

Enhancement of Laser Plasma Driven Ion Acceleration Using Structured Si Targets on Air-bridged SiO₂ Membranes

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Primary CNF Tools Used: JEOL 6300, SC4500 Evaporator, Unaxis 770 Deep Si Etcher, PlasmaTherm Versaline Deep Si Etcher, SUSS MA6-BA6 Contact Aligner, Oxford 82 Etcher, Oxford PECVD, KLA P7 Profilometer, Zeiss Supra SEM, Heidelberg Mask Writer DWL-2000, Hamatech Mask Processor, E-beam and Photolithography Spin Coaters, Resist Hot Strip Bath, Hamatech Wafer Processor, Anatech Resist Strip, FilMetrics

Abstract:

We study the acceleration of heavy ions generated by the interaction of high-power ultrashort laser pulses with structured silicon targets. We compare the yield of heavy ions produced by laser pulses incident on 1 micron-thin air-bridged silicon oxide membranes with the yield from structured silicon metasurfaces resting on similar membranes. Experiments carried out at the ALEPH laser facility in Colorado State University reveal that we obtain a greater flux of higher energy ions from the structured targets compared to the flat foil. Simulations reveal that this enhancement is due to the generation of significantly more energetic electrons during the laser's interaction with structured targets. Such high charge/flux heavy ion beams may have applications in diverse areas including cancer therapy and high-flux neutron generation.

Summary of Research:

Ultrashort, high intensity pulsed lasers have enabled the creation of tabletop ion accelerators which rely on a driving electron component and the resulting electric field created by charge separation. A typical mechanism involves target normal sheath acceleration (TNSA) where a laser beam incident on a solid thin foil target creates an electron sheath on the rear of the target which generates highly energetic ions [1]. The incident laser pulse generates hot electrons which form a charge separation field due to the target's capacitance. At the rear surface, this field is strong enough to ionize atoms, and it accelerates the ions in a direction normal to the surface.

We seek to enhance the flux and energy of the ions produced from thin foils in the standard TNSA scheme

by using nanostructured Si targets resting on air-bridged $\sim 1 \mu\text{m}$ thick SiO₂ membranes (see Fig. 1a). A laser pulse polarized perpendicular to the gap between the Si structures will draw electrons out of the Si blocks into the trench (see Fig. 1a) and accelerate them via direct laser acceleration to relativistic energies which are far greater than the energies obtained in traditional TNSA, leading to a stronger sheath electric field. The thinness of the SiO₂ membrane serves a key purpose where it prevents broadening of the sheath field while maintaining the accelerated electrons at a high temperature. We prepared both Si metasurfaces and gratings with different periods (0.6 μm and 1.2 μm) and prepared unstructured foils as control targets. We also prepared gratings oriented in the wrong direction compared to the laser polarization to check the polarization dependence of the ion-acceleration scheme.

Our targets are produced at the CNF using CMOS compatible processes (see Fig. 1b). We use a buried oxide silicon on insulator wafer and deposit 3 μm SiO₂ on the handle layer to be used as a hard mask for the handle layer etch. We carry out e-beam lithography on PMMA spun on the device layer and evaporate Al₂O₃ on the PMMA after development. The PMMA is then lifted off in acetone and the remaining Al₂O₃ acts as a hard mask for the anisotropic etching of the device silicon layer in the Unaxis 770 using a modified Bosch process recipe. We remove any remaining Al₂O₃ in Al etch and remove polymer coatings on the Si structure sidewalls using EKC polymer strip. The SiO₂ on the handle layer is then patterned via backside aligned photolithography on the MA6 mask aligner followed by etching in the Oxford 82. Finally, the substrate below the Si arrays is etched on the Unaxis 770 using the standard Bosch process.

