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First Graphene Landau Level Laser

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FIRST GRAPHENE LANDAU LEVEL LASER (GLLL)

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Synopsys of the project: Proposed almost 30 years ago, the Landau level laser has yet to be realised. Compared to conventional semiconductor 2DEGs, graphene has the following advantages with respect to magneto-lasing applications: unevenly-spaced Landau levels, large cyclotron energy, and unusual transition selection rules in graphene all working favourably for a population inversion envisaged for the Landau level laser. An estimate of the photon emission rate shows that it is orders of magnitude more efficient than in the ordinary QHE system.

In this work we will employ a large area Hall bar patterned in monolayer epitaxial graphene on SiC, covered in a polymer bilayer and gated using our photo-chemical or corona-discharge methods to tune the carrier concentration to the desired level for a robust QHE in the accessible range of magnetic fields.

- We will first study the response of the sample in the QHE regime to IR radiation from a quantum cascade laser (QCL) depending on the magnetic field.

- We will then use a double-quantum-well radiation detector to measure the stimulated emission of cyclotron radiation from the sample itself.

- By moving the sample with respect to the detector we will investigate the spatial distribution of the emission hotspots.

- Finally, we will create population inversion in graphene by pumping into higher Landau levels across the Dirac point, making use of the graphene-specific optical selection rule, and observe lasing from cyclotron transitions.

Abstract: In the first year of the LLL project we prepared and characterised the graphene samples, built the low-temperature setup for opto-magneto-transport measurements. We have observed giant quantum Hall plateaus in epitaxial graphene and explained them by charge transfer between the large density localised states in the substrate buffer layer and graphene. This charge transfer may be important in the response of the graphene to external optical illumination.

Graphene devices: Graphene was grown on Si-face of SiC wafers at T=2000 °C and P=1 atm Ar (Graphensic AB). Devices in the shape of Hall bars of different sizes, from 160 μm x 35 μm down to 11.6 μm x 2 μm, were produced on several wafers using standard electron beam lithography and oxygen plasma etching. Contacts to graphene were produced by straightforward deposition of 3 nm Ti and 100 nm Au through a lithographically defined mask followed by lift-off.

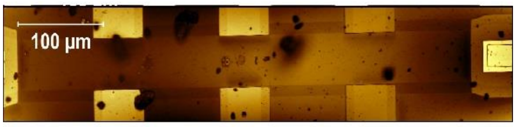
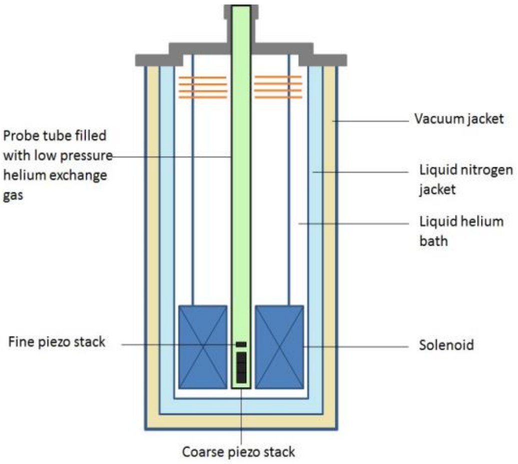
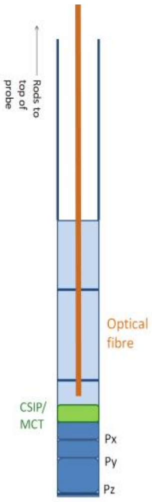


Figure 1. Atomic force micrograph of a graphene Hall bar.

Graphene on SiC is intrinsically n-doped to about 10^{13} cm^{-1}. It is not possible to use conventional electrostatic gating to efficiently control the carrier density in epitaxial graphene due to the pinning of the Fermi level [1]. Therefore we used two non-volatile ion gating methods to control the carrier density in graphene devices: photochemical gating [2] and corona-discharge gating [3].

Magneto-optic setup: A new setup was built for this project which includes a LHe cryostat with 12 T superconducting magnet, an IR semiconductor laser, a probe with optical fibre and a sample holder with piezo-positioners.





