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Landau Level Spectroscopy of Multilayer Epitaxial Graphene in the Immediate Vicinity of the Dirac Point

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Outline:

• Multilayer epitaxial graphene
• Experimental details
• Cyclotron resonance at low magnetic fields
• Cyclotron resonance at elevated temperature
• Conclusions
Multilayer epitaxial graphene on SiC substrate

Carbon (!) terminated surface of bulk SiC

Hydrogen etching + thermal decomposition (~1400°C, vacuum)

Decoupled quasi-neutral layers

Highly conducting layers

Bulk SiC

Relatively simple preparation of macroscopic samples with practically decoupled and undoped graphene layers (up to ~100 layers)


Significant difference from epitaxial graphene grown on Si terminated surface of SiC, where Bernal stacked layers are present

Experimental setup

Far infrared transmission (FIR) spectroscopy in magnetic fields (Landau level spectroscopy)

Transmission experiment probes all graphene layers simultaneously

Relative change of the sample transmission at finite magnetic field:

$$\frac{T(B)}{T(B=0)}$$
Cyclotron resonance at low magnetic fields

$T = 2 \text{ K}$

FIR transmission $T$ plotted as $-\ln(T)$

Energy spectrum:

$E_n = \text{sgn}(n) \tilde{c} \sqrt{2e\hbar B|n|}$

Selection rules for dipole-allowed transitions in graphene:

$|n| \rightarrow |n| \pm 1$


Analysis of low magnetic field data

Focus on $L_{-1(0)} \rightarrow L_{0(1)}$ line representing transitions from/to the vicinity of the Fermi level.

Well-defined line followed down to $B \sim 40$ mT at the energy of $\sim 7$ meV.

Estimation of the carrier density in quasi-neutral graphene layers

$\nu \approx 2$

$\nu \approx 6$

Filling factor

No direct signs of e-e interaction in spectra when 1st Landau level is gradually (de)populated

No signs of any gap opened at the Dirac point ($\Delta \lesssim 1$ meV)

$n_0 \approx 5 \times 10^9$ cm$^{-2}$

$\varepsilon_F = \bar{c}\hbar\sqrt{\pi n_0} \approx 8$ meV
Achievable Fermi level (density) in current graphene systems

Inaccessibility of the Dirac point in current exfoliated graphene due to electron and hole puddles


Exfoliated graphene on SiO$_2$/Si substrate

\[ n_0 \gtrsim 5 \times 10^{11} \text{ cm}^{-2} \]

K. S. Novoselov et al., Nature 438, 197 (2005)
Y. B. Zhang et al., Nature 438, 201 (2005)

Epitaxial graphene (conducting layers)

\[ n_0 \sim 10^{12} \text{ cm}^{-2} \]


Suspended graphene

\[ n_0 \gtrsim 10^{10} \text{ cm}^{-2} \]


Epitaxial graphene (quasi-neutral layers)

\[ n_0 = 5 \times 10^9 \text{ cm}^{-2} \]

Analysis of the lineshape

Linewidth nearly increases as $\sqrt{B}$ predicted for short-range scattering (independent of the carrier density)


Nearly $\sqrt{B}$-scaled increase of the linewidth continues up to very high magnetic fields....

Scattering time from the linewidth

$$\tau = \frac{2\hbar}{\delta E}$$

$$\tau \sim 150 \text{ fs}$$

$$\tau \sim 300 \text{ fs}$$

....at extremely low and homogeneous carrier density....
Comparison of scattering times in different graphene systems


\[ 300 \text{ fs} \times n_0 = 5 \times 10^9 \text{ cm}^{-2} \]

Short-range scatterers likely dominate in epitaxial graphene giving scattering time independent of carrier density.

Strong dependence of scattering time on carrier density in exfoliated graphene is given by dominant scattering on ionized impurities.

Recent results on suspended graphene

Transport properties from optical data (?)

Estimation of the zero field conductivity from Boltzmann transport theory…..

\[ \sigma = \frac{e^2}{\pi \hbar^2} (\varepsilon_F \cdot \tau) \approx \frac{10 e^2}{h} \]

\[ \varepsilon_F = \tilde{c} \hbar \sqrt{\pi n_0} \approx 8 \text{ meV} \]

\[ \delta E = 2\hbar / \tau \rightarrow \approx 3 \text{ meV} \]

Close to values of minimum conductivity in clean samples….


Mobility from the conductivity (i.e. from linewidth)

\[ \frac{\sigma(\varepsilon)}{en_0} = \mu \approx 500.000 \text{ cm}^2/(\text{V.s}) \]

Mobility from the semiclassical condition for quantization into Landau levels (i.e. from appearance of the line in the spectrum)

\[ \omega_c \tau > 1 \Rightarrow \mu B > 1 \Rightarrow \mu > 250.000 \text{ cm}^2/(\text{V.s}) \]

Main line observed down to \( B = 40 \text{ mT} \)

However…. No varification in transport experiment currently possible

Unknown behaviour of mobility with increasing carrier density

e.g. K. Nomura, A. H. MacDonald, Phys. Rev. Lett. 98, 076602 (2007)
Temperature dependence

No scattering process activated up to room temperature. No decrease of the mobility expected!!! (Record at RT?)

Decrease of the line intensity due to occupation effect

\[ I(T) = 1 - 2f_1 = 1 - \frac{2}{1 + \exp(E_1/k_B T)} \]

Conclusions

Multilayer epitaxial graphene is a well-defined system of Dirac fermions with the extremely low carrier density allowing to investigate the immediate vicinity of the Dirac point (few meV)

Mobility deduced from optical data exceeds 250.000 cm²/(V.s) and survives up to room temperature

Quantized motion of carriers in multilayer graphene surprisingly survives up to room temperature at magnetic field well below 1 T