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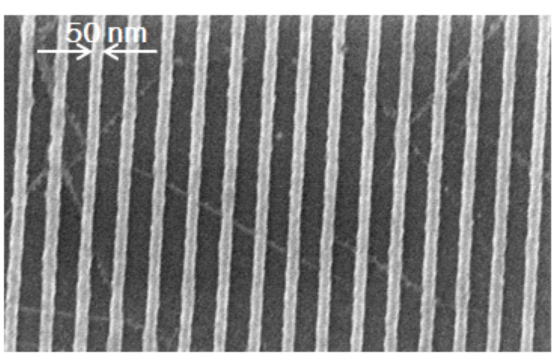
In this program, we conducted a series of experiments on the quantum transport and infrared (IR) spectroscopy of exfoliated graphene, epitaxial graphene, and chemical vapor deposition grown graphene in high magnetic fields. We employed the state-of-the art facilities at the National High Magnetic Field Laboratory (NHMFL) to the fast developing graphene research. For transport measurement, we studied the conductivity of graphene in response to sub-THz or mid-IR radiations in the quantum Hall regime, while the IR part of the project investigated the cyclotron resonance in graphene.

The long-term research goal of our program is to understand the interaction effects in graphene and related materials. In this funding period we focus in the following two areas.

1. Magnetoplasmons in Graphene Nanostructures

In graphene, plasmons, collective oscillations of Dirac electrons, have recently attracted a great deal of attention. For graphene nanoribbons (GNRs), the plasmon frequency depends on the width of the ribbon and the Fermi energy, as well as interaction effects. However, interaction effects are difficult to probe at zero magnetic field. Low-density (Fermi energy close to Dirac point) high-mobility graphene specimens are needed to achieve exceptional optical field confinement and long plasmon lifetime.

Recently we studied the plasmon-type collective excitations in quasi-neutral epitaxial GNR arrays exposed to a perpendicular magnetic field [1]. Most saliently, we revealed a peculiar scaling behavior which allows us to identify this mode with the upper-hybrid mode (UHM) between the plasmon resonance and the $L_{0(-1)} \rightarrow L_{1(0)}$ Landau level transition. This scaling is different from that of the UHM in conventional two-dimensional electron gases with parabolic bands or in highly doped graphene as well as from that of magnetoexcitons. Furthermore, we show the possibility to confine plasmons in narrow GNRs allows us to probe the dispersion relation of the UHM in a large parameter range. For the 100nm-wide GNR arrays, we observed a wavelength shrinkage of ~165, a value difficult to achieve in common plasmonic materials, but in agreement with that predicted for graphene.



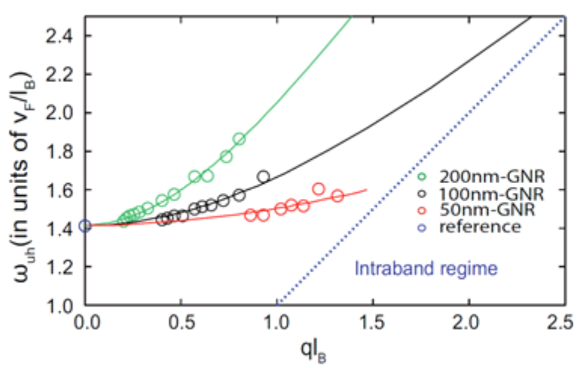


Figure 1: (Left panel) Scanning electron microscopy image of a 50nm-wide GNR array sample. (Right panel) Dispersion relation of the UHM, $\omega_{uh}(ql_B)$, in units of v_F/l_B, where ω_{uh} is the UHM frequency, q is the in-plane wave vector, v_F is the Fermi velocity, and l_B is the magnetic length.

