# Cooling of Hot-Carriers with Landau Levels in Graphene

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## Introduction

One important triumph of graphene research was the demonstration of the quantum Hall (QH) effect with unusual filling factor ±2, ±6, ±8 ··· by Geim's and Kim's groups separately in 2005. The experiments established the massless Dirac fermion properties of electrons in graphene. Later, the availability of even higher quality graphene samples enabled the demonstration of fractional QH Effect, which implies strong electron-electron interactions in graphene at high magnetic fields. However, there have been very limited efforts to directly probe the dynamics of carriers in QH regime. Such understanding will provide insights of many-body electronic states and their interactions, in harmony with the existing electrical transport achievements.

## Experimental

Our experiment focuses on the investigation of the hot-carrier dynamics in QH regime by photocurrent measurements without applied bias. The advantage of this technique is that it probes the electronic properties of graphene while utilizing the features of nano-optical spectroscopy. We used 17.5 T superconducting magnet in the DC field facility. Staff scientist Zhiqiang Li have provided tremendous help.

## Results and Discussion

At a fixed magnetic field we vary the Fermi level in our graphene sample through the use of an electrostatic gate, Vg, and measure three signals: the two terminal conductance (G), the one pulse photocurrent response (PC), and the hot carrier cooling time (Tc) defined here as the half-width-half-maximum of the dip in the ultrafast two pulse photocurrent response. The results taken at 7.5T are shown in Figure 1a. In the top frame we see the conductance displays clearly quantized steps indicating quantization of Landau levles. The PC response, Fig 1a middle, shows an oscillatory behavior with a similar period as the conductance quantization. Finally we see that the hot carrier cooling time (Tc) is also periodic, with a similar period as our other two signals (bottom panel Fig. 1a).

Using high mobility devices (edge contacted graphene sandwiched by boron nitride), we are able to observe PC response corresponding to Fractional QH state. Figure 1b shows G as a function of Vg at 17.5 T (red curve) with Landau level n=0. In addition to integer QH plateau (v=1 and 2), wiggles corresponding to Fractional QH states are also observed. The inset show the Zoom-in view of conductance within v=1, where 2/3 and 1/3 fractional states are observed. PC (blue curve) shows pronounced dips corresponding to both integer and fractional QH States.

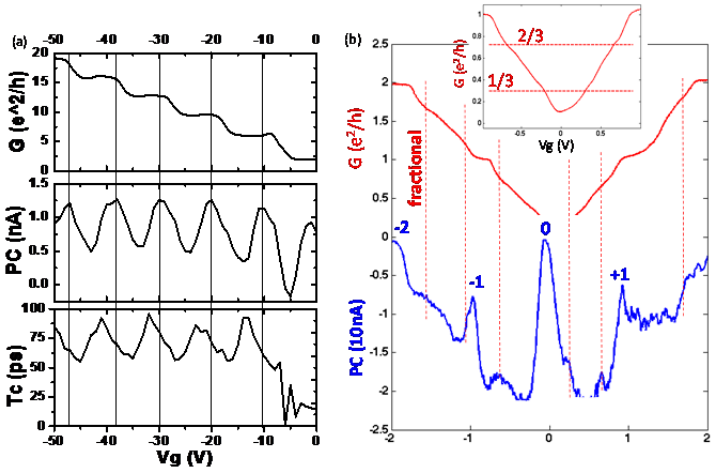


Fig.1 a, Gate dependence of the total conductance (top), edge PC (middle), and hot carrier cooling time (bottom). b, Main panel: overlay of conductance and PC as a function of gate voltage. Inset: zoon in conductance within v=1.

## Conclusions

For the first time, we observe carrier dynamics oscillating as a function of gate voltage at high B field, and photo-current response in the fractional QH regime.

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