Three-dimensional Nanofabrication on Hydrogen Silsesquioxane Using Focused Helium Ion Beam Lithography

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Various methods for fabricating three-dimensional (3-D) nanostructures have been developed, such as grayscale lithography, nanoimprint lithography and nanosphere lithography [1]. Among them grayscale e-beam lithography is a prime candidate for fabricating arbitrary three-dimensional structures because of its high spatial resolution and its ability to create arbitrary patterns [2]. Recently introduced focused helium ion beam lithography (HIBL) has demonstrated unique capability in lithography applications. Since the interaction volume of helium ions in resist materials is much smaller than electrons of similar energy, it's possible to develop new 3-D fabrication capabilities using focused beam of helium ions. We have performed experimental and analytical study on the point-spread function (PSF) of focused helium ion beam and proposed a numerical model for simulating the volumetric energy dissipation of helium ions in HSQ. Based on this model, fabrication of complex 3-D nanostructures in HSQ via focused helium ion beam lithography is demonstrated in this work.

Figure 1 demonstrates the fabrication of a hollow nanosized channel embedded in HSQ using focused helium ion exposure of thick HSQ resist through a silicon nitride membrane. 3-D energy dissipation of incident helium ions in HSQ resist is schematically illustrated in fig. 1a. 600 nm thick HSQ was spin-coated on a 20 nm thick silicon nitride film and dried in vacuum at room temperature for 12 hours, then placed upside down and exposed by focused helium ion beam. After exposure, the HSQ was developed by a salty developer solution (aqueous mixture of 4% w.t. NaCl and 1% w.t. NaOH) for 60 seconds. Only the HSQ exposed with deposited energy higher than a threshold remained on the silicon nitride membrane after development. Fig. 1c is the vertical cross-section of calculated normalized energy density in HSQ using our model at the minimal gap (~50 nm) induced by 15 kV helium ion exposure. Clearly, a hollow nanosized channel was formed in HSQ as shown in the SEM photograph in Fig. 1d.

3-D fabrication of HSQ can also be realized on a silicon substrate. In this demonstration, a 200-nm thick HSQ layer was spin-coated onto silicon substrate and then exposed by focused helium ion beam with a specially designed dose pattern. Since the thickness of cross-linked HSQ varies with the exposure dose pattern, suspended structures with varying thickness can be obtained after development. Fig. 1e and 1f shows suspended HSQ beams formed by focused HIBL with doses of 50 $\mu C/cm^2$ and 80 $\mu C/cm^2$ respectively and supported by fully crosslinked pedestals at the ends. A small gap was observed between the beam and substrate.

Our method provides a new way of using focused helium ion beam for 3-D nanofabrication. New device applications may be developed from this fabrication method.

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[2] J. Kim, D. Joy, S.-Y. Lee, Controlling resist thickness and etch depth for fabrication of 3D structures in electron-beam grayscale lithography, Microelectron Eng, 84 (2007) 2859-2864.

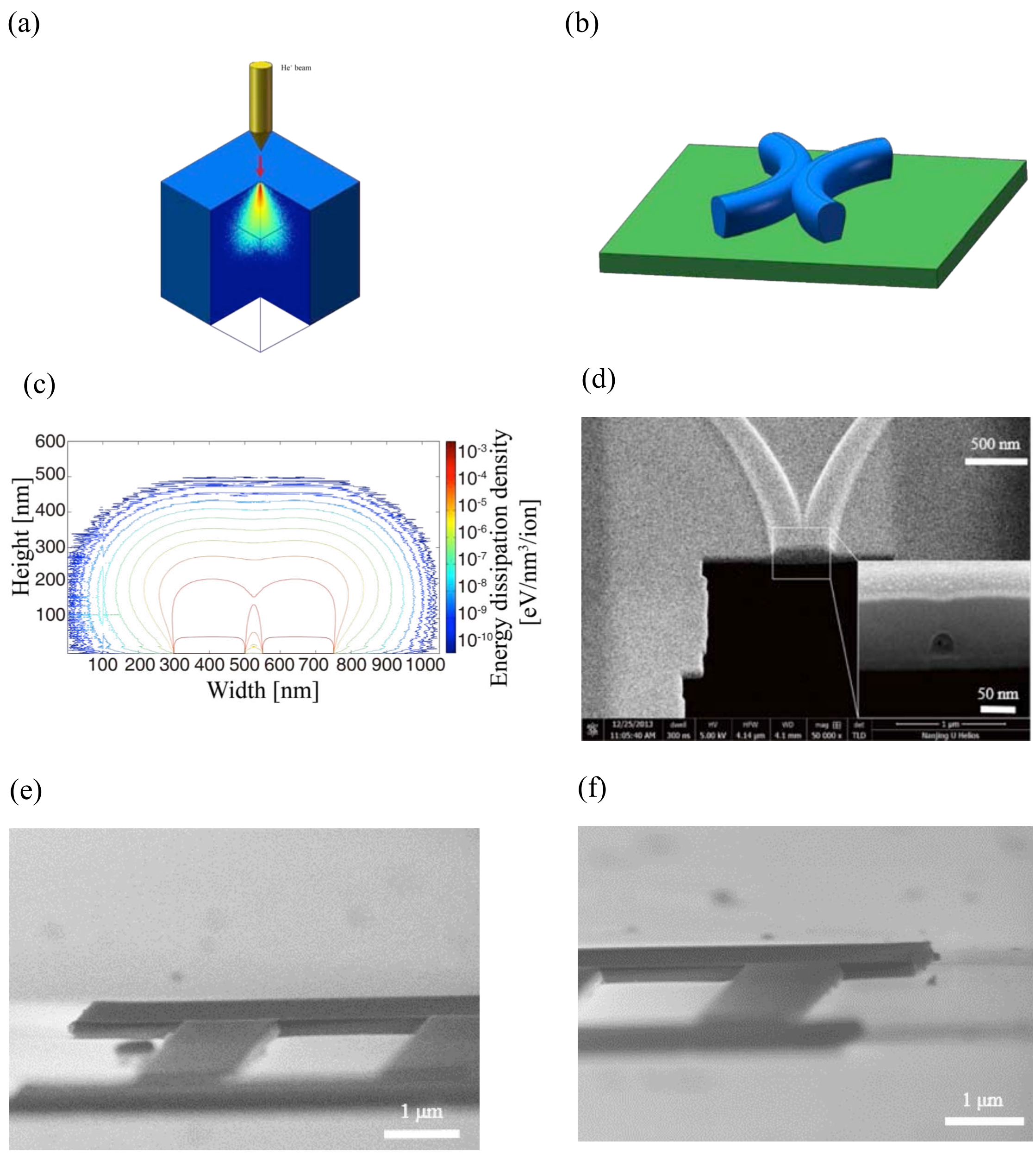

Fig. 1 Schematic illustration of the fabrication of HSQ patterns defined by HIBL. (a) A schematic diagram of cross-sectional view of volumetric energy dissipation in exposed photoresist of helium ion injected into a thick layer of HSQ; (b) Schematic diagram of enclosed channel formed in thick HSQ layer and (c) corresponding X-Z contour of normalized volumetric energy dissipation of helium ions in HSQ; (d) SEM photograph of HSQ patterns cut by FIB, an enclosed channel was formed; (e) SEM photograph of a suspended beam created by focused helium ion beam with dose of 50 $\mu C/cm^2$ and (f) 80 $\mu C/cm^2$.