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Micromachining of Si_3N_4 by Ga^+-Ion Implantation and Dry Etching

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With regard to fabrication of precision nanostructures and microstructures Focused Ion Beam (FIB) has proved to be a powerful and versatile tool whose benefits are largely exploited in Ion beam lithography (IBL). Alternative Ion beam lithography methods include the fabrication of nanostructures by direct milling, which allows for maskless and resistless patterning. In this context direct write IBL methods were utilized to fabricate Fresnel Zone Plates (FZP) for X-Ray focusing. The fabrication of a binary FZP *via* a simple and fast direct writing IBL method [1] and a 3D kinoform lens for X-Ray focusing *via* an robust grayscale IBL method [2] has been presented.

However, during the sputtering process, the bombarding ions are implanted into the material leading to amorphization of initially crystalline surfaces. This changes the material irreversibly. Nevertheless, these unwanted surface modifications for many applications, can be turn in to an advantage during a subsequent reactive ion etching (RIE) step. A noticeable selectivity between Ga^+-Ion beam irradiated and non-irradiated areas show an etch retardation effect in silicon [3] which has been utilized in the fabrication of 3D nanopatterns [4, 5]. Besides direct implantation into silicon, it also has been proposed to apply Ga^+-Ion implantation to form a mask in a resist-like silicon nitride (Si_3N_4) coating on top of the silicon sample in order to protect the silicon from FIB irradiation [6]. When unexposed regions are etched off, the pattern in Si_3N_4 layer is transferred into either a binary or 3D structure of the underlying silicon while the crystal structure of the silicon stays intact [6]. When compared to the electron beam lithography (EBL), the bombarding ions in a FIB exhibit a smaller scattering volume shown to allow the fabrication of ultra-high resolution patterns [7].

In this work, we focus on the fabrication of binary nanostructures realized fully in thick Si_3N_4 films, taking advantage of a Ga^+-Ion implanted top layer as a mask during subsequent RIE to achieve high aspect ratios. Calculations show that FZPs made out of silicon nitride could perform very efficiently from extreme UV and well into the soft X-ray energy regions. Diffraction efficiency (DE) calculations for a binary rectangular FZP predict DEs of up to 30 % (see Figure 1). The combination of ion implantation and RIE provides a fine control by avoiding extensive sputtering due to significantly lower Ga^+ ion dosages compared to direct milling route. Lower dosage limits the unintended damage to the unexposed areas while markedly increasing the pattern writing speeds. This potentially can allow the fabrication of larger patterns without being disturbed by drifts.

In the preliminary studies, arrays of varying structure sizes as shown in Figure 2a were implanted into Si_3N_4 films of 500 nm on 5×5 mm sized Si wafers. Each array consists of 10×10 squares, which all have the same size within an array (from 1 µm to 100 nm) but differ in implantation dosage. Line-to-space ratio was chosen to be 1:1 in all cases. A 30 kV beam of 30 pA current, 10 nm step size and 0.266 µs of minimum dwell time combined with 100 passes resulted in the dosages ranging between 0.5×10^{16} and 1.43×10^{16} ions/cm^2 (Figure 2b) and exhibited no significant sputtering during implantation.

Initial RIE trials (see Figure 2c) indicated that the implantation dosages and RIE parameters need further optimization in order to achieve the required sensitivity for the realization of efficient, high aspect ratio, and high resolution binary Si_3N_4 FZPs.

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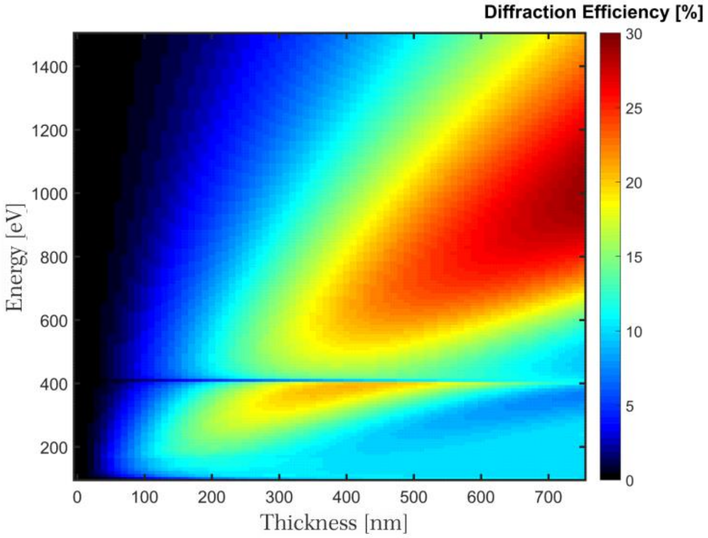

Figure 1. Diffraction efficiencies for a rectangular Si_3N_4 FZP with a thickness up to 750 nm**.** For a thickness of 300 to 400 nm reasonably high diffraction efficiencies are predicted for a rather large energy range covering L_2 edges of many interesting elements. The higher the etch depth the more efficient the FZP becomes at higher energies.

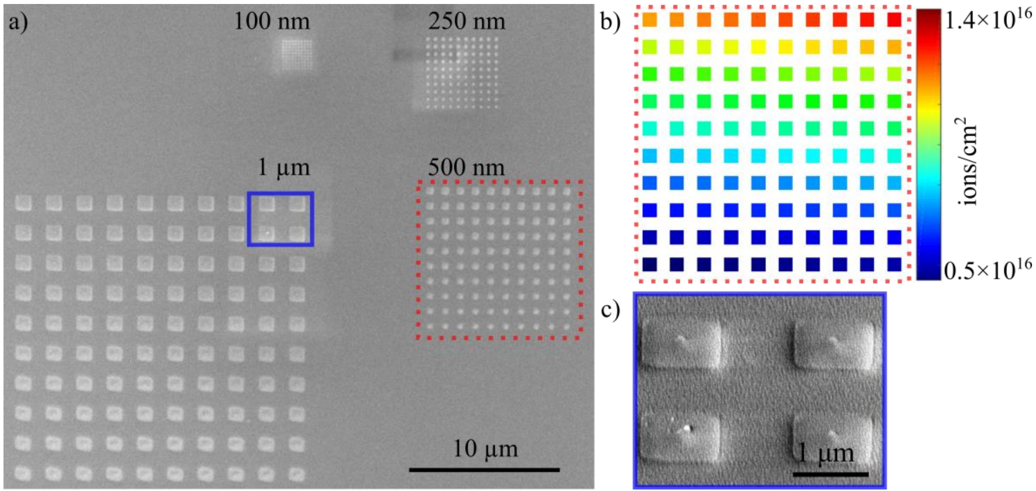

Figure 2. Initial Ga^+-Ion implantation trials in Si_3N_4. a) SEM image of the implanted regions with pitches of 1 µm, 500 nm, 250 nm and 100 nm. b) A schematic of the arrangement and the implantation dosage of one array. c) An SEM image of an implanted region after RIE under tilted view.