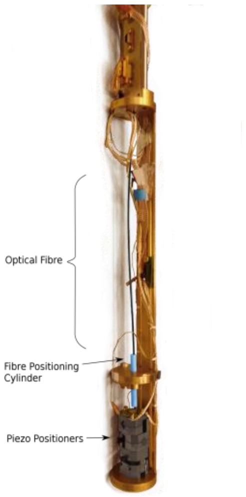


Figure 2. Details of the cryogenic probe assembly

In photoconductivity experiments we used polycrystalline $AgCl_xBr_{1-x}$ fibre (Art Photonics). These fibres have high transmittance from 4 µm up to 18µm, but their performance could not be guaranteed at low temperatures. We have engineered vacuum-tight feedthrough solution, which enabled integration of the fibre into the probe and extensively tested the assembly upon thermal cycling to LHe temperature.

We used a quantum cascade laser, QCL (Alpes Lasers) as the source of optical radiation at MIR wavelegths, typically around 10 µm, and optimised its coupling to the fibre using a pyroelectric sensor and a power-meter at room temperature, and a mercury-cadmium-telluride bolometer (MCT) in liquid nitrogen. We further optimised the coupling of the radiation to the sample at LHe temperature by moving the sample with respect to the cold end of the fibre using piezo-positioners (attocube).

IR detector: The detection device currently preferred for this study was supplied by the Komiyama group at Tokyo University. .The device known as a Charge Sensitive Infrared Phototransistor (CSIP) is a vertical double quantum well (QW) structure fabricated in one block of GaAs/AlGaAs. The device was fully characterised at Tokyo at cryogenic temperatures and demonstrated NEP = 7×10^{-20} W/Hz$^{1/2}$ or D* = 1.2×10^{16} cm Hz$^{1/2}$ /W with the quantum efficiency η in the range 7-10% very similar to the values previously published in [4]. The device was characterised also at NPL using a heated blackbody source.

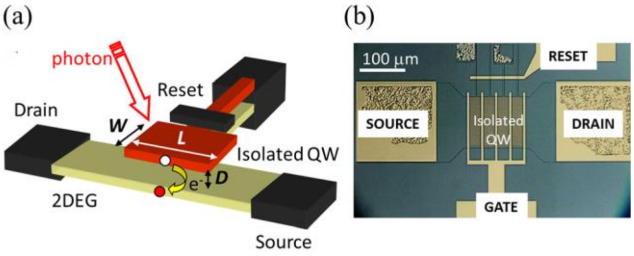


Figure 3. Schematic and micrograph of the CSIP detector.

Magneto-transport: The samples were extensively characterised in terms of their magneto-transport properties. We have studied the breakdown and the temperature dependence of the quantum Hall effect using high magnetic fields and very low density epitaxial graphene grown on SiC. We observed the widest quantum Hall plateau to date extending over 50 T [5], attributed to an almost linear increase in carrier density with magnetic field. This behaviour is strong evidence for field dependent charge transfer from charge reservoirs with exceptionally high densities of states in close proximity to the graphene. We have shown that the quantum Hall effect breakdown current can be used to accurately measure this increase in carrier density with field, which is found to be over an order of magnitude in some cases. Using the models that we propose, we have been able to accurately describe and predict some of the most important features of the field dependent charge transfer process and its effects on the quantum Hall breakdown. Our models and results are widely applicable towards a broader and deeper understanding of the high magnetic field transport properties of graphene and are crucial for engineering epitaxial graphene devices for a variety of applications. This new research sponsored by the AFRL grant was published in [6].