2. Magnetophonon resonance in graphite

We studied the magnetophonon resonance in thin graphite layers using IR transmission spectroscopy. In particular, we observed two distinct resonant behaviors due to coupling of charge carriers to the large momentum *K*–point phonons (1329 cm^{-1}) or the zero momentum *Γ*–point phonons (1581 cm^{-1}), when cyclotron resonance (CR) energy crosses the corresponding phonon energies [2]. Figure 2 summarizes our experimental results and best fits to the data. Interestingly, we find the electron-phonon coupling (EPC) to the *K*–point phonons is about 7 times stronger than to the *Γ*–point phonons. The strength of EPC is commonly described by a dimensionless parameter λ, and we obtain $\lambda = 5.2\text{x}10^{-2}$ at the *K*–point and $\lambda = 7.2\text{x}10^{-3}$ at the *Γ*–point. We interpret the EPC to *K*–point phonons as the consequence of short-range scattering at the edges (including the flake edges and the steps edges on the surface), which breaks the AB sublattice symmetry, while the Fano resonance-like behavior at the *Γ*–point is due to the inference between the discrete phonon mode and the broader CR.

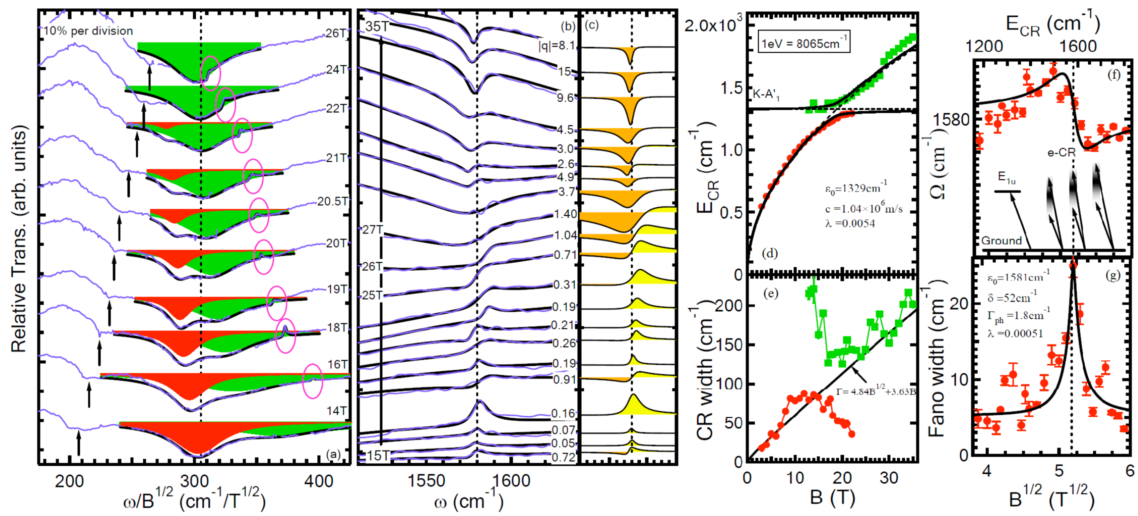


Figure 2: (a) Normalized magneto-IR spectra of thin graphite layers with respect to scaled frequency, $\omega/B^{1/2}$, at selected magnetic fields. The vertical dash line marks the expected position for the CR without EPC. The thicker black lines are best fits to the data (thin blue lines) using two Lorentzian functions. (b) Normalized magneto-IR spectra as a function of magnetic field near the *Γ*–point phonon energy (vertical dash line). (c) Best fits to the data in (b), after subtracting a background using a Fano formula. (d-g) Extracted energy and linewidth from the fits in (a-c) for EPC to the *K*-point phonons, (d) and (e), and to the *Γ*-point phonons, (f) and (g).

Reference:

[1] J.M. Poumirol, W. Yu, X. Chen, C. Berger, W.A. de Heer, M.L. Smith, T. Ohta, W. Pan, M.O. Goerbig, D. Smirnov, and Z. Jiang, Phys. Rev. Lett. **110**, 246803 (2013).

[2] L.-C. Tung, W. Yu, P. Cadden-Zimansky, M. Kindermann, D. Smirnov, and Z. Jiang, in preparation.