Single-nanometer graphene patterning with helium ion beam for extreme sensing and phonon engineering applications

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In recent years, ultrafine patterning of graphene by a Helium ion microscope (HIM) has been actively explored. The main advantages of He^+ ion beam milling over conventional gallium focused ion beam (FIB) milling are higher precision and less damage. Carving suspended graphene into single-nanometer (< 10 nm) structures (Fig. 1(a)) is getting particularly interested for various advanced applications such as single-molecular detection [1] and nanoscale phonon engineering [2].

We have demonstrated a ~6 nm wide suspended graphene nanoribbon (GNR) patterned on mechanically exfoliated graphene and reported on the room temperature electrical characteristics. A large range of drain current, at which current suppression occurs, has been observed [3]. Very recently we also succeeded to pattern 100 nm wide monolayer CVD based suspended GNRs [4]. The structures were prepared by electron-beam lithography and thin-film processing. Before HIM milling, the graphene was released by buffered hydrofluoric acid etching (60 sec) and critical point drying. Annealing in H_2/Ar atmosphere (275°C, 2 hours) is used to remove the resist contamination. It should be noted that proper device cleaning is crucial to successful HIM milling, as any contaminants are re-deposited during milling and significantly affect the dose requirements. Figures 1(b1)-(b3) show some of the GNR devices (30 keV acceleration voltage, 1.1×10^{18} ion/cm^2). Electrical transport characterization was conducted by varying temperature, and remarkable band gap opening due to quantum confinement was observed at room temperature along with an increase in the transport gap with lowering temperature. We will discuss the milling results and electrical characterization in detail along with their potential impact on the performance of graphene-NEMS-based extreme sensing.

Furthermore we show our recent attempt of large-area patterning of single-nanometer-size nanopores in graphene by HIM. Arrays of pores of 3 – 4 nm in diameter spanning a complete suspended ribbon were successfully patterned with a pitch down to ~16 nm [4]. Thanks to a very high Young's modulus and therefore a high Debye temperature of graphene, the phononic bandgaps are expected to be formed in the bandwidth of a few THz with such single-nanometer pore arrays. This enables us to control thermal transport dominated by heat phonons for relatively low temperature (< 200°C). We will discuss the possibility of graphene-based heat phonon engineering and potential device applications.

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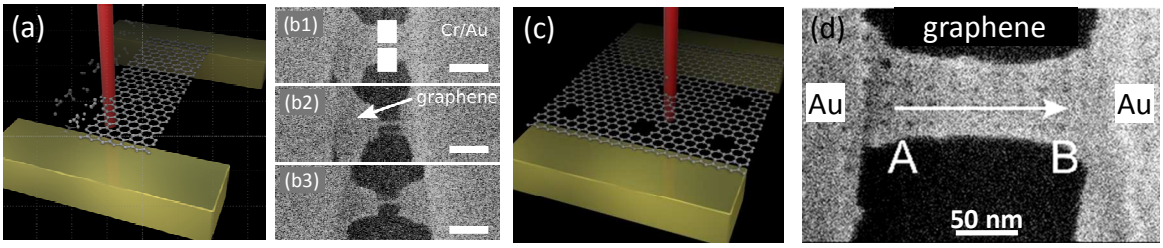

Figure 1: (a) Artwork for He^+ ion carving suspended graphene into GNR. (b1)-(b3) HIM images of suspended GNR before and after milling. Scale bar is 100 nm. (c) Artwork of patterning nanopore array onto suspended GNR. (d) Nanopore array formed on 200-nm-long CVD graphene with pitch of ~16 nm.