Debris mitigation in a laser-produced tin plume using a magnetic field

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Debris mitigation in a laser-produced tin plume is one of the most important issues for its use as an extreme ultraviolet source in next generation lithography. We investigated the use of a magnetic field for controlling the kinetic energies of various species in a laser-produced tin plasma. 1.06 μm, 8-ns pulses from a Nd:yttrium aluminum garnet laser were used to create the tin plasma in vacuum that expanded across a transverse magnetic field. Time-of-flight optical emission spectroscopy was used to measure the velocities of excited neutral and singly ionized tin species. Our studies showed a significant reduction in the kinetic energies of the plume species with a modest magnetic field of 0.64 T. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1999851]

One of the most formidable problems confronting the advancement of extreme ultraviolet (EUV) lithography is the design and experimental demonstration of a reliable, debris-free, and high efficiency plasma source that meets very stringent production-line criteria.[1] The debris damage to the x-ray optics is the biggest obstacle to the application of laser-produced plasmas as EUV sources in projection lithography. The debris from a laser-generated plasma includes energetic ions, neutrals, particulates, and molten droplets. Considerable effort has been made in exploring the feasibility of using laser-created gaseous plasmas from xenon where the debris is limited compared to solid targets.[2] However, the maximum conversion efficiency obtained with xenon gas jets is only $\sim 1\%$.[3] High-Z solid targets such as tin characteristically emit broadband spectra around 13.5 nm that originate from a range of ionization stages.[4] Conventional solid metal targets, however, can pose extreme debris problems in commercial lithography processes. Mitigation of the debris has been attempted using various methods including tape targets,[5] mass-limited droplet targets,[6] addition of ambient gas,[7] and application of electrostatic repeller fields.[6]

We report the controlling of laser-produced tin plasma using a moderate magnetic field of 0.64 T. The presence of a magnetic field (B) during the expansion of a laser-produced plasma may initiate several interesting physical phenomena which includes conversion of the plasma thermal energy into kinetic energy, plume confinement, ion acceleration, emission enhancement, plasma instabilities, etc.[8–10] Tsui *et al.*[11] demonstrated the effectiveness of debris reduction using magnetically guided pulsed laser deposition. Time-of-flight emission spectroscopy is used to study the flight time and velocity of the singly ionized tin (Sn^+) and neutral tin (Sn) species at various spatial points in the plasma. It is extremely important to understand the evolution of excited neutral and ionized species since these will act as debris in a tin plasma-based EUV source. For the sake of comparison, plume dynamics in the presence and absence of magnetic field are studied.

Details of the experimental techniques employed here are given elsewhere.[12] Briefly, plasma was generated by laser ablation of tin target, placed in an evacuated chamber (pressure $\sim 10^{-6}$ torr), using 1.06-μm radiation pulses from a Q-switched Nd:yttrium aluminum garnet (YAG) laser. The tin target was mounted on an x-y translator to provide a fresh surface for each laser shot. For spectroscopic studies, an optical system was used to image the plasma plume onto the entrance slit of a 0.5-m monochromator/spectrograph. One of the exit ports of the spectrograph was coupled to an intensified charge-coupled device (CCD) camera and the other exit port was coupled to a photomultiplier tube (PMT). By translating the optical system along the direction of target normal, the spatio-temporal information about the plume's emission could be detected. For time-resolved studies of a particular species in the plume, the specific emission lines were selected by tuning the grating and imaging onto the slit of the PMT. Recording the temporal profiles was accomplished by coupling the output of the PMT to a 500-MHz digital phosphor oscilloscope. The ambient magnetic field is supplied by an assembly of two permanent magnets (B_{max}, 1.2 T) mounted in a steel core, creating an optimal field configuration over a volume of $5 \times 2.5 \times 1.5$ cm^3. The maximum magnetic field is 0.64 T and is nearly uniform along the direction of plume expansion.[8] The target is placed at a distance of 1 cm from the pole edges, resulting in a uniform magnetic field along the plume's expansion direction.

Time-of-flight (TOF) studies of the plasma give vital information regarding the time taken by a particular state of the constituent to evolve after the onset of plasma. This technique gives details on the velocity and hence kinetic energy of the emitted particles and parameters that are of fundamental importance in establishing the mechanisms responsible for the particle emission.[8,13] To study the influence of a magnetic field on various species in the plasma, TOF profiles are taken at different distances from the target surface in the presence and absence of the magnetic field. Time-resolved studies were made for Sn^+ (335.2 nm, $5p^2\,{}^2D - 3f^2F^0$) and Sn (317.5 nm, $5p6s\,{}^3P_1^0 - 5p\,{}^{23}P_2$) species. Typical TOF profiles recorded for Sn at a distance of 13 mm from the target surface in the presence and absence of the magnetic field are

