Substitutional magnetic dopants in graphene: Kondo screening or RKKY interactions

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Imprinting magnetism in graphene has been an important challenge since its discovery. In the dilute regime, magnetic impurities are expected to couple to the Dirac electrons via the Kondo effect in a paramagnetic phase. In the less dilute regime, magnetic impurities in graphene may develop long-range magnetic order mediated by the conduction electrons via the Ruderman-Kittel-Kasuya-Yoshida (RKKY) interaction. Today, the Kondo and RKKY-exchange physics of Dirac electrons in graphene is still elusive while theory predicts competition between a non-trivial Kondo unscreened phase against a RKKY-coupled phase. Considerable experimental efforts have been devoted in this context, with the local magnetic moments originating from carbon vacancies, from adsorption and intercalation (of atoms, clusters or molecules), and from substitutional foreign atoms. Here, we report the incorporation of substitutional manganese (Mn) atoms into graphene as a model case of magnetic doping with transition metals. Ultra-low energy (ULE) ion implantation allows us to precisely tune the kinetic energy of Mn ions, providing control over the form of incorporation and concentration while preserving the structural and electronic properties of graphene [1]. Using low-temperature scanning tunneling microscopy (LT-STM) together with density functional theory (DFT), we identified and characterized point defects that are associated with substitutional-Mn in a carbon single vacancy (Fig.1). Based on an x-ray magnetic circular dichroism (XMCD) study, we demonstrate an overscreened Kondo phase in the system of graphene with dilute (up to 1%) substitutional Mn. These results are complemented by synchrotron-based X-ray photoelectron spectroscopy (XPS), angle-resolved photoemission spectroscopy (ARPES), Raman spectroscopy, among others. The new insights provided by our work establish a framework for the controlled incorporation of magnetic dopants in graphene and other 2D materials, using ULE ion implantation.

References

[1] P.-C. Lin *et al.*, ACS Nano 15 (3), 5449 (2021).

Figures

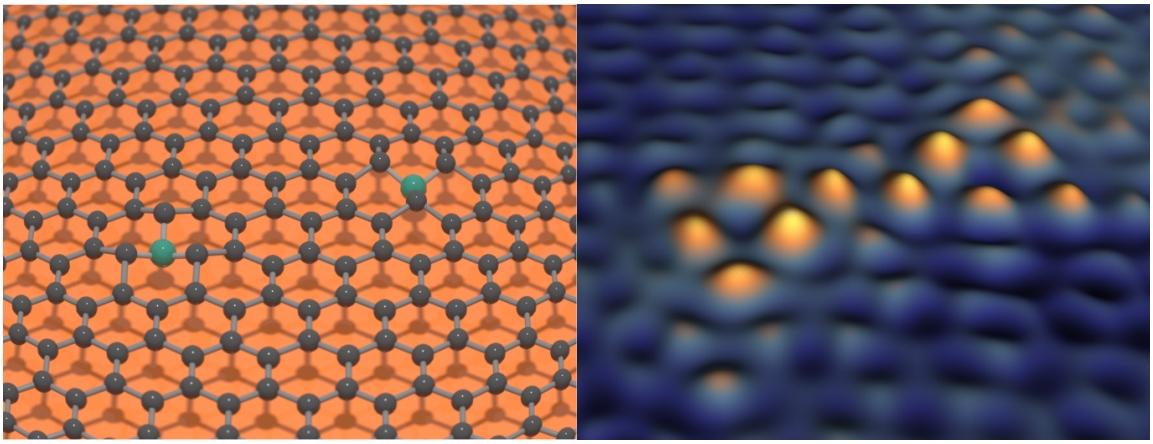

Figure 1: (Left) Cartoon of the atomic structure and (right) STM topography of graphene with two substitutional Mn atoms.