# Ferromagnetism of graphene-related materials: Methods and conditions for its identification

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Magnetic moments in graphene can be due to defects such as edges, vacancies or functional groups covalently bounded to carbon atoms on a graphene surface. According to theoretical predictions, these moments can be magnetically ordered [1,2]. Ferromagnetic ordering of the edge states on the zig-zag edges [3] was foreseen theoretically and observed by ferromagnetic resonance (FMR) [4]. Surface magnetic moments located in one sublattice interact ferromagnetically, while an interaction between moments located in two sublattices has antiferromagnetic character [5]. Low mass magnetization makes it difficult to observe ferromagnetism in graphene-related materials. Carbon atoms on zig-zag edges in graphene constitutes a small part of the total number of atoms. For the surface magnetic moments generated by covalent functionalization, using in particular hydrogen atoms, situation is more complex. A significant ferromagnetism is expected for one-side hydrogenated graphene [6], which is difficult to obtain and unstable. Hydrogenation of materials consisted of graphene or graphene oxide flakes inevitably leads to two-side functionalization resulting in a formation of ferromagnetic domains as well as nonmagnetic graphane-like regions. Detection of ferromagnetism in such materials requires sensitive methods such as SQUID or FMR recorded using EPR spectrometers.

In this report, we present data proving the existence of ferromagnetic order in graphene, graphene oxide and reduced graphene oxide. We analyze peculiarities of magnetometry and FMR in these materials. Additionally, an origin of para- and diamagnetic contributions revealed in field dependences of magnetization is discussed. We also demonstrate the crucial role of the strength of magnetic field in temperature dependences of magnetization. Finally, we point significant differences between FMR signals of the ordered zig-zag edge states and of the exchange-coupled magnetic moments located on the graphene surface in one sublattice.

**References:**

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