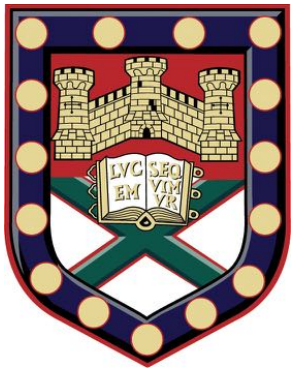
Two dimensional atomically thin materials and hybrid superconducting devices



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A thesis submitted for the degree of

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Two dimensional atomically thin materials and hybrid superconducting devices

Submitted by David Christopher Hudson to the University of Exeter as a thesis for the degree of Doctor of Philosophy in Physics.

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I certify that all material in this thesis which is not my own work has been identified and that no material has previously submitted and approved for the award of a degree by this or any other university.

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Abstract

In this thesis a variety of topics concerning 2D materials that have been separated from bulk layered crystals are discussed. Throughout the thesis, single and few layers of graphene, fluorinated graphene, MoS_2 and WS_2 are used. Two new methods of freely suspending 2D materials are presented as well as a method of removing the background from optical images. This aids contrast measurements for the determination of the number of layers.

Fluorinated graphene is found to be sensitive to beta radiation; the resistance of fluorinated graphene transistors is shown to decrease upon exposure to the radiation. This happens due to the carbon-fluorine bond breaking. The sp^3 hybridised structure of the fluorinated graphene is reduced back into the sp^2 hybridised structure of pristine graphene.

The superconducting properties of molybdenum-rhenium are characterised. It is shown to have a transition temperature of 7.5 K. It is also discovered that the material has a resistance to hydrofluoric acid; the acid etches nearly all other superconducting materials. This makes MoRe a possible candidate to explore superconductivity in conjunction with high mobility suspended graphene. To see if the material is compatible with graphene, a supported Josephson junction is fabricated. A proximity induced super current is sustained through the junction up to biases of ~ 200 nA.

The temperature dependence of the conductivity is measured for both suspended MoS_2 and WS_2 on a hexagonal boron nitride substrate. The dominant hopping mechanism that contributes to the conductivity at low temperatures is found to be Mott variable range hopping, with the characteristic $T^{-1/3}$ dependence. The hopping transport is due to impurities that are intrinsic to the crystals, this is confirmed by comparing the results with those of supported devices on SiO_2.

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List of publications

Electrical transport in suspended and double gated trilayer graphene. T. Khodkov, F. Withers, D. C. Hudson, M. F. Craciun and S.Russo, *Appl. Phys. Lett.* **100**, 013114 (2012)

Electron transport of WS_2 transistors in a hexagonal boron nitride dielectric environment. F. Withers, T. H. Bointon, D. C. Hudson, M. F. Craciun and S. Russo, *Scientific Reports* **4**, 4967 (2014)

Molybdenum-Rhenium superconducting suspended nanostructures. M. Aziz, D. C. Hudson, and S. Russo, *Appl. Phys. Lett.* **104**, 233102 (2014)

Beta radiation detection using fluorinated graphene. D. C. Hudson, M. D. Barns, S. E. Martins, M. Dubois, and S. Russo (in preparation)

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