Enhancement of laser plasma driven ion acceleration using dielectric metasurfaces

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Primary CNF Tools Used: JEOL 6300, SC4500 Evaporator, Unaxis 770 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 aim to study the acceleration of heavy ions generated by the interaction of high-power ultrashort laser pulses with structured solid targets. We compare the yield of heavy ions produced by laser pulses incident on thin flat silicon oxide (SiO2) membranes with the yield from structured silicon metasurfaces resting on similar SiO2 membranes. Simulations as well as preliminary 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. 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. The incident laser pulse generates hot electrons which penetrate the foil and while a few electrons escape, the target's capacitance traps most of the electrons which end up forming a charge-separation field. At the rear surface, the electric field is strong enough to ionize atoms, and it accelerates the ions in a direction normal to the surface.

We are investigating a scheme to enhance the acceleration of the heavy ions compared to standard TNSA from a foil target by structuring the target. Specifically, we create arrays by patterning a silicon layer which lies on a thin (~1 µm) silicon oxide membrane. Blocks of silicon comprising the array are separated from each other by high aspect ratio trenches. A laser pulse polarized perpendicular to the trench will draw electrons out of the silicon blocks into the trench (see Fig. 1a) and accelerates them to relativistic energies which are far greater than the energies obtained in traditional TNSA, leading to a stronger sheath electric field [1]. Simulations predict that the structured targets will enhance both the energy and flux of the ions produced (see Fig. 1b).

Our targets are produced at the CNF. We start with a buried oxide silicon on insulator wafer and deposit 3 µm SiO2 on the handle layer which will be patterned as a hard mask to etch the substrate. We carry out e-beam lithography on PMMA deposited 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 customized recipe based on a modified Bosch process. After that we remove the Al2O3 in Al etch and remove polymer coatings on the sidewall 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 silicon arrays is etched on the Unaxis 770 using the standard Bosch process.

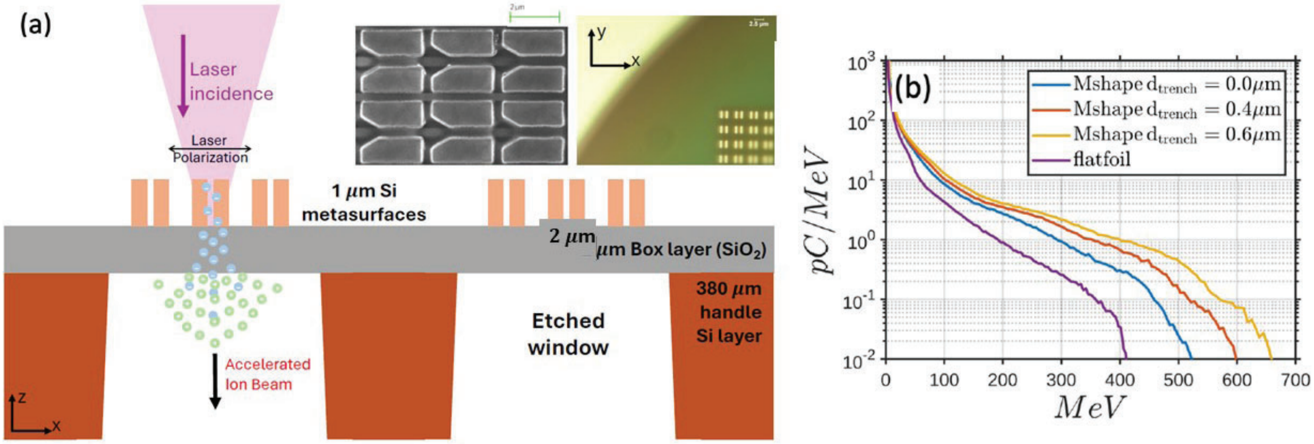

Fig. 1: (a) Schematic showing the laser incident on a structured target on a membrane. The insets show optical and SEM images of two different structured targets. (b) Simulation results predicting higher energy ions from structured targets.

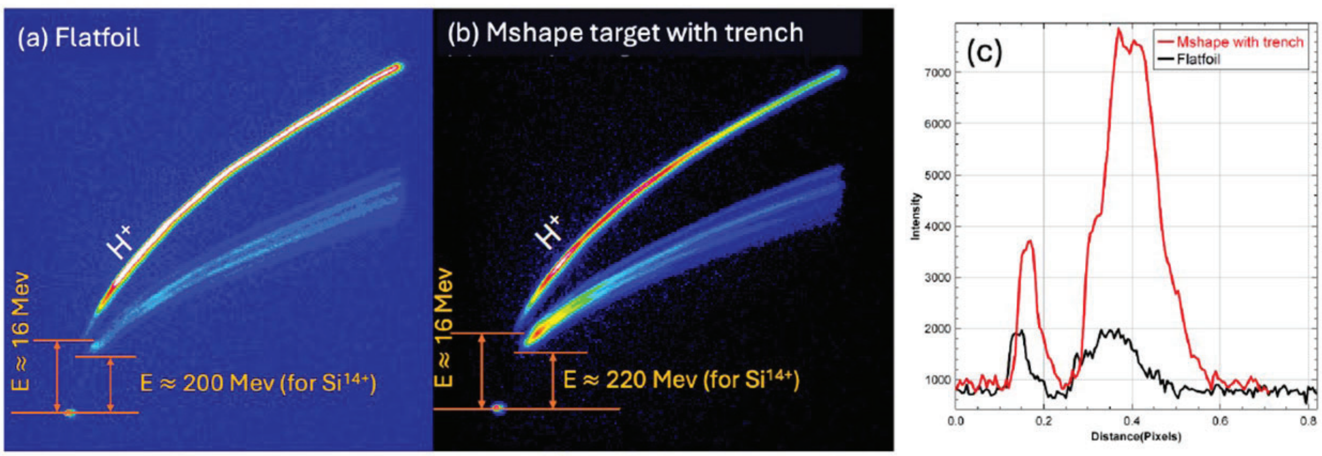

Fig. 2: Thompson parabola spectrometer output showing traces for different ion species with laser incident on (a) flat foil and (b) structured target. (c) Comparison of image intensity at a fixed energy.

Conclusions and Future Steps:

Our proposal was evaluated in a competitive process, and we were awarded beam time at multiple laser facilities across the US (ALEPH at Colorado State University, SCARLET at Ohio State and ZEUS at the University of Michigan). Preliminary results from experiments carried out at the ALEPH facility have shown that the structured targets produce a higher flux of heavy ions at higher energies as recorded on Thompson parabola spectrometers (see Fig. 2). We are currently preparing for further experimental campaigns to confirm our results. To this end we are also updating our target design based on feedback from previous experiments.

References:

[1] Shcherbakov, M. R. et al. Nanoscale reshaping of resonant dielectric microstructures by light-driven explosions. Nat Commun 14, 6688 (2023).

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