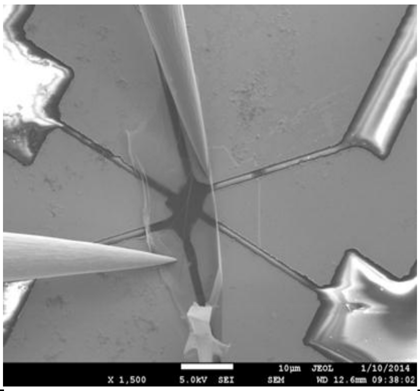
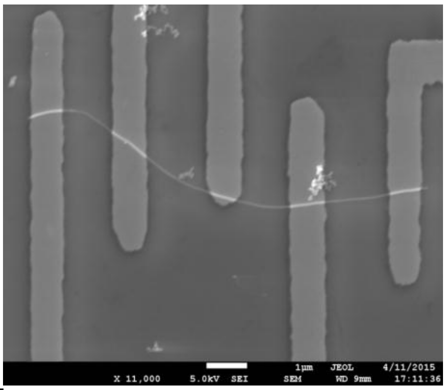
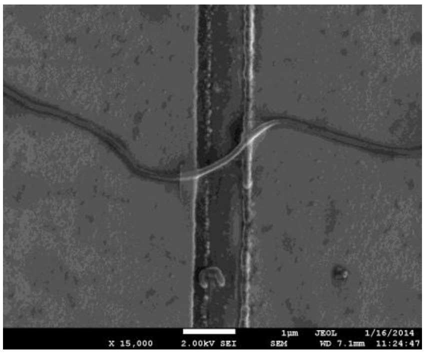
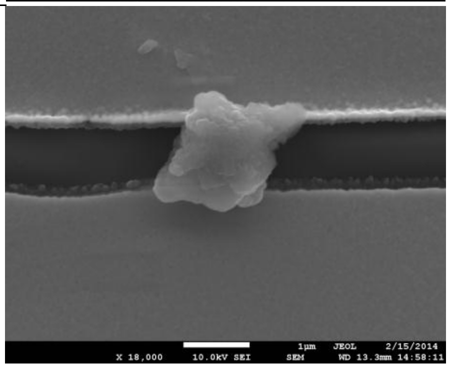
Carbon based Nano-electronic and Spintronic Device Applications Project: New Research Directions

With the support of South African government funding agencies (NRF) I have been successful in establishing a research group, the Nano-Scale Transport Physics Laboratory (*NSTPL*) which has facilities for the nanoelectronic device fabrication and study of quantum transport in nano-materials at low temperatures (300 milli Kelvin), high magnetic fields (12 Tesla) and high frequencies (10 MHz - 65GHz). All of our works during 2012-2015 were performed in the NSTPL have been successful in the following areas: http://www.wits.ac.za/nstpl/.

- Disorder induced superconductivity in diamond films both experimentally and theoretically [several publications].
- Quantum transport in nanotube and silicon nanowire-based devices created by *e*-beam lithography.
- Device (waveguides) fabrication using nano-manipulators from graphite flakes.
- High frequency response measurements up to 67 GHz in nanotube devices at 4 K.
- Theoretical model explaining the quantum transport in carbon films: Superlattice structures.