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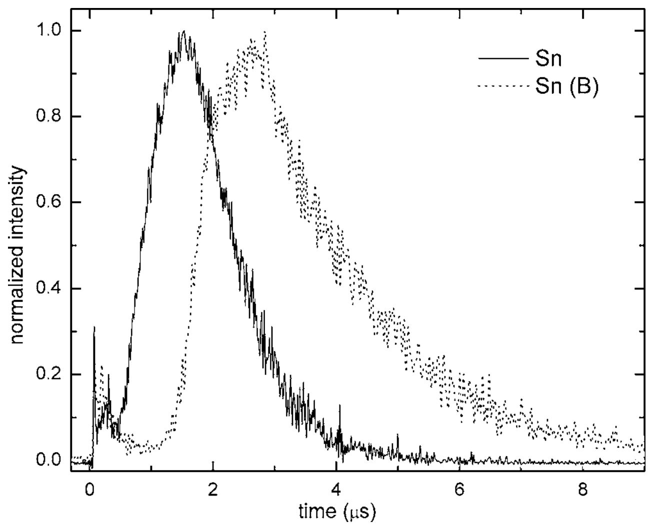

FIG. 1. Typical TOF profiles of Sn species recorded at a distance of 13 mm from the target surface in the presence (slowed one) and absence (faster profile) of magnetic field.

given in Fig. 1. The initial spike in the figure is due to scattering or prompt electron emission, and can be used as a time marker.[13]

The distance-time plots derived from the TOF profiles are given in Fig. 2. The laser irradiance used was 300 GW cm^{-2}. In the absence of the magnetic field the plume expands freely as indicated by the approximate straight-line fit in the *R*-*t* plots. The expansion velocities of the ionized species were found to be greater than the excited neutrals which is consistent with previous observations.[12] The maximum expansion velocities of Sn^+ and Sn in the field-free case were found to be $1.6\pm0.2\times10^6$ and $0.8\pm0.1\times10^6$ cm/s corresponding to kinetic energies (KEs) of 160 and 40 eV, respectively. When the magnetic field was introduced, KEs of all species were considerably reduced at distances greater than 3 mm. The velocity distributions of the species were weakly affected at shorter distances. This suggests that the magnetic field had very little effect on the early stages of the development of the plume, primarily because the plasma pressure greatly exceeded the magnetic pressure. In the presence of *B* and at larger distances (>5 mm), the Sn^+ were found to move with a reduced velocity of $0.9\pm0.1\times10^6$ cm/s (KE=50 eV) while the velocity of Sn species slowed to $0.5\pm0.1\times10^5$ cm/s (16 eV). The observed deceleration of neutrals and ions in the presence of the field is consistent with a magnetohydrodynamics (MHD) model in which kinetic energy of expansion is converted into random electron motion (Joule heating).[14] We also noticed that compared to the field-free case, the kinetic-energy distributions of the Sn species were significantly broadened.

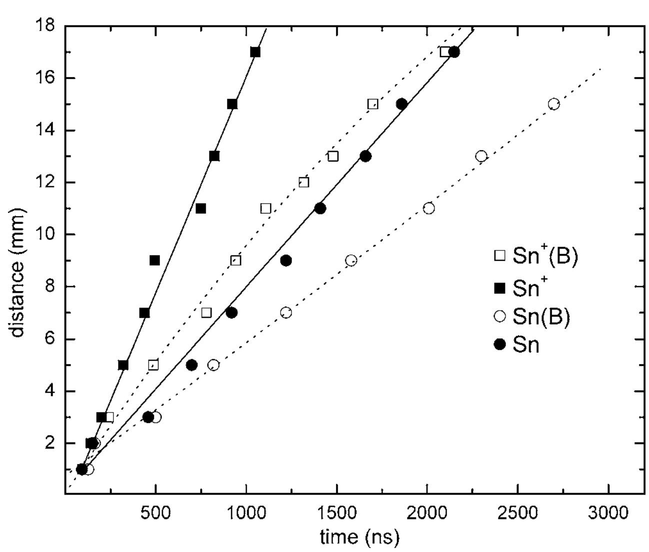

FIG. 2. The $R-t$ (position-time) for the Sn (●,○) and Sn^+ (■,□) species in the presence (hollow symbols, dot lines) and absence (filled symbols, solid lines) of magnetic field is given. The laser irradiance used is 300 GW/cm^2.

