Research Group for Molecular Spintronics

Group Leader : Seiji Sakai
Members : Yoshihiro Matsumoto, Shiro Entani, Manabu Ohtomo, Pavel V. Avramov, Shinjiro Arai, Hiroshi Naramoto

Spintronics is an emerging technology taking advantage of the dual property of electrons, i.e., the charge and spin degrees of freedom. Over the past decades, spintronics has been developed based on inorganic materials like metals and semiconductors. Recent studies have started to shed light on the spintronics applications of carbon-based materials (organic molecules and nanocarbons). We call this new field "Molecular Spintronics". In molecular spintronics, the efficient control of spin transport in carbon-based materials is essential for device applications by taking advantages of their potentials for transfer and storage of spin information. Our group focuses on establishing the advantages of nanocarbons like graphene by designing the hybrid nanostructure. For this purpose, the novel spectroscopic and fabrication techniques are employed properly, which allow the microstructure analysis and control at the atomic layer level to be possible. We successfully made distinguished achievements on the spintronics application of graphene as follows. We are now developing efficient spin operation sources and exploring new spintronic nanostructures for nanocarbon-based spintronics.

Tailor-made graphene for spintronics applications

After the discovery of the convenient fabrication method by the exfoliation from graphite (A. Geim and K. S. Novoselov, the 2010 Nobel Prize in physics), graphene has attracted worldwide attention as an innovative nanoelectronic material. In the field of spintronics, graphene is expected to be an ideal spin transport material owing to the extremely long spin relaxation length and high carrier mobility. Exfoliated graphene, however, does not appear to be relevant for device applications due to the size limitation (less than 10 μm in diameter) and the non-uniformity in the layer number, which make it difficult to control the spin transport properties. Accordingly, a new fabrication method that enables us the structural tailoring of graphene is indispensable for graphene-based spintronics.

From this viewpoint, ultrahigh vacuum chemical vapour deposition can be a promising alternative method because of no size limitation and structural tunability based on the catalytic growth on the substrate surface. We focused on the ultrahigh vacuum chemical vapour deposition growth of graphene by using metal thin films as catalytic substrates and hydrocarbon molecules as precursors [1].

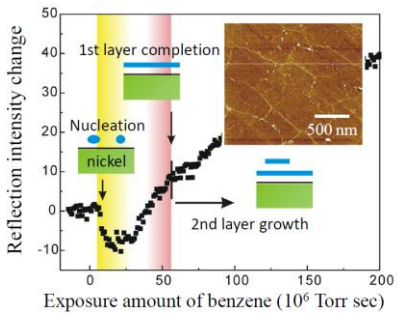

Fig. 1 Reflection intensity change with the benzene exposure on the nickel surface. The growth process of graphene can be controlled by the exposure amounts. The inset image shows monolayer graphene obtained under the optimized exposure condition.

It was successfully demonstrated that single-crystalline graphene with a controlled layer number can be synthesized by *in-situ* monitoring the reflection intensity of the electron beam from the surface, which reflects the process of the layer-by-layer growth of graphene on the substrate as shown in Fig. 1. It was also found that the electronic uniformity of graphene obtained by this method could be remarkably high compared to exfoliated graphene by controlling the growth condition so that the growth of the respective layers was completed.

This technique for the tailor-made synthesis would facilitate the development of graphene-based spintronics.

Spin orientation transition across graphene / magnetic metal interface at atomic layer level

Efficient injection of spin-polarized electrons into graphene is the most fundamental issue of graphene-based spintronics. Basically, the spin-injection is performed via the interface between carbon-based materials and magnetic electrodes, and therefore the understanding and control of the interface structure are essential for the device design.

In this study, we first explored the spin-electronic structures of the interface between graphene and a nickel thin film by applying the depth-resolved X-ray magnetic circular dichroism technique with atomic layer resolution. This innovative approach led to the finding of the abrupt spin orientation transition across the graphene/nickel interface (2). The spin polarization direction in the nickel thin film changes from in-plane to out-of-plane within the region of several Ni atomic layers from the interface. The out-of-plane spin-polarization is induced in monolayer graphene on the interface by contacting with nickel. Furthermore, the sign of the spin polarization reverses between the first and the second layer from the interface in the case of bilayer graphene [3] (Fig. 2).

The modulation of the spin-electronic structures across the graphene/magnetic metal interface as found in this study would be of particular importance not only in controlling the spin-injection but also in building up spintronic functions of graphene-based devices at the atomic layer level.

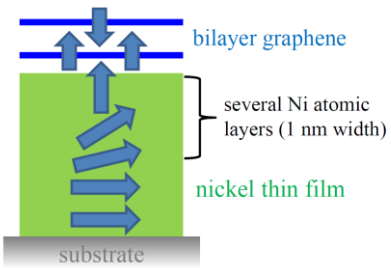

Fig. 2 Spin orientation transition across the bilayer graphene/nickel thin film interface. The arrows indicate the spin direction.

References

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[3] P. V. Avramov *et al.*, J. Appl. Phys. **112**, 114303 (2012).