^6 times greater. A coplanar waveguide (CPW) structure was chosen for the demonstrator since this ensures that only planar lithography is required to achieve such a large scale reduction. The modelling of impedance matching at varying length scale is also simplified. Cubic single crystal magnesium oxide (MgO) was chosen as the substrate material since it is an excellent low loss microwave material with isotropic dielectric constant. A demonstrator chip consists of multiple devices on a single substrate, of either 12 or 15 in number, consisting of 500nm Au on top of a 20nm thick titanium (Ti) layer, used as an adhesion layer, evaporated onto single crystal magnesium oxide substrates. The patterned CPW structures were defined by standard optical lithography from a glass mask. Some devices were designed to have CNT interconnects attached across a gap in the centre conductor of a tapered CPW structure while others were designed to be calibration artefacts for the vector network analyser (VNA) protocol which was used to define the interconnect microwave performance. These consisted of a series of open lines and short circuits of various lengths as well as CPW containing tapered regions with continuous Au centre lines.

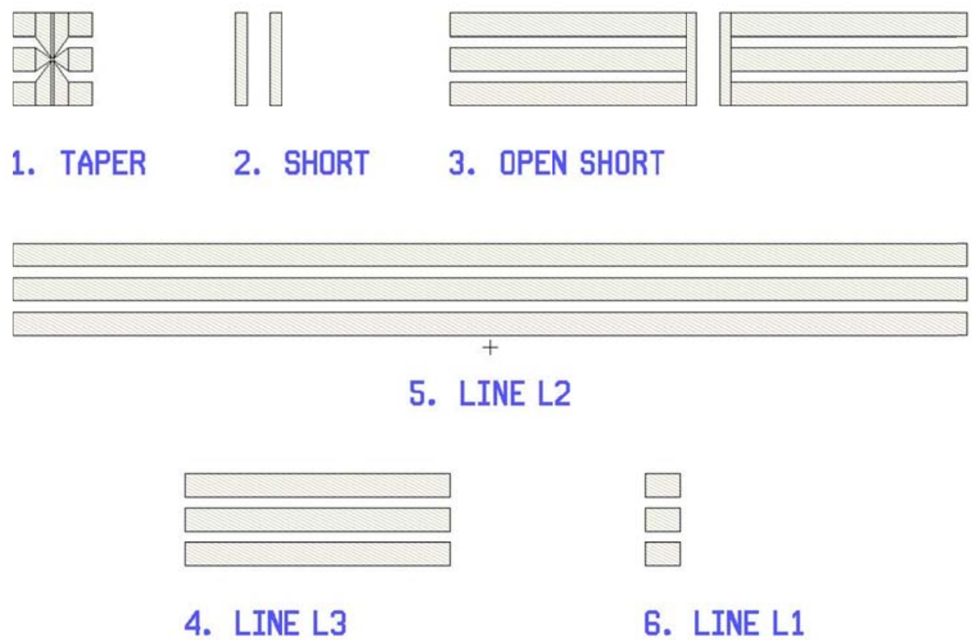

Fig. 1 The zoomed view of part of the mask layout showing the basic taper structure (1) and calibration devices (2 to 6).

To obtain the nanoscale geometry required for the electrodes in the region of the CNT interconnects optical lithography cannot be used as it offers insufficient resolution. While we could have defined the electrode structures with electron beam lithography this would have been both time consuming and costly due to the sequential nature of electron beam lithography. A practical compromise was to define the basic geometry of the devices with optical lithography and, where high spatial resolution is required in the electrode regions, we use focused ion beam (FIB) milling.

The excellent insulating properties of the MgO substrate led to some problems. When the devices were mounted in the FIB the localised build-up of charge, from the Scanning Electron Microscope (SEM), was so great that imaging was impossible. To solve this problem it was decided to sputter a thin layer of Aluminium (Al) (~20nm) over the entire sample, providing a conductive layer to prevent charge build-up from the SEM. With the Al layer less than a few tens of nm the outline of the Au structure was visible and the test structures could be milled. The Al film was removed by immersion in NaOH solution which did not damage the Au film.

