Infrared Magnetospectroscopy of Two-dimensional Electrons in Epitaxial Graphene

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Abstract. Far infrared transmission experiments are performed on ultrathin epitaxial graphite samples in a magnetic field. The observed cyclotron resonance-like and electron-positron-like transitions are in excellent agreement with the expectations of a single-particle “relativistic" model of massless Dirac fermions in graphene

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INTRODUCTION

The recent discovery [1, 2] that it is technologically possible to obtain robust free-standing layers of graphene - single atomic layers of graphite - has fuelled a renewed interest in this material. Well studied theoretically, it was predicted to exhibit several unusual properties [3], stemming from the linear dispersion relation governing its free electrons. Such electrons are believed to behave as relativistic, massless particles, analogous to photons but endowed with an electric charge. Transport measurements [4, 5] have confirmed the unusual character of the quantum Hall effect observed in such systems. Here we present direct optical measurements of the dispersion relation in graphene.

SAMPLES AND EXPERIMENT

The experiments were performed on epitaxial graphene layers grown in vacuum by the thermal decomposition method [2], on single crystal (4H) SiC. This type of structure consists of a few (3-5) graphene layers [2, 6]. We investigated several such structures, which show a similar behaviour.

The far infra-red transmission of the samples was measured at T = 2K as a function of the magnetic field, using a Fourier transform spectrometry and light-pipe optics. All experiments were performed with non-polarized light, in the Faraday geometry. The SiC substrate used was completely opaque for energies between 85 meV and about 200 meV (shaded area in inset to Fig. 2).

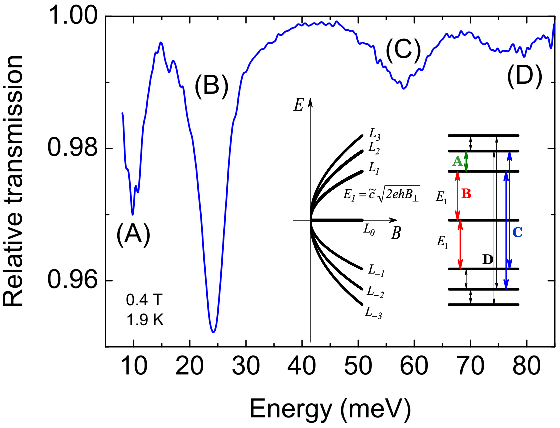

FIGURE 1. Relative transmission spectrum of epitaxial graphene. Four different transitions, labelled A-D, are clearly identified in this spectrum. The inset shows a schematic of the evolution of the Landau levels with magnetic field, as well as the assignments of the observed transitions.

Several absorption lines are visible in the spectra. A representative transmission spectrum, at 0.4 T, is shown in Fig. 1. These lines evolve with the magnetic field. As shown in Fig. 2, their energies, plotted as a function of the square root of the magnetic field, trace perfect straight lines. Other lines, weaker in intensity, whose positions depend linearly on the magnetic field, are also shown in this figure. Experiments performed in a tilted configuration show that the position of the transition line (filled symbols in Fig. 2) depends only on the component of the magnetic field perpendicular to the sample plane. Unusually, the intensities of the two main lines (B and C in Fig. 1) increase markedly with increasing magnetic field [7], with the lower-energy line (B) always remaining stronger. The higher-energy lines are too weak to allow an analysis of their intensities.

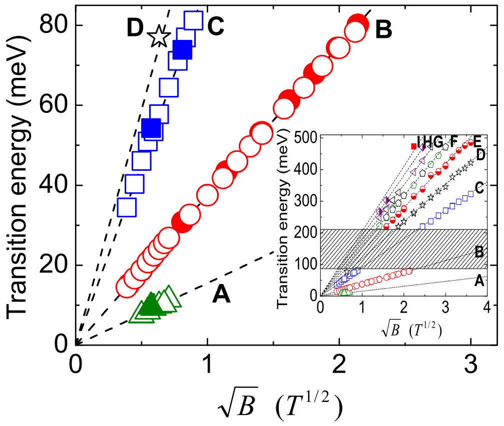

FIGURE 2. Peak positions of the observed transitions, plotted against the square root of the magnetic field. Filled symbols correspond to the perpendicular component of the magnetic field. The inset shows a wider energy range. The shaded area is the substrate opacity range.

