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Substrate dependence of cyclotron resonance on large-area CVD graphene

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ABSTRACT

Cyclotron resonance has been investigated on single-layer large-area graphene which was synthesized by chemical vapor deposition. Absorption peaks of the cyclotron resonance are clearly observed on the graphene sample and these peak energies exhibit $\sqrt{B}$-dependence in terms of an unequally spaced Landau Level structure in Dirac fermions. We find significant substrate dependence of the band velocity $\tilde{c}$. The derived $\tilde{c}$ of the sample on a GaAs substrate is enhanced by about 10% from that on a glass substrate which almost coincides with that of the multi-layer epitaxial graphene, indicating that the $\tilde{c}$ is strongly affected by the condition of the substrate.

1. Introduction

Graphene, a monolayer two-dimensional (2D) system, has attracted great deal of attention because of the promising potential in applications such as nanoscale optoelectronic devices, in addition to its unique electric property characterized by the 2D massless Dirac fermions, since the discovery of an unusual half-integer quantum Hall effect in high magnetic fields [1–5]. Among several approaches for graphene synthesize, recent development of chemical assembly using chemical vapor deposition (CVD) enable us to grow large-area graphene with high crystalline quality and to transfer it onto arbitrary substrate [6–9], which will be essential for device application. The transport property of the CVD synthesized graphene has been improved to be comparable in quality to exfoliated one [10]. Cyclotron resonance (CR) measurement is a powerful tool to reveal an unequally spaced Landau Level (LL) structure of the graphene in the presence of magnetic fields. The LL structure of the graphene is described as following [11],

$$E_\mathrm{n} = \mathrm{sgn}(n)\tilde{c}\sqrt{2e\hbar B|n|}, \tag{1}$$

where n is the LL index, and $\tilde{c}$ is the band velocity. Concerning the CR measurements of the graphene, the $\sqrt{B}$-dependence was observed on a fragment of the single-layer exfoliated graphene on Si/SiO_2 [12] and multi-layer epitaxial graphene on SiC [13–16]. The CR was also investigated using the photoconductive response on a small peace of the single-layer graphene [17]. Enhancement of the band velocity $\tilde{c}$ and the deviation from the precise scaling of $(\sqrt{|n+1|}+\sqrt{|n|})$ in the CR energy were reported on the graphene on Si/SiO_2 [12]. On the other hand, such anomaly was not observed on the multi-layer graphene and its band velocity was found to be similar with that of the very thin bulk graphite [18,19]. The anomaly was argued to indicate the presence of the many-body correction to the CR [20,21]. The many-body correction term depends on dielectric constant ε of the substrate which supports the graphene sample. The CR energy of the lowest inter-LL transition shifts according to the LL filling factor ν, and exhibits maximum around $\nu = 0$ [22], while the detailed mechanism for the energy shift is still under controversy [22–24].

In this study, we have performed the CR measurements in high magnetic fields on single-layer graphene samples which were synthesized by CVD and transferred to different kinds of substrates, in order to investigate the substrate dependence of the CR.

2. Experiments and discussion

The single-layer large-area graphene samples on different kinds of substrates were prepared. The graphene sheets were synthesized by CVD of methane gases on Cu foils. After the underlying Cu foil was etched by the $FeCl_3$ solution, the graphene was transferred to put

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onto the other substrate. In order to investigate the substrate dependence of the CR, we used two kinds of the samples on the different substrates. Namely, the sample *A* is the CVD graphene sheet transferred on a semi-insulating GaAs (001) substrate, the sample *B* is that on a soda-lime glass substrate. The dimension of these samples was about 6×6 mm^2. The graphene sample was checked to be more than 90% monolayer by the micro-Raman scattering measurements. The CR measurements were performed using a Fourier-transform spectrometer (BOMEM DA8) combined with a 15 T superconducting magnet at low temperature down to $T = 1.7$ K.

Fig. 1(a) shows the normalized transmission spectra of the sample *A* in the magnetic field between 5 and 15 T. The GaAs substrate is opacity in the energy range below 75 meV. Two CR absorption peaks are clearly observed around 85 meV and 230 meV at $B = 5$ T, and both peaks shift toward higher energy with increasing magnetic fields. Hereafter, the lower-energy peak and the higher-energy one are labeled as P_{A1} and P_{A2}, respectively, as shown in Fig. 1(a). The line shape of P_{A2} is symmetric, and it can be well fitted by a Lorentzian curve. On the other hand, the line shape of P_{A1} becomes asymmetric at higher magnetic fields above $B = 9$ T, while it is almost symmetric at lower magnetic fields. The asymmetric line shape of P_{A1} can be well described as overlap of two Lorentzian curves with different line width, as shown in Fig. 1(b). The lower-energy-side Lorentzian component and the higher-energy-side one are labeled as P_{A1}^{L} and P_{A1}^{H}, respectively. The magnetic field dependence of the integrated intensity and the full width at half maximum (FWHM) of each CR peaks are shown in Fig. 1(c). From the curve fitting analysis, the intensity of P_{A1}^{H} (P_{A1}^{L}) increases (decreases) with increasing magnetic fields.

The normalized magneto-transmission spectra of the sample *B* are shown in Fig. 2(a). The glass substrate is opacity in the energy range below 185 meV. Two CR absorption peaks, labeled as P_{B1} and P_{B2}, are observed around 200 meV and 260 meV, respectively at $B = 5$ T, and the energies of both peaks increase with magnetic fields. Their line shapes are almost symmetric. Fig. 2(b) and (c) shows the integrated intensity and FWHM of P_{B1} and P_{B2}, respectively.