Three different nanotube sources were looked at. The first CVD-grown sample was not found to be suitable at all due to the tubes being short, with large diameter distribution and very badly clumped together, thus making manipulation extremely difficult. The second sample was arc-grown CNTs and prepared and aligned using an electrophoretic cartridge methods, but the length of these CNT tubes proved is too short and not suitable for manipulation. The third sample was of CVD multiwall carbon nanotubes, produced by Tsinghua University using high temperature CVD growth. Tubes were harvested from their substrate in one piece as a mat of several mm square. Inspection revealed the distribution of diameters showed that the majority of the tubes were close to 50nm in diameter, some were found to be extremely long with the extreme being greater than 200μm in length.

A complex micromanipulation process was developed, to remove a single CNT from the source of tubes, to manipulate it close to the milled gap in the CPW structure, to weld it to the centre conductor in two places and to detach the micromanipulator. The process became quite reliable though somewhat time consuming.

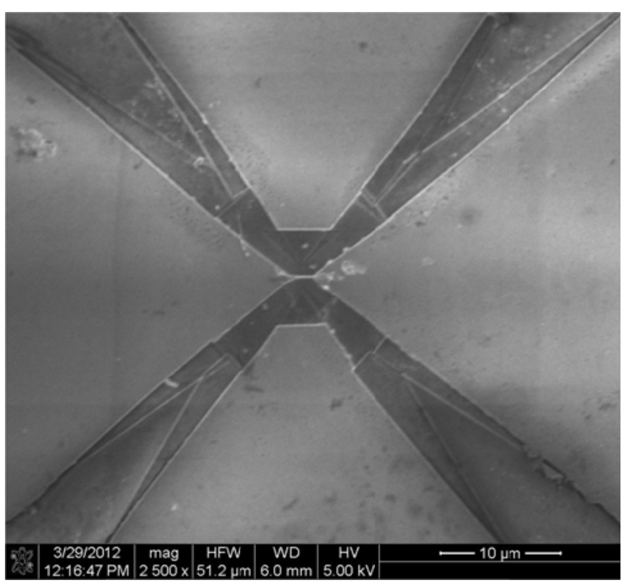

Fig. 2. SEM image of the completed device, with a Tsing Hua University CNT, 4μm long interconnect , CPW ground planes cut back 8μm to show attempt to reduce

parasitic capacitance. 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.

Electrical Characterisation:

Preliminary d.c resistance measurements showed that the successful yield of conducting CNT interconnects was in line with the expected proportion of metallic tubes. D.c resistances were typically 20kΩ compared with much lower resistances (a few ohms) for the Au interconnects. However it must be realised that the cross sectional area of the Au interconnect is some hundreds of times greater than that of the CNT so that the effective resistivity are much closer than it might appear.

Microwave transmission measurements up to 50GHz when compared with modelling bore out the effective high frequency resistance of the CNT interconnects. It also revealed that there was a parasitic capacitance associated with the CNT CPW structure of some 2fF. Attempts to reduce this by milling away the electrode material in the neighbourhood of the interconnect failed to significantly reduce the parasitic value.

Further devices were constructed, using the CNTs supplied by Tsing Hua University. We were able to reduce the d.c. and microwave resistances of these interconnects by a further factor of 10 in the best cases, to around 2kΩ. The measured frequency dependent transmission was in good agreement with the model, again assuming a parasitic capacitance of 2fF. Note that the current density being carried by the CNT at microwave frequencies is extremely high, several orders of magnitude higher than could be achieved with a normal metallic conductor of the same cross-section.