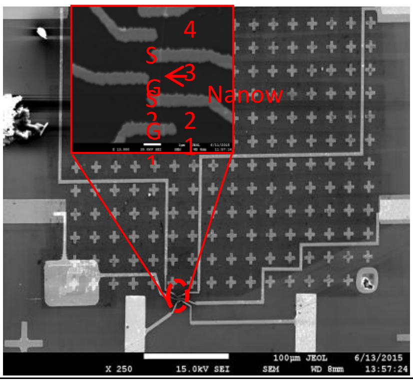



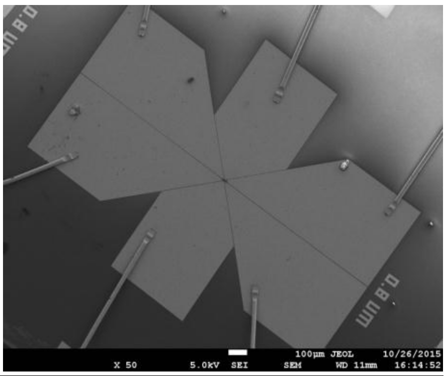
Devices produced in NSTPL
(left) Graphene layers created by nanomanipulators show SdHO arxiv.org/abs/1504.02325
(right) Silicon nanowire four terminal device Europhys. Lett., **113**, 47002 (2016)

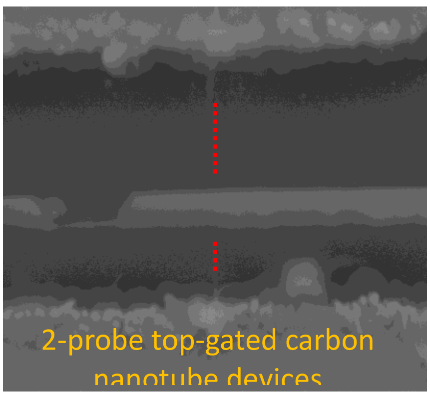
(left) Nanotubes for high frequency transport (65 GHz) AIP Advances **4**, 087136 (2014)

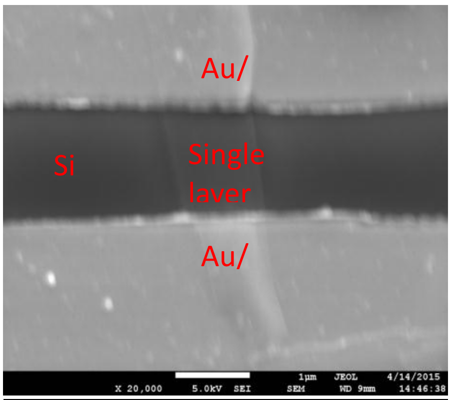
(right) Nanodiamond used for high frequency transport (65 GHz) Europhys. Lett. **109**, 67002 (2015)





(left) e-beam lithographically define silicon transistor device and (right) photolithography defined electron with a graphene layer at center demonstrating our ability and potential for large large scale integrated circuits all the way to wire bonding.





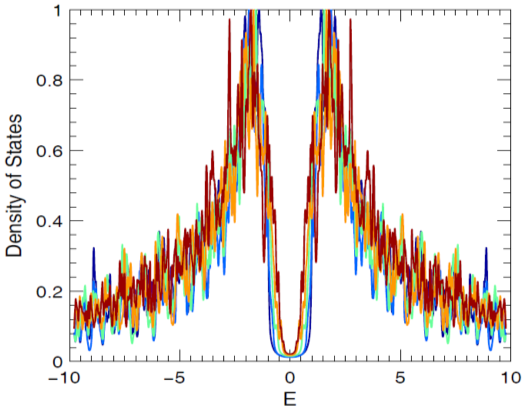
(left) Top gated carbon nanotube transistor device.
Red dotted lines are used for guiding eyes.

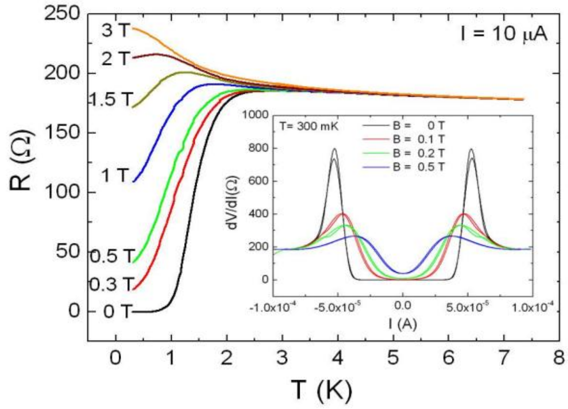
(right) Back gated single layer graphene transistor device.