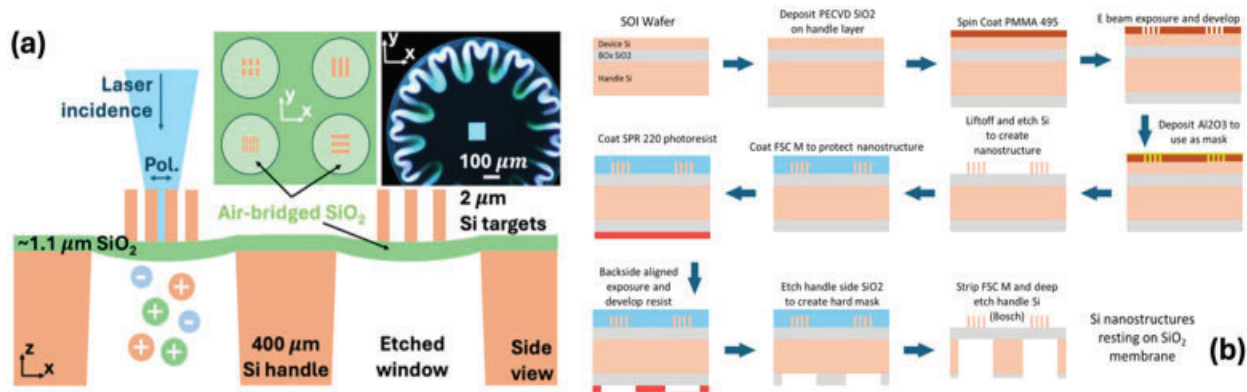


Figure 1: (A) Schematic of the targets and laser incidence with the top right inset showing a dark field micrograph of a Si nanostructure array on a $\sim 1 \mu\text{m}$ SiO_2 membrane. (B) Fabrication process flow.

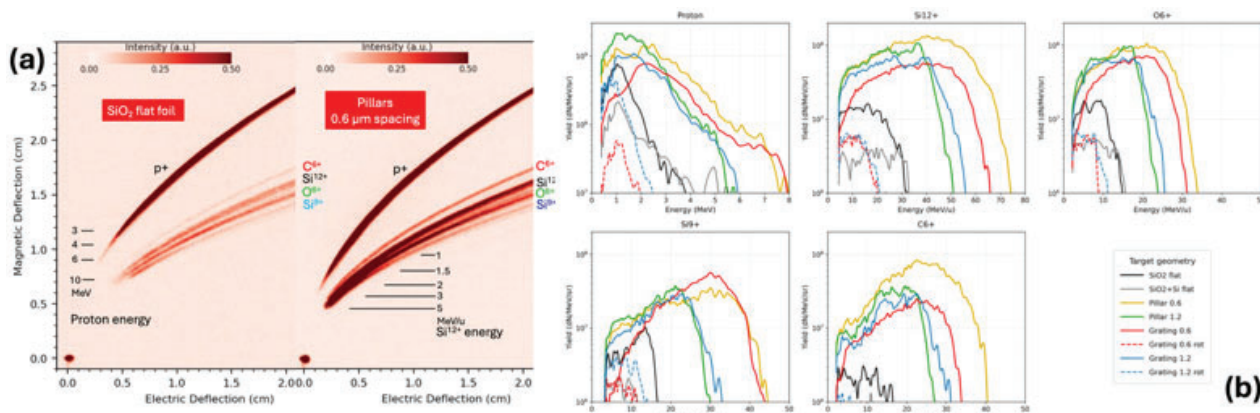


Figure 2: (A) Image plates from a TPS showing traces corresponding to positively charged ion species and a X-ray spot. (B) Spectrum for various positively charged ions obtained from different target types.

We perform our experiments at the ALEPH laser facility in Fort Collins, Colorado where a 400 nm, ~ 50 femtosecond laser deposits $\sim 4 \text{ J}$ of energy in a $\sim 2 \mu\text{m}$ diameter focal spot on our targets leading to intensities of $\sim 2.5 \times 10^{21} \text{ W/cm}^2$. The energies of the ions generated are measured using a Thompson Parabola spectrometer (TPS) and phosphor image plates which are then scanned using a 635 nm laser scanner. Scans of two image plates comparing shots on unstructured SiO_2 foil with 0.6 μm spacing Si metasurfaces on similar foil are shown in Fig. 2a. The structured targets produce significantly higher flux and higher energies for various positively charged ion species. Using the geometry and electric and magnetic fields in the TPS, we can fit various ion species to the traces obtained on the image plate and find H^+ , Si^{12+} , Si^{9+} , O^{6+} , and C^{6+} , among others. We compare the yields and energies for these various ion species from different targets in Fig. 2b and find that the metasurfaces and gratings with 0.6 μm spacing provide the highest yields and energies while the foils and the rotated gratings with the “wrong” alignment have the lowest yields.

Conclusions and Future Steps:

We have demonstrated a scheme to enhance the acceleration of protons and massive ions from nanostructured Si targets on thin, air-bridged SiO_2 membranes fabricated using CMOS compatible processes. The CMOS-compatible fabrication process lends our scheme to easier translation to industrial settings as well as greater control over target geometry compared to standard nano-wire targets. In the future we plan on running our experiments with additional diagnostics and modified geometries to accelerate other massive ions from Au or W films layered on our targets.

References:

- [1] Roth, M. & Schollmeier, M. Ion Acceleration—Target Normal Sheath Acceleration. CERN Yellow Rep. 231 Pages (2016) doi:10.5170/CERN-2016-001.231.