Resistively detected spin resonance and zero-field pseudo spin splitting in epitaxial graphene

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Graphene[1] is an appealing material for electron-spin quantum computing (QC) and spintronics, due to the expected weak spin-orbit interaction, and the scarcity of nuclear spin in natural carbon. Due to QC and spintronics, the electrical detection and microwave control of spin have become topics of interest, now in graphene nanostructures, where the small number of spins limits the utility of traditional spin resonance. This work reports the resistive detection of spin resonance in epitaxial graphene, and ESR based measurements of the g-factor, the spin relaxation time, and the pseudo-spin (valley - degeneracy)-splitting at zero-magnetic-field.[2]

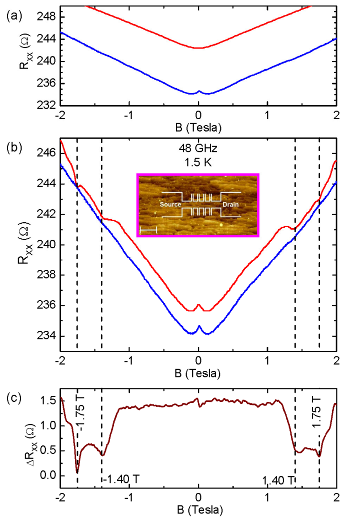

Figure 1) Resistively detected microwave-induced spin-resonance at f = 48 GHz in a three layer epitaxial graphene specimen. (a) The diagonal resistance, R_{xx}, is exhibited vs. the magnetic field, B, at temperatures T = 90K (red trace) and T = 1.5 K (blue trace). (b) R_{xx} is exhibited vs. B without microwave excitation (blue trace), and under constant f = 48 GHz microwave excitation at P = 4 mW (red trace), at T = 1.5 K. Resonant reductions in the R_{xx} are observed in the vicinity of B = ± 1.4 T and B = ± 1.75 T. Inset: An AFM image of the EG/SiC surface. (c) The change in the diagonal resistance, ΔR_{xx}, between the photo-excited and dark conditions in panel (b), i.e., $\Delta R_{xx} = R_{xx}$ (4 mW) - R_{xx} (dark), is exhibited vs. B.

Transport studies were carried out in the B ⊥ c-axis configuration on p-type epitaxial graphene Hall bar specimens. The epitaxial graphene (EG) was realized by the thermal decomposition of insulating 4H silicon carbide (SiC),[127] and the c-face of the EG/SiC chip was processed by e-beam lithography into micron-sized Hall bars with Pd/Au contacts. The specimens were immersed in pumped liquid Helium, and irradiated with microwaves over the frequency range $10 \leq F \leq 50$ GHz, at a source-power $0.1 \leq P \leq 10$ mW.

Figure 1(a) exhibits the diagonal resistance, R_{xx}, vs. B, for a trilayer sample at 90K (red) and 1.5K (blue). These data indicate $dR_{xx}/dT > 0$ at B = 0 Tesla. Fig. 1(b) illustrates the influence of microwave-excitation at f = 48 GHz. Here, for B < 1 Tesla, microwave-excitation produces a positive displacement of the photo-excited R_{xx} (red curve, Fig. 1(b)) relative to the dark trace (blue curve, Fig. 1(b)), akin to increasing the temperature. However, at B > 1 Tesla, R_{xx} exhibits resistance-valleys as the photo-excited curve approaches the dark curve. Fig. 1(c) shows two noteworthy features in $\Delta R_{xx} = R_{xx}$ (4 mW) - R_{xx}(dark): a high magnetic field resonance at |B| = 1.75 Tesla, and a low magnetic field feature at |B| = 1.4 Tesla. The high B-field resonances of Fig. 1 followed the relation f(GHz) = 27.2 B(T) vs. the microwave frequency, while the low-B resonances followed f(GHz) = 10.76 + 26.9 B(T), with a non-zero intercept, f_0 = 10.76 GHz. The observed slopes, for the low (high) field resonance correspond to spin resonances with $g_{//} = 1.92 \pm 0.028$ ($g_{//} = 1.94 \pm 0.014$). The non-zero intercept is associated with a zero-field pseudo spin splitting.

[1] S. Das Sarma, S. Adam, E. H. Hwang, and E. Rossi, Reviews in Modern Physics 83, 407 (2011).
[2] R. G. Mani, J. Hankinson, C. Berger, and W. de Heer, Nature Communications 3, 996 (2012).