The magnetic field dependence of the CR energies on both the sample *A* and *B* is shown in Fig. 3. Each CR branches of both samples exhibit the $\sqrt{B}$-dependence which is the evidence for the Dirac fermions. According to the LL structure as described in Eq. (1) and the selection rules for the infrared-active electric dipole inter-LL transition $\Delta n = \pm 1$, we assigned P_{A1}, P_{A2}, P_{B1} and P_{B2} to the inter-LL

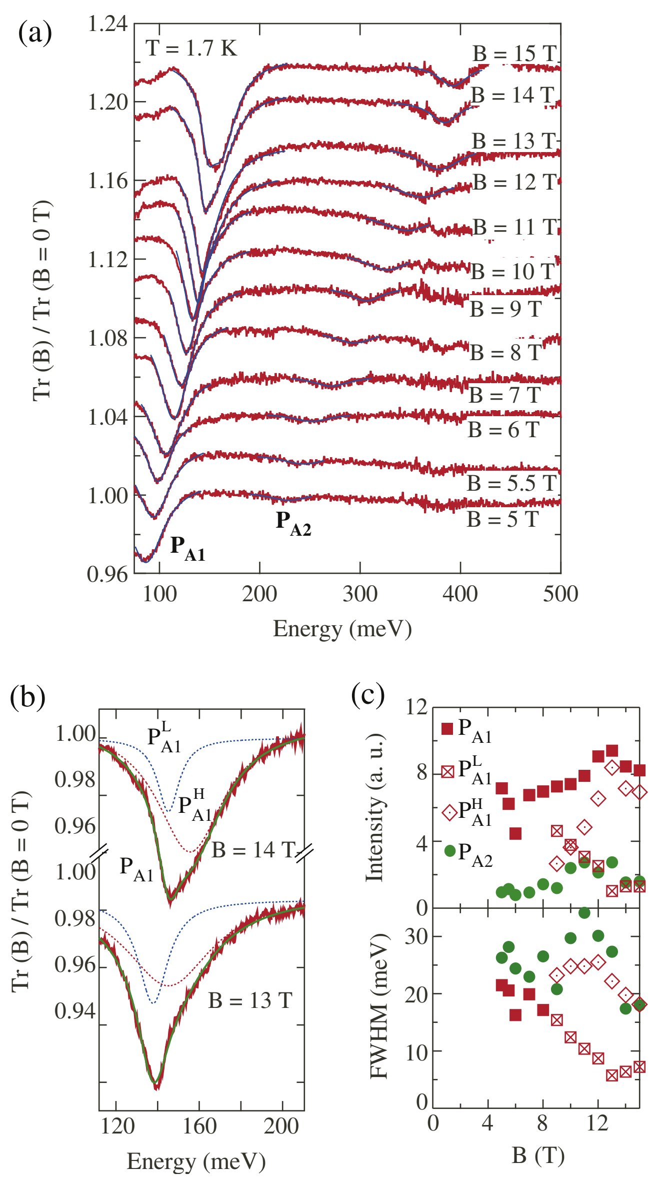

Fig. 1. (a) Normalized magneto-transmission spectra at various magnetic fields of sample *A*. Two CR absorption peaks are labeled as P_{A1} and P_{A2}, respectively. (b) Curve fitting of asymmetric line shape of P_{A1} using two Lorentzian curves which are labeled as P_{A1}^{L} and P_{A1}^{H}, respectively. (c) Magnetic field dependence of the integrated intensity and FWHM of each CR peaks.

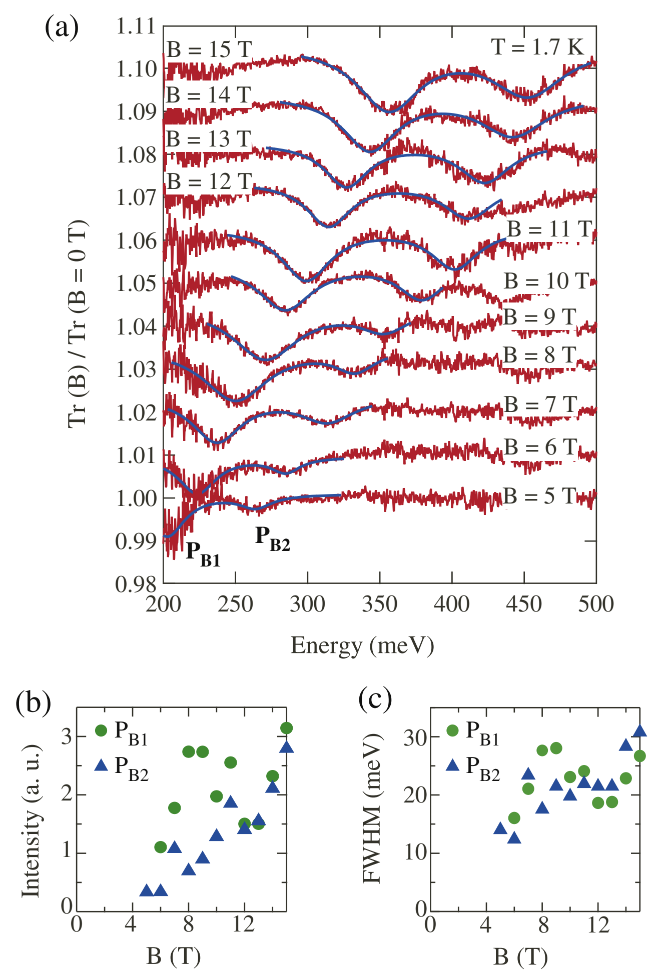

Fig. 2. (a) Normalized magneto-transmission spectra of sample *B*. Two CR absorption peaks are labeled as P_{B1} and P_{B2}, respectively. (b) Magnetic field dependence of the integrated intensity of CR peaks. (c) FWHM as a function of magnetic field.