Achievements:
Development of nano-device fabrication facility in South Africa together with the installation of facilities for low temperatures (300 milli Kelvin), high magnetic fields (12 Tesla) and high frequencies (65 GHz).

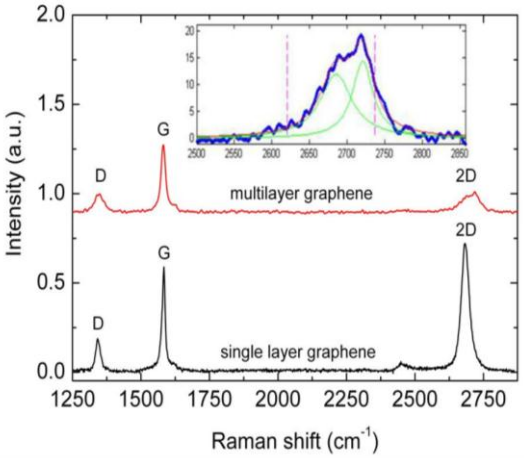
Target:
Experimental conditions of temperature (micro-Kelvin) and frequency (terahertz) to study quantum critical phase in superconducting carbon system.

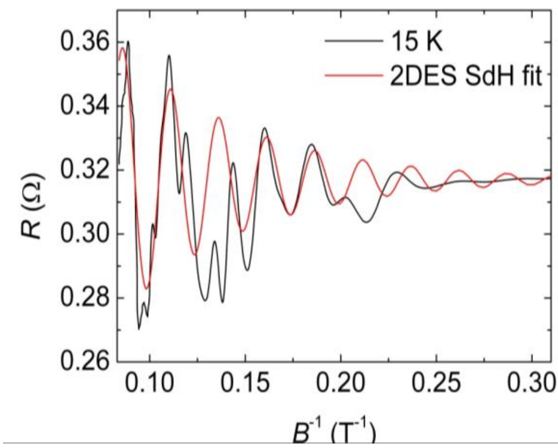
Some examples of recent work:



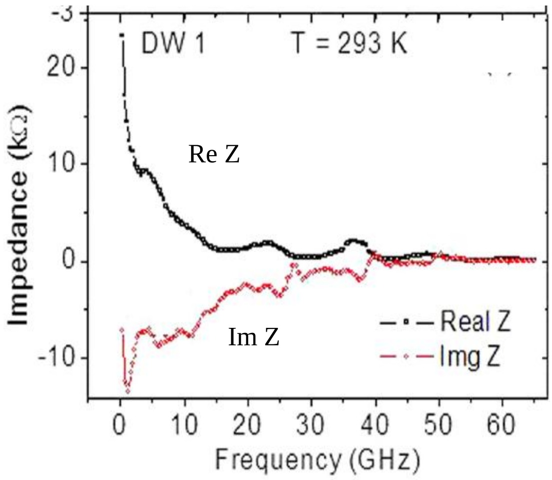


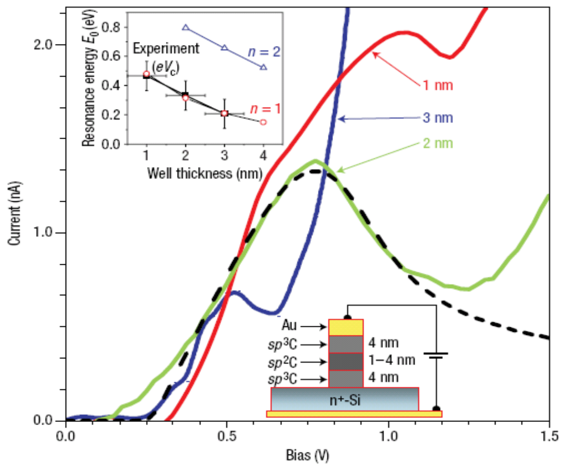
Superconducting nanodiamond films
(left) Calculated DOS show the gap for various levels of disorder.
(right) Superconductor –insulator transition in nanodiamond.
Inset: Differential resistance curve shows a superconducting gap at low *B* and *T*.