TABLE 1. Observed lines and their assignments

Line	**Slope in units of** $\tilde{c}\sqrt{2e\hbar}$	**Transition**
A	$\sqrt{2}-\sqrt{1}$	$L_1 \rightarrow L_2$
B	1	$L_0 \rightarrow L_1(L_{-1} \rightarrow L_0)$
C	$\sqrt{2}+\sqrt{1}$	$L_{-1} \rightarrow L_2(L_{-2} \rightarrow L_1)$
D	$\sqrt{3}+\sqrt{2}$	$L_{-2} \rightarrow L_3(L_{-3} \rightarrow L_2)$
E	$\sqrt{4}+\sqrt{3}$	$L_{-3} \rightarrow L_4(L_{-4} \rightarrow L_3)$
F	$\sqrt{5}+\sqrt{4}$	$L_{-4} \rightarrow L_5(L_{-5} \rightarrow L_4)$
G	$\sqrt{6}+\sqrt{5}$	$L_{-5} \rightarrow L_6(L_{-6} \rightarrow L_5)$
H	$\sqrt{7}+\sqrt{6}$	$L_{-6} \rightarrow L_7(L_{-7} \rightarrow L_6)$
I	$\sqrt{8}+\sqrt{7}$	$L_{-7} \rightarrow L_8(L_{-8} \rightarrow L_7)$

DISCUSSION

The linear dispersion of electrons in graphene means that they may be considered as quasiparticles obeying the relativistic Dirac equation, with an effective velocity $\tilde{c}$ replacing the speed of light in vacuum. The evolution with magnetic field B of the Landau levels in graphene is expected to follow the expression [8, 9] $E_n = \tilde{c}\sqrt{2e\hbar B|n|}$, where $n = 0, \pm 1, \pm 2 \ldots$. A straight line fit to the experimental points corresponding to the strongest line (B) shown in Fig. 2 yields a very accurate value for $\tilde{c}$, (1.03 $\pm$0.01) $\times 10^6$m/s, close to those used in the interpretation of Hall effect measurements in exfoliated graphene [4, 5]. The parameter $\tilde{c}$ is related to the energy overlap γ_0 between neighbouring atoms in a hexagonal lattice, $\tilde{c} = (3/2)a_0\gamma_0/\hbar$, where a_0 is the distance between the atoms. With this value, which is the **only** adjustable parameter in the transition energy, the positions of all the other observed lines are extremely well recreated (see Fig. 2), which allows the lines to be assigned to transitions between different Landau levels (Table 1).

Three classes of optical excitations may thus be distinguished, occurring between levels L_n and L_m, allowed by the selection rules $|n| = |m| \pm 1$. The first are analogues of cyclotron resonance – transitions between adjacent Landau levels, $L_n \rightarrow L_{n+1}$. Note that, as distinct from a conventional 2D electron system with a single cyclotron frequency, transitions between different pairs of such levels occur at markedly different energies. The second class contains transitions from hole states ($n < 0$) to empty electron states ($m > 0$). These are the particle-antiparticle creation and annihilation events in the Dirac formalism. The fact that electron and hole states are built of the same atomic orbitals leads to a full particle-antiparticle (electron-hole) symmetry. Finally, the transitions involving the L_0 level constitute a third class: the exceptional character of this level, which is both an electron and a hole level, means that the main observed transition (B in Fig. 1) contains electron cyclotron-resonance-like, hole cyclotron-resonance-like, and electron-hole-like excitations.

Concluding, we have measured the optical excitation spectrum of massless Dirac fermions in a condensed matter system. These fermions are found in thin layers of epitaxial graphite, most probably in the form of single (or weakly coupled) graphene layers.

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