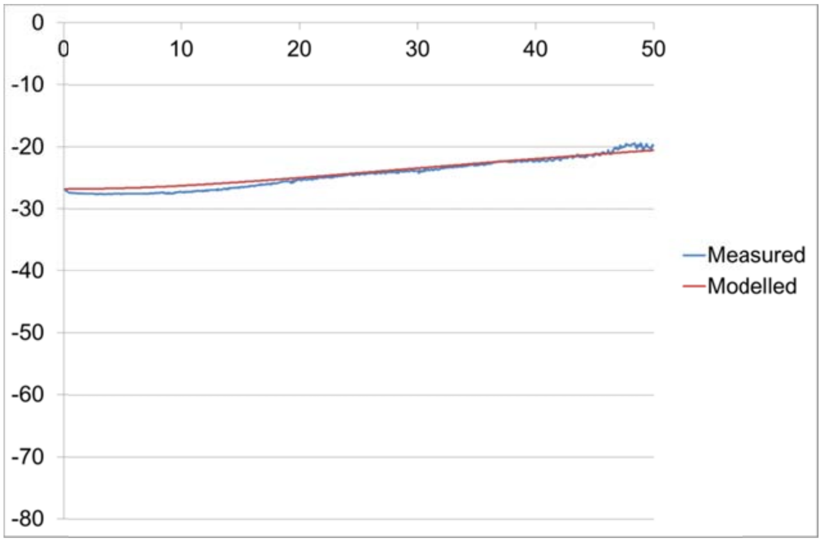

Fig. 3 Measured and modelled results for CNT R1 D3. R = 2.1 kΩ, C = 2.75 fF.

Conclusions on the Proposed CNT Interconnect Scheme:

Carbon nanotubes possess a number of unique properties which make them potentially useful for future microwave circuit interconnects. These include extreme strength and stiffness (making them ideal for micromanipulation), extremely high current breakdown values, far exceeding that of similar metallic interconnects of the same cross sectional area, and extremely high thermal conductivity (the highest known of any material except possibly graphene). The latter two properties make CNT interconnects intrinsically important for high power, nanoscale high frequency interconnects and it is expected that conventional metal interconnects would be significantly out-performed by optimised CNT interconnects of equivalent dimensions. To demonstrate this hypothesis experimentally it will be necessary to carry out the remaining weld-length experiment and, additionally, if possible, a high power experiment to try to determine the maximum current density achievable.

1. *Compatibility between thin metallic films and carbon nanotubes*

A major limitation in the present work has arisen due to the uncertainty of the resistance of the contact region between the thin Au film and the micro-manipulated carbon nanotube. It appears from our experimental data that it is difficult to reduce this below around 1kΩ per contact without increasing the welded length to be comparable or greater than the interconnect length itself.

2. Selection of metallic carbon nanotubes

The yield issue is also important. As mentioned above only approximately 30% of naturally grown single walled carbon nanotubes are metallic, the remainder being semi-conducting or insulating and therefore unsuitable as r.f. interconnects. There is no high yielding process available at present to sort out these types of tubes and this presents a serious impediment to the wider use of CNTs in mass-produced electronic circuits.

Recommendations for Future Research and Development Work

1. Further Work (microwave)

It can be seen that the capacitance that has been ascribed to the gap is the dominating factor in modelling the microwave electrical properties of the CNTs. Further works should be done to find the true cause of the capacitance and to reduce this to as low a level as practicable. This will allow investigations of other properties of the CNT such as its inductance and origins of stray capacitances and resistances due to the weld. In the first instance this should be investigated by models, quasistatic and full 3D simulation, of the CPW geometry. Further experimental work could also be contemplated if the weld-length issue can be resolved satisfactorily.

2. Further Work Based on Graphene

Single atomic layers of carbon have only been known since 2004 [K. S. Novoselov, A.K. Geim, S. V. Morozov, D. Jian, ‘Electric Field Effect in Atomically Thin Carbon Films’, Science v.306, pp.666-9 (2004)]. The hexagonally co-ordinated layers are essentially unrolled single wall carbon nanotubes. The interpenetrating sub-lattices of carbon produce some even stranger electronic properties than those exhibited by CNTs. In addition to sharing the strength and high thermal conductivity that CNTs demonstrate graphene layers have one very significant advantage over CNTs. All samples exhibit similar electronic properties and behave as a zero band-gap semiconductor. This means that there should no longer be a yield issue of the type that has plagued CNTs. A further huge advantage is that these graphene layers can have controlled conductivity through electric-field gating. Greater attention has been paid to achieving low contact resistances between single layer graphene and thin film metallic electrodes so this is less of a problem than for CNTs. The planar nature of the interconnects would also allow better and more realistic modelling of the structures at microwave frequencies. Our own microwave measurements at ~ 10GHz on single layer graphene conductivity of 4.5×10^7 S/m [to be published] suggests that an interconnect 2 μm wide by 4 μm long should have an intrinsic un-gated resistance of around 90 Ω. It is to be expected that the thermal transfer to a substrate (such as SiC) would be exceptionally high, given the planar nature of the interconnect film, with corresponding high power handling capability.