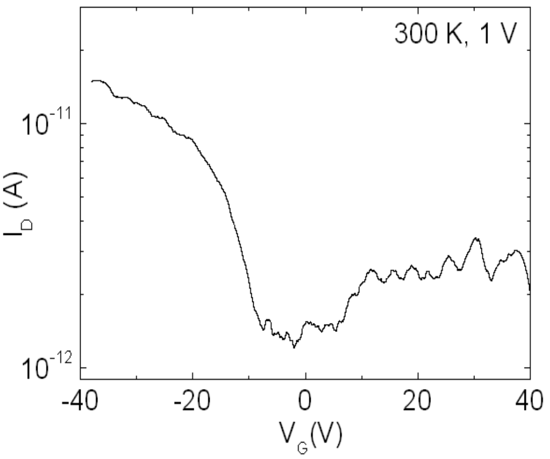


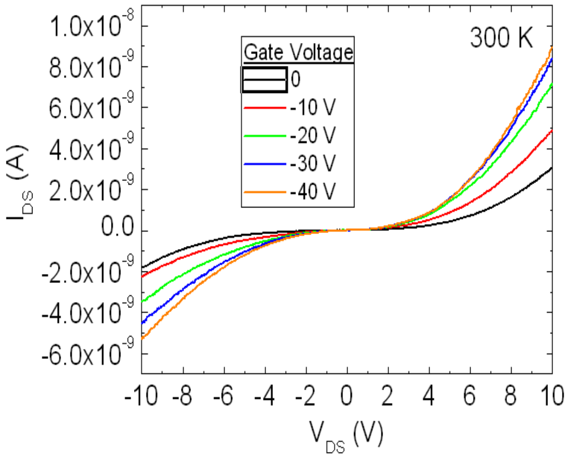
Oscillation of magneto-resistance
(left) from graphene produced by nanomanipulators arxiv.org/abs/1504.02325.
(right).
Raman spectrum of the graphene.





High frequency transport showing oscillations in carbon nanotubes
(left) Appl Phys. Lett. 2014
(right) Negative differential resistance from carbon superlattice structures. Nat. Mater. 2006





SWNT Field Effect Transistor

(left) Gate modulated transport in nanotube FET
(right) I-V characteristics at different gate voltages at room temperature

International partners/Consultants

My group benefits from advisory role provided by Prof. Deji Akinwande (University of Texas at Austin), Prof. David Tomanek (Michigan State University), Prof. Klaus Ensslin (ETH, Switzerland), Prof. Milos Nesladek (Universiteit Hasselt, Belgium), Prof. Emmanuel Flahaut (Toulouse, France), Prof. Ping Sheng (HKUST), Prof. S.R.P. Silva (University of Surrey, UK) as well as from several collaborators at the national level.

I. Project on carbon spintronics: Development of Carbon Fermionic-Bosonic-Spintronic Quantum Information Devices in *tandem* with a search for evidence for elusive theoretically predicted critical phenomena

1.1 Objectives: Our objective is to develop the next-generation quantum information systems based on quantum transport properties of low dimensional carbon based systems such as heavily-doped diamond, graphene, nanomagnet percolated carbon nanotubes, carbon-superconductor, carbon-ferromagnet hybrid materials and heterostructures of carbon and also emergent2D materials such as silicene and phosphorene. The main phenomena to be utilized are the well-established Hanle Effect (Spin valve effect), Coulomb blockade, quantum anomalous Hall effect, spin-triplet superconductivity and Kondo Effect (see below). In the later phase, the project will also be extended to include nano-electro-mechanical systems (NEMS such as suspended graphene membranes), plasmonics, magneto-optics and spin-phonon. The *multi-quantum-effect approach* is adopted to ensure quantum information loss or quantum decoherence immune or error-free communication systems in which a decay in one effect can be compensated by real-time adaptation of the system to the next phenomenon.

