Electrically tunable transverse magnetic focusing in graphene

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Outline

• Motivation and Introduction
• General concepts of transverse magnetic focusing (TMF)
• TMF in monolayer (MLG), bilayer (BLG) and trilayer (TLG) graphene
• TMF as a ballistic electron spectroscopy method
• Temperature dependence of the TMF spectra
• Summary and conclusions
Motivation and Introduction

Ballistic motion of electrons over macroscopic distances → Focusing of electrons with a transverse magnetic field

TMF used to study:
- Fermi surface of metals [1]
- and semiconductor heterostructures [2]
- Andreev reflection [1]
- Spin-orbit interaction [3]
- Detection of composite fermions [4, 5]

And the quality of graphene edges:
- Exploring the graphene edges with coherent electron focusing [6]
- Boundary scattering in ballistic graphene [7]

General concepts of TMF

Magnetic field $B_f$ is required to focus electrons at a distance $L$:

$$B_f^{(p)} = \left( \frac{2\hbar k_F}{eL} \right) p = \left( \frac{2\hbar \sqrt{\pi n}}{eL} \right) p$$

$p-1$: # of reflections off the edge

In graphene the density can be tuned continuously from the hole to the electron regime.

For negative density (holes) the sign of $B_f$ changes as well!
Investigated Hall bar devices

- hBN-supported MLG, BLG and TLG
- Field-effect mobility = 100’000 cm²/Vs
- mfp = 1µm

High mobility and low disorder enables TMF
TMF in monolayer graphene

- For $|B| \geq 2.5$ T SdHOs are visible
- No SdHOs in quadrants 1 and 3 due to interference of different trajectories
- For $|B| \leq 2.5$ T three unusual peaks are visible (TMF)

$L = 500$ nm

$n$ known from QH

\[ B_{\parallel}^{(p)} = \left( \frac{2\hbar k_F}{eL} \right) p = \left( \frac{2\hbar \sqrt{\pi n}}{eL} \right) p \]

- Discrepancy between calculation and experiment
  - Finite width of injector and collector
  - Charge accumulation at the edges
  - Density fluctuations and small angle scattering
Specularity at the edge

- Multiple focusing peaks observed in all investigated devices
- Significant fraction of charge carriers gets specularly reflected at the edges
- Measured specularity defined as ratio between amplitudes of second and first peaks
- For this experiment 0.2 – 0.5
- < 1 for focused-ion-beam-etched devices
- > 1 for electrostatically defined edges

Edge quality influences the specularity
TMF in MLG, BLG and TLG

- TMF spectra very similar (despite the different band structures)
- Both have a circular Fermi surface, resulting in the same circular orbit and $\sqrt{n}$ - dependence of $k_F$

TMF spectrum of TLG remarkably different (multiband character of its band structure)
TMF as a ballistic electron spectroscopy method

- Band structure: massless MLG-like and massive BLG-like subbands
- Both subbands give rise to their own TMF spectra
- No higher order peaks from MLG-like subband, masked by the stronger peaks from the BLG-like subband

- TLG band structure can be tuned and controlled by a transverse electric displacement field $D$
- TMF is sensitive to the occupation of each of the TLG subbands

Enables the use of TMF as a probe of the change in the bandstructure
TMF as a ballistic electron spectroscopy method

A finite D induces a potential difference between the layers → hybridization MLG-like and BLG-like subbands

As D increases the α-peak starts to shift downward and eventually disappears at low density
Temperature dependence of TMF spectra

Two effects of temperature:
1. Increase in dephasing
2. Loss of ballistic transport due to new scattering channels

- Finestructure at low T due to interference between different paths travelling to the collector
- If broadening of $k_F$ is on the order of $1/L$ the interference is washed out
- Should appear at $T = 15$ K

- Decreasing focusing peak amplitudes with T (linear for MLG and saturating for BLG)
- A potential scattering mechanism includes longitudinal acustic phonons which give rise to a linear T-dependence of the scattering rate
- More theoretical work is needed to understand the temperature dependence!
Remarkable robustness of TMF in graphene

- First mode clearly visible indicating room-T ballistic transport well into the $\mu$-regime
- $T$ three times higher than in semiconductor heterostructures
- Lack of remote interfacial phonon scattering from hBN
Summary

• Observation of TMF in MLG, BLG and TLG
• The use of TMF as a ballistic electron spectroscopy method to investigate controlled changes in the electronic structure
• TMF in graphene survives up to 300 K

Conclusions

• Could we design an experiment to study the edge quality of H-plasma defined edges by TMF?

Thank you for your attention!