Design and fabrication of single-nanometer-scale graphene phononic crystals for thermal engineering by using focused helium ion beam

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Thermal conductivity reduction at the nanoscale can be achieved by hindering the propagation of the thermal phonon waves. Specifically designed periodic arrays can reduce the heat propagation by the wave interference when the wavelength of thermal phonon (high frequency phonon in THz regime) is equal to the periodic spacing of nanopores. These type of materials are called phononic crystals (PnCs) [1], exhibiting phononic bandgap (PnBG) where the propagation of certain phonon wavelength is suppressed. The study of phononic materials has garnered much interest due to the prospect of futuristic applications like hypersound and heat control, acoustic and thermal cloaking, thermal diode etc. In comparison to the commonly used semiconductor material of silicon, graphene is regarded as a promising candidate for the phononic crystals [2]. Owing to the high Young's modulus and Debye temperature in graphene, the minimum pore size and the spacing of nanopores to realize THz PnBG is larger than silicon. Moreover, we have developed a technique to fabricate suspended graphene phononic crystals with pore size of 3 to 4 nm and pitch 18 to 25 nm based on sub-1 nm helium ion beam milling technique [2].

We carried out three-dimensional finite element analysis of the graphene phononic crystals (GPnC) with the cross-shaped nanopore structures to investigate the formation of PnBG. The formation of partial and complete PnBG is confirmed in the cross-shaped nanopores with different dimensions (Fig. 1(a-b)). At low w/a ratios (0.10 ~ 0.30), clear complete PnBG is formed. In contrast, PnBG can be hardly found at the regime w/a > 0.35 and w/a < 0.7. From this simulation result, it can be seen that the PnBG strongly depends on w. Interestingly, PnBG features with specific phonon modes are found at higher w/a ratios. In addition, multiple PnBG formations were obtained depending on the shape. This PnBG formation originates from the interferences of phonon waves along the length and the width directions. Furthermore, with the increase in the pore intervals (i.e., decrease in the unit cell size) the phonon dispersion relation shifts to higher frequencies. As the w/a ratio increases, multiple PnBG appears. Although PnBG is small, it will result in reduction of heat conduction as the dispersion branches are parallel which results in the reduction of group velocity.

In order to measure the influence of such periodic nanopores in the fabricated nanopore samples, we are using the heat spreader method. It uses microfabricated metal lines to create thermal gradient through the sample and resistance thermometry is used for in plane thermal transmission measurement. Owing to the high in-plane thermal conductivity, we are aspiring to study the temperature profile using a source heater and three resistance temperature sensors as shown schematically in Fig. 1(c). To measure the resistances at different distance from the source, we utilize the 4-probe measuring technique, which uses two separate pairs of current-carrying and voltage-sensing electrodes and offers higher sensitivity compared to the two-terminal methods. As shown in Fig. 1(d-e), we developed a special chip assembly and fabrication of a suitable device to support a total of 16 measurement probes.

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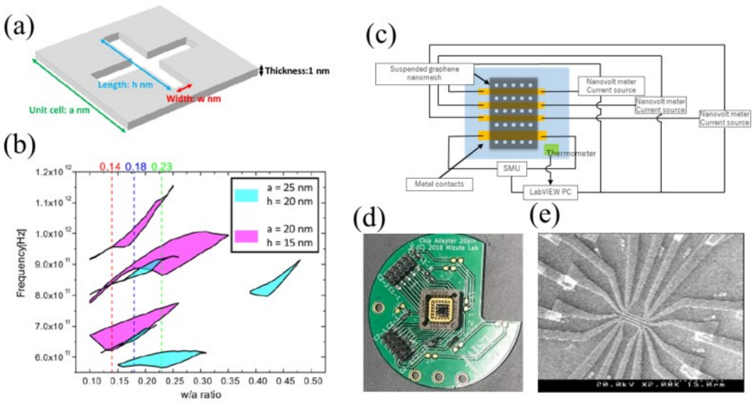

Fig. 1 (a) GPnC model of cross-shaped nanopore structure with unit cell dimensions of a nm, and thickness 1 nm, and cross-shaped pore of width w nm, and length h nm (b) PnBG opening for the different w/a ratio (c) Schematic diagram of the thermal conductivity measurement setup (d) Customized chip assembly for heat spreader measurement setup (e) SEM image of the microfabricated gold metal lines for thermal conductivity measurements.

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