1.2 State-of-the-art carbon based spintronic devices

There are three major device ideas/concepts that have come up in carbon based spintronics. One idea is to use a combination of ferromagnetic electrodes and non-ferromagnetic metals to inject spin polarized current in graphene. The other idea is the placement of nanomagnets on a nanotube. The third idea is to inject cooper pairs into a spin polarizable graphene or nanotube channel.

1.3 Future – Our Device Concepts

Our group is interested in pursuing many extra-ordinary device ideas which can find applications in next-generation electronics but also help in providing evidence for electron transport phenomena predicted theoretically and other inter-disciplinary physical phenomena. These include Quantum Spin Hall Effect, topological insulator phenomenon, high T_C superconductivity, Higgs boson analogs, Kondo effect, gravitons in solid state and magnetic monopoles.

- Hybrid carbon superconductor – graphene- ferromagnetic spintronics

The idea is to sandwich a thin (~5 nm) layer of a ferromagnetic or superconducting material between two graphene layers perched on superconducting electrodes. This requires graphene transfer onto prefabricated superconducting electrodes. I have successfully been able to exfoliate graphene and transfer it to prefabricated gold electrode.

- Topological transistors (QSHE)

This devices exploit edge or surface protected symmetry of topological insulators. There are suggestions in literature that graphene can sustain a TI phase {A.F. Young et al. Nature Letters **505** (2014) 528}. These states can be switched on and off with externally applied magnetic field. Further, I will create holes on suspended graphene using plasma etching. These holes will behave as anti-dots whereas on the remaining ribbons I will place ferromagnetic material that will lead to spin scattering. In so doing I hope to create half-flux scenarios.

- Heterostructure carbon-emergent 2D devices

The idea is to create a multilayer device with alternating monolayers of graphene and atomically thick emergent 2D materials such as silicene and phosphorene as channel for transistor devices. By adding other 2D materials with large spin-orbit interaction transistor devices exploiting both gaps and topological insulator phases can be developed. By casting the monolayers onto superconducting diamonds electrodes prefabricated using wet and dry etching techniques plus focused ion beam milling the devices can also be used at low temperature for quantum computer circuitry. Since one can make diamond with critical temperature T_C up to 10 K quantum computers comparable to commercially available dilution fridge cooled D-Wave quantum computer systems can be developed that could have advantages of radiation hardness from diamond and more efficient thermal management from graphene high thermal conductivity. If successful this can a project of huge commercial impact and useful for military applications and information security. Radiation hard diamond based quantum computers could be immune or less susceptible to damage from electromagnetic pulse attacks. Such circuitry may also be useful in space application in highly radiative environments where conventional detectors could fail.

Device where a semiconducting nanowire or nanoribbon is sandwiched between two superconducting electrodes is an ideal candidate for the realization of elusive majorana fermion modes.

II. Project on high speed electronics (near terahertz regime):

I envision various applications of carbon nanotubes, silicon nanowires and graphene based electronic devices. For example, silicon nanowire and carbon nanotube based field effect transistors can be utilized in the development of gas sensors. Carbon nanotubes can be used to develop radiation sensors such as Infrared (IR) sensors. The nanotubes in particular can also be used to develop high speed transistors with characteristic *RC* frequency of up to 6 THz. The transconductance cut-off frequency is related to the gate length of the transistor device by $f_T = 80\ GHz/L(\mu m)$ for largest observed transconductance of 20 µS. Using our electron beam lithography system it is possible to create gate length of about 100 nm that could give cut-off frequencies of 800 GHz. Our role in this project is to design, fabricate and test the core elements of sensors. In collaboration with industry I can contribute towards manufacture and packaging of the final product and marketing of the product. Also other carbon nanomaterials based devices such as graphene and nanodiamond-based devices can be developed. Devices based on the partner's own materials may be made in their facility with their expertise. The main projects are: (i) Carbon nanotube based devices. (ii) Graphene based devices. (iii) SiNW based devices. (iv) Diamond-based devices (v) Carbon heterostructures and quantum well system. A solid understanding of the device physics that I have acquired from the theoretical work will be useful in the development of novel devices concepts and simulation of devices.

