

# Large intrinsic band gaps, ferromagnetism, and anomalous magnetoresistance oscillations derived from grapheme edge states: Nanoribbons and Antidot-lattice Graphenes

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A variety of quantum phenomena observed in graphene is attracting significant attention. In contrast, few works have experimentally reported edge states and related phenomena, although there are so many theoretical reports, which predicted that electrons localize at zigzag edges of graphene due to presence of flat bands and the electron spins strongly polarize. One main reason for lack of experimental reports is high damages at edges introduced by lithographic fabrication.

Here, in the talk, I will present the following two systems fabricated by non-lithographic methods in order to reveal edge-related phenomena; 1. Graphene nanoribbons (GNRs) fabricated by chemical unzipping of carbon nanotubes (CNTs) and 3-stepped annealing [1] and 2. Antidot-lattice graphenes (ADLGs; graphene nano-pore arrays) fabricated using nano-porous alumina templates as etching masks [2, 3].

In the GNRs, we confirm low defects by Raman spectrum, HRTEM, single electron spectroscopy, and also electrical measurements. I present a large an intrinsic energy band gap of 55 meV, which is 7-times larger than those in lithographically fabricated GNRs with defects. It can be understood by calculation for arm-chair edge GNRs.

In the ADLGs, we confirm high electronic density of states at antidot (nano pore) edges by STM. I will show appearance of room-temperature ferromagnetism and anomalous magnetoresistance oscillations derived from edge-localized spins in hydrogen-terminated ADLGs. They can be qualitatively understood by theories for zigzag edges. These results must open a new door to all-carbon (rare-metal free) magnets and also spintronic devices based on spin Hall effects by inducing spin-orbit interaction.

1. T.Shimizu, J.Haruyama, et al, "Large intrinsic energy bandgaps in annealed nanotube-derived graphene nanoribbons" *Nature Nanotech.* **6**, 45-50 (2011) (Selected for Latest Highlights, News&Views, and Cover index)
2. T.Shimizu, J.Haruyama, et al, "Edge-state-derived ferromagnetism and anomalous magnetoresistance in antidot-lattice graphenes" To be published on *Phys.Rev.Lett.*
3. K. Tada, J.Haruyama, et al, "All-carbon ferromagnetism derived from edges states in graphene nano-pore arrays" *Nature Nanotech.* **In-depth Review**