We estimated some important parameters of plume's expansion across the transverse magnetic field. The electron temperature (T_e) and density (n_e) of the tin plasma were measured employing optical emission spectroscopy using Boltzmann plots of Sn^+ line intensities and Stark broadening, respectively.[15,16] An initial temperature and density of about 3 eV and 6×10^{17}cm^{-3} were observed and rapidly decayed to much lower values within 200 ns. Visible spectroscopic studies also indicated that the bulk ion component within the plume was Sn^+, whose Larmor radius is ~3.5 mm. The estimated electron Larmor radius is very small (<1 μm). When a plume expands across a magnetic field the following parameters control the plume behavior, *viz.*, magnetic pressure ($P_B=B^2/2\mu_0$), thermal pressure ($P_T=nkT$), and directed or ram pressure ($P_d=nmv^2/2$). Our analysis showed that thermal beta (β_t) of the plasma approaches unity ~100 ns after formation of the plasma. Even though β_t approaches unity, however, TOF spectroscopic studies showed that the plume species propagate without much deceleration. After the initial conversion of thermal energy to directed energy, directed β (β_d) becomes an important parameter. The estimated β_d is observed to vary by several orders of magnitude within the expansion duration of the plume. In the early phase of the plume expansion, β_d is on the order of a few thousand, indicating that the plume is in the regime of diamagnetic expansion. Diamagnetic currents exclude the magnetic field from the interior of the plume, and may interact with the steady-state magnetic field through the $J\times B$ force, tending to inhibit plume expansion. The laser-produced plasma diamagnetic cavity (magnetic bubble) expands until the total excluded magnetic energy becomes comparable to the total plasma energy.

It is known that by varying the power density of the incident laser one can optimize the EUV in-band output of the emitting plasma. Hence, we analyzed the kinetic distributions of the species with laser irradiance ranges from 50 to 500 GW cm^{-2}. The selection of this laser irradiance range is based on the fact that the reported in-band emission from the Sn plasma is peaked around this intensity regime.[17] The variation of time delay with laser irradiance is given in Fig. 3 for two spatial points in the plume, *viz.*, 3 and 10 mm. At 3 mm, the expansion velocities of the species are approaching the same value both with and without the magnetic field at higher power-density levels. This indicates that plasma pressure scales with laser intensity and at high laser irradiance levels, the effect of magnetic pressure on plume

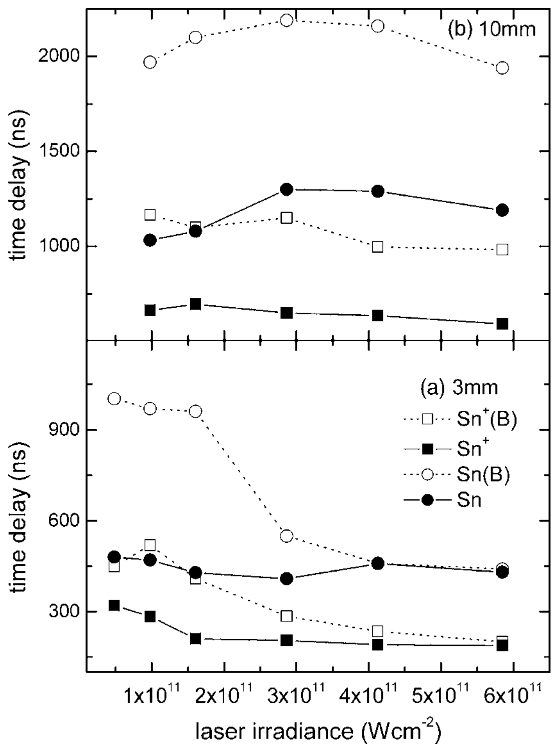

FIG. 3. The dependence on laser irradiance of the arrival time for Sn (●,○) and Sn^+ (■,□) species is given for B (hollow symbols, dot lines) and with out B (filled symbols, solid lines) for different distance from the target surface [(a) 3 mm and (b) 10 mm].

expansion is negligible at short distances. The difference between the velocities of the species is more evident at larger distances from the target surface where the plasma pressure is considerably reduced. From Fig. 3(b), one should also note that the delay of neutral species increases with laser irradiance (up to 3×10^{11} W cm^{-2}) which contradicts the standard observation of increased kinetic energy at higher laser intensities. This may be caused by selective depletion of high velocity neutral species with increase in laser intensity because of ionization. Pappas *et al.*[18] also observed similar behavior for C_2 species and explained as preferential dissociation by electron impact.

In the presence of the B, the kinetic-energy distributions of the neutral species are slowed down as well as broadened. In principle the field will not affect neutral species. However, collective effects in the plume as it expands across the field lead to enhanced collisionality, which may cause slowing of the atomic species. This is supported by the fact that the time histories of the neutral species are broadened in the presence of the field.

In conclusion, we investigated the use of a magnetic field for controlling the excited neutral and ions in a laser-produced Tin plasma. Time-of-flight optical emission spectroscopy was used for measuring the expansion velocities of plasma species in the presence and absence of the magnetic field. Our studies showed that the kinetic energies of the plume species were considerably reduced even at short distances with a modest magnetic field of 0.64 T. Optical emission spectroscopy is not a good tool for measuring the kinetic distributions of the various species at distances greater than 20 mm from the target surface because of low emission intensity. The ion electrostatic energy analyzer will be more useful for measuring the kinetic distributions of various ions in the plume at larger distances.[19] Nevertheless, our results indicate that the applications of higher-field permanent magnets or pulsed magnets will more effectively control the energetic ions and neutrals and it will be helpful in keeping the collector mirrors free from debris in a laser-produced plasma EUV source.

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