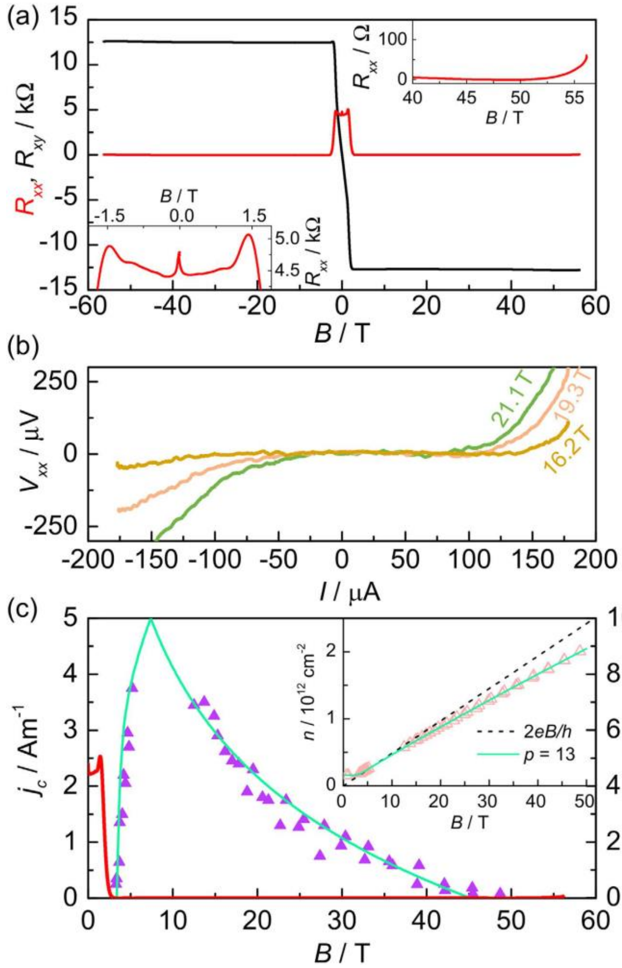


Figure 4. Giant quantum Hall plateaus. Pulsed magnetic field measurements of the quantum Hall effect in epitaxial graphene on SiC at T = 2 K as observed in the longitudinal resistance (R_{xx}, red) and Hall resistance (R_{xy}, black) showing an exceptionally wide (~50 T) ν = 2 plateau. Upper inset: The end of the plateau at B > 50 T. Lower inset: R_{xx} at low magnetic fields showing clear Shubnikov-de Haas oscillations and weak localisation. (b) Examples of high speed I − V_{xx} traces taken during a single pulsed magnetic field measurement, showing that clear quantum Hall breakdown behaviour is observed. (c) Magnetic field dependence of the breakdown current (purple triangles) for the ν = 2 plateau. The red line shows the longitudinal resistivity and the inset shows the corresponding magnetic field dependent carrier density.

Photo-response:

The response of the sample at low temperature to monochromatic light was studied as a function of magnetic field. It was concluded that the photo-response is due to a combination of the bolometric (thermal) response and a magnetic field driven change in the carrier density and hence the resistivity.

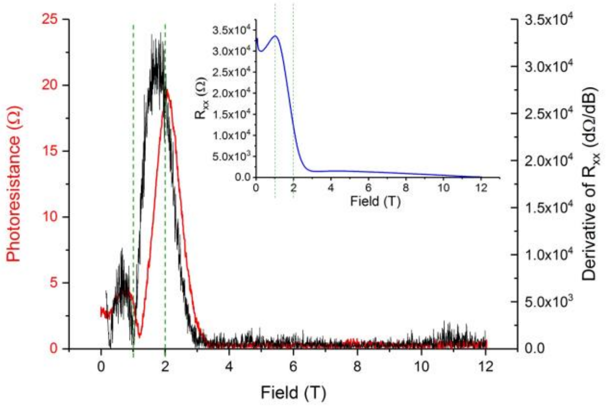


Figure 5. The photo-response expressed in terms of the change in the longitudinal resistance of the sample under 10 mm radiation from the QCL is compared to the derivative of the magneto-resistance oscillations. The inset shows the longitudinal resistance of the sample as a function of magnetic field.

Progress elsewhere: An interesting discussion has emerged on whether the Auger processes may be important in establishing the population inversion in graphene LLs. In particular, while [7] shows that efficient Auger scattering rapidly establishes a thermal distribution of electrons in graphene, which cannot support a population-inverted state suitable for light amplification, [8] proposes a pumping scheme which uses Auger scattering to create population inversion. It is feasible to test these predictions in our future experiments.

Intermediate conclusions: Despite the observation of photo-response in a wide range of magnetic fields, at the present stage of the project we have not observed – electrically – resonant absorption of IR photons by monolayer graphene on SiC at the field corresponding to the LL transitions – the cyclotron resonance. We tentatively explain this as due to the influence of charges in the buffer layer. In the second year experiments are in process to elucidate this and to engineer and test various schemes of creating inverse population of carriers.

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