Fabricating Nanostructures On Bulk Silicon Substrates Using Helium Ion Microscope

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The Helium Ion Microscope shows promising applications in nanofabrication such as nanopore drilling and graphene cutting via direct ion milling, with the ability to fabricate features as low as 2-3 nm on suspended films [1]. However, there exists a critical challenge of applying helium ion milling to bulk substrates due to the swelling from ion implantation [2].

In this work, we firstly used an AFM to scan the topography of the He^+ ion milled nanopatterns on Pt electrodes in order to characterize the swelling characteristics. For all the experiments, the acceleration voltage of the helium ions was set at 30 kV. Starting at around 1nC/μm^2, swelling of the substrate surfaces became visible. At around 4.6 nC/μm^2, the height of the swelling increased to 40 nm for a 100 nm size square pattern with 20 nm thick Pt metal and 100nm thick silicon dioxide protection layers on top of the silicon. Without the protection layers, the substrate swelled to 32 nm in height at an even smaller dose of 0.17 nC/μm^2 (equivalent to 522 ions/nm^2) and 145 nm in height at 0.8 nC/μm^2 dose, as shown by cross-section TEM images in Figure 2 and in agreement with data reported in [2]. Helium ion irradiation into silicon substrates can cause serious substrate swelling that distorts the shape of the nanopatterns, and can turn single crystal silicon into amorphous silicon, deteriorating the material properties such as the electron transport.

To achieve formation of high-resolution nanopatterns directly on bulk substrates, we present our work of using helium ion lithography to fabricate nanostructures. Figure 3(a,b) shows 100nm deep and 30nm wide nanofluidic channels fabricated by dosing 100nm thick HSQ films at a line dose of 10 ions/nm, less than 10 times smaller than the threshold helium ion dose that can cause substrate swelling. Therefore, this presents a practical route for fabricating structures on bulk substrates using the helium ion microscope. Figure 3(c, d) shows 20nm pitch and 14nm wide HSQ line patterns that are 10 nm thick, which can potentially alter the band structure of graphene through a periodically varied gating for nanoelectronics applications [4].

1. G. Hlawacek, et al., "Helium ion microscopy." *JVST. B,* 32(2) (2014)
2. R. Livengood, et al., *JVST. B,* 27(6) (2009)
3. D. Winston et al., *JVST. B*, 27(6) (2009)
4. C-H. Park, *Nature Physics* 4, 213-217 (2008)

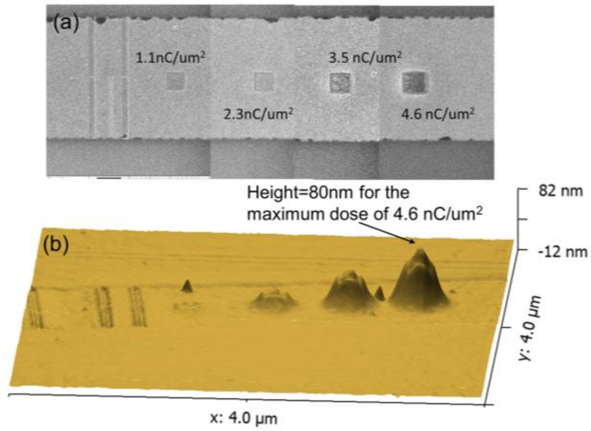

Figure 1. (a) Helium Ion Microscope image of 30 KeV He^+ ions milled nanopatterns on 20nm thick Pt film; (b) Corresponding AFM topography scanning image of nanopatterns directly showing the swelling of substrates. Swelling height is 80nm for maximum dose of 4.6 nC/μm^2.

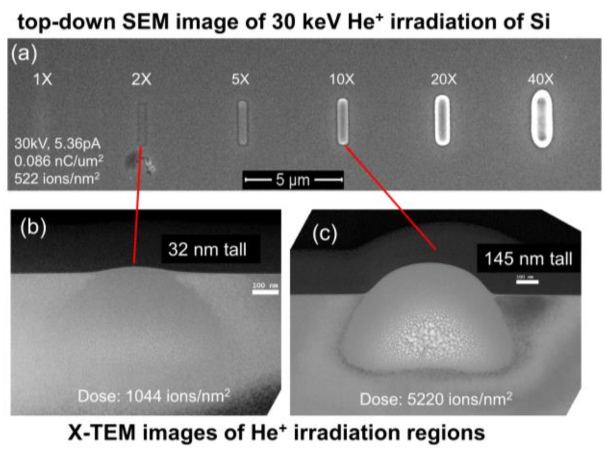

Figure 2. (a) Top-down SEM image of 30 KeV He^+ irradiation of silicon with different doses from 522 ions/nm2 to 20,880 ions/nm^2. (b) and (c) are two cross-section TEM images of He^+ irradiated regions showing the swelling

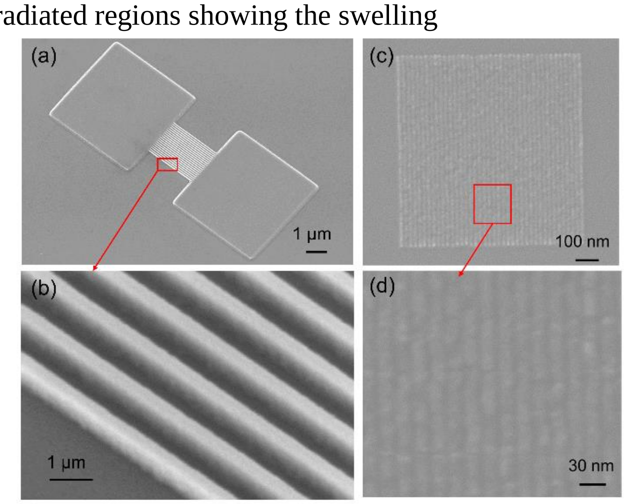

Figure 3. (a, b) 30nm wide, 100nm deep HSQ nanofluidic channels with 100nm pitch fabricated by helium ion lithography; (c, d) 14nm wide, 10nm deep HSQ nanoline patterns with 20nm pitch potentially useful for regulating the bandgap of graphene.