Energy and charge distribution of Si ions in EUV ablation plasma

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Recent developments on high-power compact EUV sources have enabled us study the materials ablation induced by the irradiation of intense EUV light [dinh, Rocca, tallents, tanaka]. The interactions of extreme ultraviolet (EUV or XUV) with matters along the ablation have potential advantage for the use in advanced materials processing. We have studied the fraction of ion charge states in the EUV ablation plasma using an ExB mass-charge analyzer, and ablation dynamics by calculating the plasma parameters and ion charge abundance for both heating and expanding time regime by HELIOS and PRISM SPECT simulation codes [helios]. An incoherent EUV light with continuous wavelength of 7-20 nm, 10 ns pulse length, and intensity of 4 x 10^9 W/cm^2 was irradiated onto a Si wafer (111 P-type) target with an incident angle of 45 degrees. The ions expanding from the ablated Si target was detected by the ExB ion-charge analyzer as mass and charge separated kinetic energy spectra at the distance of 750 mm. Both experiment and simulation were also conducted for laser ablation at the same ablation parameters by using a 1064 nm Nd:YAG laser. The experimental results showed only Si^+ spectrum for EUV ablation and Si^+, Si^{2+}, Si^{3+} spectra for laser ablation. Further, the ion spectra of laser ablation showed higher kinetic energy distribution than that of EUV ablation. The dynamics of ablation process was simulated for both EUV and laser ablations. In the heating regime (0-10 ns), the plasma parameters and ion abundance showed noticeable difference between those two light sources. The ion charge abundance was largely affected by the electron temperature, and thus ionization was suppressed in EUV ablation near the surface, where electron temperature stays at few eV. In the expansion regime (1-10 μs), the ion abundance of low kinetic energy component showed only Si^+ ions due to progress of recombination, and that of high kinetic energy component in laser ablation showed Si^+ to Si^{4+} ions implying that the recombination was "frozen" at some point so that highly charged ions were preserved at the detector. The simulation results explained the experimental results, showing the electron temperature and resulting ion charge fraction in heating regime and the speed of expansion determines the consequent ion charge abundance in the expanding particles. Further discussion will be presented at the conference.

[1] Dinh, T., Medvedev, N., Ishino, M. *et al.* Controlled strong excitation of silicon as a step towards processing materials at sub-nanometer precision. *Commun Phys* **2,** 150 (2019)
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[4] Nozomi Tanaka, Masaya Masuda, Ryo Deguchi et al, "Characterization of material ablation driven by laser generated intense extreme ultraviolet light", Applied Physics Letters, **107,** 114101 (2015)
[5] HELIOS Radiation-Hydrodynamics Code(http://www.prism-cs.com/Software/Helios/Helios.htm)