Graphene nanoelectromechanical (GNEM) devices functionalized by using helium ion beam for nanoscale thermal engineering

JAIST [1], YNU[2], AIST[3], Hitachi Cam Lab[4] °H. Mizuta[1,4], M. Haque[1], S. Kubo[1], M. Koyano[1], Y. Oshima[1], M. Muruganathan[1], Y. Arashida[2], I. Katayama[2], J. Takeda[2], S. Ogawa[3], M. E. Schmidt[1]
E-mail: mizuta@jaist.ac.jp

When a solid body is periodically patterned with a period close to the one of waves, the complete blockade of transmission due to band gap formation can be observed under certain conditions [1]. This has been demonstrated for acoustic and photonic crystals, where the required periodicity is well above the technological limitations. Phononic crystals (PnC), however, are considerably more difficult to realize due to the much reduced wavelength of phonons. In particular, room temperature phonons in silicon, the most popular material for nanostructuring, would require periodic patterning with sub-1-nm in three dimensions. There is no current technology that is able to achieve this. Nevertheless, the prospect of being able to fully suppress heat conduction through the formation of a phononic bandgap (PnBG) is so important, that several groups in Japan and around the world are working to push the technological limits and understanding.

Apart from reducing the periodicity, using graphene for PnCs should be preferred over silicon due to the high Young's modulus of 1 TPa (compared to ~200 GPa in silicon) and the higher Debye temperature. This increases the wavelength of phonons at given temperature, thus relaxing the fabrication requirements. Furthermore, the true 2D nature of graphene allows restricting the phonon flow and elimination of leakage paths and out-of-plane scattering (in case of suspended graphene). In conclusion, to fabricate PnCs in graphene that allow effective excitation and measurement, suspended graphene with several microns of size and a reliable sub-10-nm patterning technique are required.

Figure 1a illustrates the suspended graphene sample preparation process that we recently developed [2]. By using chemical vapor-deposited graphene, a large number of devices can be prepared simultaneously. Key aspects of the suspended graphene preparation are two-step electrode patterning, and the gentle hydrofluoric acid etch. In consequence, suspended monolayer graphene with length up to 4.8 um and 16 um width were demonstrated, but larger size is expected. The thorough removal of organic contaminants by furnace annealing is paramount to a successful patterning [3].

Patterning of the PnCs is done by focused helium ion beam milling (HIBM) with a beam current of 1 pA and a beam diameter of <0.5 nm. Each pore is realized by a spot exposure, where the dwell time is adjusted to control the ion dose per pore. Figure 1b shows that by careful adjustment, sub-10-nm pitch (9 nm) is possible with ($6.3x10^5$ ions/pore). Such dimensions are not possible by traditional, resist-based patterning, and no post-patterning processing is required that would certainly break suspended graphene with such large dimensions. Large-area patterning with pitch down to 11 nm was successful, as well (Fig. 1c); however, the extraneous exposure by the Gaussian beam tail appears to be the limiting factor. We will also briefly discuss the possible ways to excite and measure coherent phonons [4] in the suspended graphene PnCs as well as measurement of the nanoscale thermal conductivity change.

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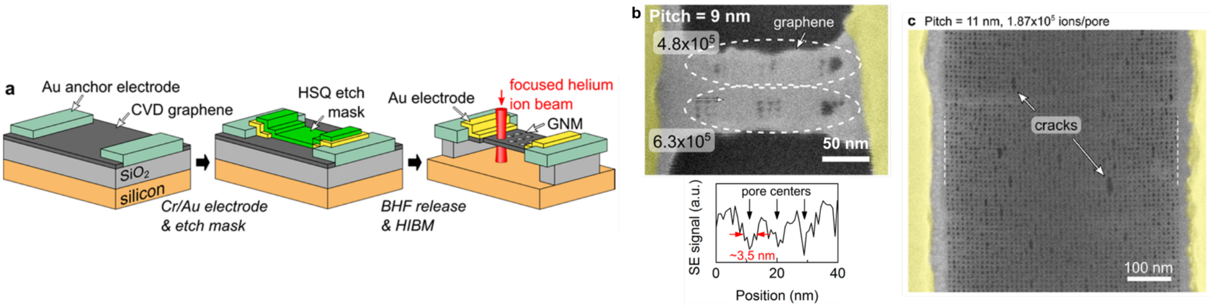

Figure 1: (a) Fabrication of large-area suspended graphene for focused helium ion beam milling. (b) 3x3 pore array with 9 nm pitch (pore dose: $6.3x10^5$ ions). Pore diameter of ~3.5 nm estimated from secondary electron image. (c) 11-nm pitch large area graphene nanomesh. Isolated cracks are observed.