Massive Dirac Fermions and Hofstadter Butterfly in a Graphene-hBN Moiré Superlattice

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Introduction

The problem of electrons in a periodic potential and a magnetic field (Fig. 1a) was famously solved by Hofstadter in 1976 and resulted in a fractal structure in the available energy states, which resembled a butterfly [1]. The moiré pattern produced by placing graphene on hexagonal boron nitride (hBN) acts as a periodic potential, and its wavelength λ can be tuned by varying the twist angle between the two 2D crystals. The Hofstadter spectrum should appear when the length scale for cyclotron motion is of the same order as the wavelength of the periodic potential.

Experimental

We used magnetoconductance and magnetocapacitance measurements of a graphene-hBN transistor with a moiré superlattice potential to study the Hofstadter problem. The 45T Hybrid magnet, combined with the moiré potential (with λ~10 nm), provided us with just the right conditions to be able to observe the Hofstadter butterfly [2].

Results and Discussion

The conductance as a function of magnetic field and gate voltage (i.e. electron/hole density) in Fig. 1c can be viewed as a "Wannier spectrum" in which energy gaps in the Hofstadter spectrum appear as straight lines described by two quantum numbers, one related to the Landau level filling index (the slope) and the other related to the Bloch "miniband" filling index (the x-intercept). These minibands are due to the moiré periodic potential, of which the lowest spans the range between about -1.4 and +1.4 V at zero magnetic field (Fig. 1c). Applying a large magnetic field reveals horizontal features when the magnetic flux *BA* is a rational fraction 1/*q* of the flux quantum $\phi_0 = h/e$ (*A* is the moiré unit cell area), and at about 29 Tesla, $BA/\phi_0 = 1$. Above this field we observed unambiguous signatures of the Hofstadter butterfly in the lowest Landau level (white dashed box), which appear as a non-monotonic sequence of quantum Hall plateaus in the conductance with increasing electron/hole density.

As an additional interesting feature of the data, we observed that the interaction between the graphene and the hBN opened up a bandgap at the Dirac point in zero magnetic field, imparting the normally massless carriers with a mass [2]. The size of this bandgap was found to increase with the wavelength of the moiré pattern.

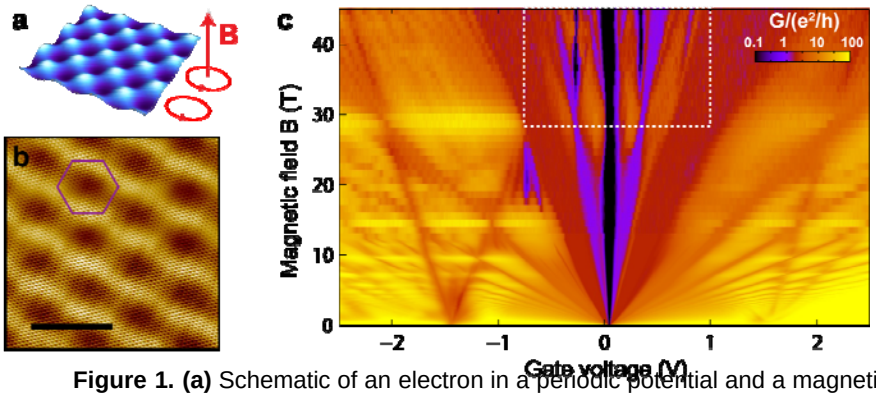

Figure 1. (a) Schematic of an electron in a periodic potential and a magnetic field B. **(b)** STM topograph of moiré pattern of graphene on hBN. Scale bar is 5 microns**.** The moiré unit cell A is the purple hexagon. **(c)** Conductance G vs gate voltage and magnetic field for a graphene-hBN transistor that exhibits a moiré pattern. Within the white dashed region, above 29T, we observe signatures of the Hofstadter butterfly in the lowest Landau level (which is contained within the red plateaus at G=+/-2e^2/h).

Conclusions

Using the moiré pattern produced by small twist angle graphene on boron nitride as a periodic potential, we achieved, for the first time in monolayer graphene, the regime of $\phi/\phi_0 > 1$, and observed signatures of the Hofstadter butterfly in the magnetoconductance.

Acknowledgements

We acknowledge support from the Department of Energy through grants DE-SC0001819 (PJH) and DE-FG02-08ER46514 (RCA), The Gordon and Betty Moore Foundation GBMF2931, and the Pappalardo fellowship (AFY). Work at the NHMFL was done under NSF Cooperative Agreement No. DMR-1157490, the State of Florida, and the U.S. Department of Energy.

References

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[2] Hunt, B., et al. *Science* **340**, 1427-1430 (2013).