III. Carbon Resonant Tunnel & Spintronic Devices: Extended to spin tunnel & superconducting junctions

Another idea for this work is to establish spin-resonant tunnel diodes extended to spin-resonant tunnel transistors. In order to achieve this I have to establish spin transport in carbon tunnel barriers. Intrinsic (free) spin of nano-structured carbon is a major issue, which has not been established yet firmly. In addition researchers have tried to incorporate ferromagnetic dopants in nano-carbon to induce spin transport. To verify free spins (via magnetic moments) susceptibility measurements is very important. Earlier I tried to build up transport mechanisms for low-dimensional amorphous carbon films through the understanding of the complexity of charge dynamics. I were motivated by the observation of resonant tunnelling & an enhancement of (AC) mobility by applying microwave frequency with DC bias and tuning the relaxation time in picoseconds in amorphous carbon quantum wells {S. Bhattacharyya et al., Nature Materials **5,** 19 **(**2006)}. The tunnel conductivity was measured at 77 K and the frequency response of these carbon devices was found in 100 GHz range (measured at 300 K) which can be extended at lower temperatures in the presence of high magnetic fields. There has been significant effort to understand the spin transport mechanism in low-dimensional carbon, which can be utilized in developing carbon RTDs doped with ferromagnetic metals. In fact, making efficient spin-RTDs in semiconductors is also challenging. Under the proposed project I would like to perform these measurements in metal incorporated carbon RTDs at 1.6 K to maximize the frequency of oscillation (in terahertz range). I wish to investigate the microscopic origin of spin transport and ferromagnetism in nano-structured carbon together with ballistic conductance at low temperatures and in the presence of high magnetic field, particularly within band modulated carbon Quantum Well (QW) structures. Fabricating (carbon) spin tunnel transistors will be attempted provided the proposed spin diode project is successfully completed.

In graphene similar studies are not so well established. High-frequency properties of iron-incorporated CNTs are motivated for spintronics. Although spintronic properties of CNTs has been demonstrated the role of metals and interactions with semiconductors is unknown which can be performed by magneto-resistance and spin susceptibility measurements both at low temperatures and high magnetic fields. I would like to study the exchange interactions in nano-graphite and in graphene and investigate the interplay between edge states & conduction pi-electrons also in the presence of high frequency.

Device**:** A network of nanotube hybrid devices for magneto-opto-electronics (interference in condensed states)

- *Carbon nanotube based device* on coplanar waveguides for combined high frequency, magnetic field dependent and gate response studies. Radiation detectors based or nanotube network.
- Coulomb and Pauli blockade transport spectroscopy devices: In these devices quantum transport through a nanotube channel is tuned by an array of gates located between drain and source electrodes. Back-gated field effect transistors: These devices are suitable for sensor applications with functionalised nanotube channels.
- Memory devices: NRAM based on crossed nanotubes or network of nanotubes of special geometry.
- Suspended Si nanowires devices*:* Four-terminal back gated transistor devices for combined magnetoresistance and gate modulated transport measurements with multiple gate.
- Graphene based devices: Graphene on coplanar waveguides for combined high frequency, field dependent and gate response studies used for the detection of waves such as gravity.
- Diamond based devices: Superconducting ultra-nanocrystalline diamond film based devices and Diamond on coplanar waveguides for combined high frequency, magnetic field dependent and gate response studies.