MAR11-2010-000692
Abstract for an Invited Paper
for the MAR11 Meeting of
the American Physical Society

Quantum Linear Magnetoresistance and Extraordinary Magnetoresistance in Graphene

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Graphene, a single atomic layer of hexagonally arranged carbon atoms, presents the optimal platform to study rarely-observed magnetoresistance (MR) effects because of its temperature-independent mobility and linear band structure with zero band gap. Linear magnetoresistance (LMR), which is characterized as a large, non-saturating linear MR, is one such unusual effect. Normally, the resistance of a conductor in an applied magnetic field increases quadratically with field and then saturates at a relatively low value. Models that explain LMR behavior have been proposed that include both quantum and classical origins, but most systems studied thus far can be explained by a purely classical model. However, we find that quantum LMR is observed in multilayer epitaxial graphene grown on SiC at temperatures as high as 300 K and with a magnitude greater than 200% at 12 Tesla (T). In addition, a phenomenon closely related to classical LMR called extraordinary magnetoresistance (EMR) and characterized by even larger MR, can be realized in metal-shunted graphene devices. Here, due to the different magnetic-field-dependent resistances of the metallic shunt, graphene, and shunt-graphene interface, current flows easily through the shunt in zero and low magnetic field, while in high magnetic field, more current flows around the shunt and is redistributed in the graphene. Devices made from chemical vapor deposition (CVD) graphene grown on copper and transferred to a SiO_2/Si substrate with Ti/Au shunts display gate-tunable longitudinal MR of $\sim$600% at 12 T and also show promise for use as Hall sensors. Graphene magnetoresistance devices have many possible applications including magnetic field sensors and magnetic read-heads. In contrast with the many proposed electronic uses for graphene, which necessitate the creation of a band-gap, graphene magnetoresistance devices that exploit LMR or EMR provide a use for as-grown or deposited graphene.