EUV Source Design Flexibility for Lithography

T Nishikawa¹, A Sunahara², A Sasaki³, and K Nishihara⁴

¹ Department of Electrical and Electronic Engineering, Okayama University, 3-1-1
Tsushima-naka, Okayama 700-8530, Japan
² Institute of Laser Technology, 2-6 Yamada-oka, Osaka 565-0871, Japan
³ Quantum Beam Science Directorate, Japan Atomic Energy Agency, 8-1 Umemidai,
Kizu, Soraku, Kyoto 619-0215, Japan
⁴ Institute of Laser Engineering, Osaka University, 2-6 Yamada-oka, Osaka 565-0871,
Japan

E-mail: nisikawa@elec.okayama-u.ac.jp

Abstract. We have studied why high conversion efficiency from YAG laser of 10 ns pulse
duration to EUV light of 13.5 nm of 2 % bandwidth is achieved by using tin oxide, while the
conversion efficiency is reduced into about 1 % by using simple tin target. In a plasma
generated by tin oxide, number density of tin becomes one half of that by tin if the electron
density profile is assumed to be the same. As a result, absorption of 13.5 nm emission at low
density corona region is suppressed and higher conversion efficiency is obtained. From this
discussion, more efficient targets for longer pulse YAG laser is proposed.

1. Introduction

For the next generation semiconductor lithography from 32 nm node, a device using extreme
ultraviolet (EUV) light with reflection optics is scheduled. As required power of EUV light of 13.5
nm of 2 % bandwidth is raised up to 180 W, EUV source using laser-produced plasmas (LPP) of tin
with pulse laser system becomes a most possible candidate. Since large part of the light source’s cost
is attributed to laser system, CO₂ and YAG laser are currently considered. Although we can expect
high conversion efficiency from laser to EUV light more than 3 % using CO₂ laser, available energy
per shot is small. This is simply because emission power is proportional to plasma density. Therefore,
higher repetition rate about 100 kHz is necessary. On the other hand, YAG laser-produced plasma is
relatively dense compared to CO₂ laser’s one, and therefore, about 10 kHz operation can be possible.
High conversion efficiency about 2 % has been obtained with laser pulse duration of 2.2 ns using
metallic tin target [3]. From the point of developing commercial product, 2 ns YAG laser system is
expensive. Okuno et al. showed that more than 2 % conversion efficiency from laser to EUV light
with YAG laser of 10 ns pulse duration has been obtained using tin oxide (SnO₂) [2]. If the laser can
operate with longer pulse duration, for example, about 10 ns, EUV source’s cost could be substantially
reduced. In this paper, we study differences between plasmas which are generated by tin and tin oxide
and clarify why the higher conversion efficiency is achieved by tin oxide target. For realistic EUV
source design, we propose new targets for YAG laser system from engineering point of view.

2. Power balance model

© 2008 IOP Publishing Ltd
Nishihara et al. have successfully explained conversion efficiency from laser to EUV light of 13.5 nm of 2 % bandwidth using the power balance model [1]. In the model, isothermal expansion in a plasma is assumed. In reality, owing to the large electron conductivity in corona region, isothermal expansion is almost realized in laser-produced plasmas although laser power is locally absorbed into laser’s cut off region. For planar geometry, self-similar solution on ion density $n_i(x,t)$ and velocity $v(x,t)$ can be obtained as

$$n_i(x,t) = n_0 e^{-x/c_s^t}, \quad v(x,t) = \frac{x}{t} + c_s,$$

where $c_s$ is ion sound speed, $n_0$ is the critical density where isothermal expansion begins, and usually it corresponds to laser cut-off density. Once laser pulse duration is determined, losses for the plasma kinetics, ionization, and radiation are determined. The total loss to sustain the plasma profile has been assumed to be input laser power. The various loss fluxes for tin plasmas as a function of laser intensity are shown in fig. 1. We can see that main loss in laser-produced tin plasmas is by radiation. The other losses due to ionization and kinetics are about one order of magnitude lower. This means that most of absorbed laser power is converted into EUV light.

In the case of YAG laser-produced plasmas, the critical ion density is about $10^{18}$ (cm$^{-3}$), since average charge state of tin is about tenth at electron temperature of 20 ~ 30 eV where maximum conversion efficiency is obtained. At maximum conversion efficiency (pulse duration is 2.2 ns), a peaked EUV spectrum around 13.5 nm has been observed by experiment. On the other hand, a EUV spectrum with dip around 13.5 nm has been observed when the laser pulse duration is 10 ns. From the numerical analysis of the power balance model and hydrodynamic simulations as well, this dip is owing to the absorption at low density region around laser-irradiating surface. From inside the region where laser energy is deposited in, peaked spectra are observed for both cases. Therefore, to seek an answer why high efficiency is obtained using tin oxide is deduced into seeking a reason why the absorption is reduced in the tin oxide plasma.

3. Differences between plasmas generated from tin and tin oxide

To see differences between plasmas generated from tin and tin oxide, we have calculated basic plasma properties. In the calculation, the average ion model with $(n,l)$ state has been used [1]. Population of bound electron is assumed to be in the local thermodynamic equilibrium to free state. In the case of laser-produced tin plasmas, the equilibrium assumption becomes not bad since ions are immersed in the intense radiation field of EUV range and rich electron density. More precise
calculation could be done if we can calculate atomic processes involving radiative excitation and ionization with hydrodynamics. In fig. 2, 3, and 4, plasma’s average ionization state ($Z^*$), number density of free electron, total energy of bound electron plus free electron as a function of electron temperature and number density of tin are shown. To avoid negative values, we used a definition that bound electron’s total energies of neutral tin and tin oxide are equal to zero.

From fig. 2, we can see that average ionization state of tin is not so different between two plasmas at electron temperature of 20 ~ 30 eV and ion number density less than $10^{18}$ (cm$^{-3}$). But from fig. 3 and 4, number density of free electron and electron total energy of tin oxide become two times larger than those of tin at the same range. This is owing to the oxygen addition. Oxygen’s average
ionization state could be considered as about five. Effect on oxygen addition is concluded that average ionization state of tin are not so changed, but electron density and total energy of electron becomes two times larger. Since wavelength of laser is the same, i.e., critical density is the same, and therefore, density profile of free electron does not change even if the plasma is generated from tin oxide. But number density of tin becomes one half from the plasma generated from tin of the same number density of electron. As a result, absorption around 13.5 nm at corona region is suppressed. Moreover, opacity of 13.5 nm range becomes smaller than that of the same number density of tin, especially in low density. At the surface of laser-produced plasmas, excited state population reduced owing to the radiative decay. This induces the above-mentioned absorption dip at 13.5 nm. In the tin oxide plasmas, electron collisional processes are emphasized compared to simple tin plasma due to the twice number of electron, and therefore, excited state population becomes larger. Radiation loss due to oxygen is small compared to that of tin since oxygen is low-z material. From fig. 1, main loss in tin oxide plasma is still owing to radiation of tin although ionization loss and kinetic loss of tin oxide becomes larger due to the existence of oxygen. Therefore, oxygen addition simply results in twice number of free electrons. By experiment, laser intensity which gives maximum conversion efficiency does not become one half, but that of tin oxide is $5 \times 10^{10}$ W/cm$^2$, while that of tin is $8 \times 10^{10}$ (W/cm$^2$).

As shown in fig.1, most laser power is converted into EUV light by tin. But to absorb laser power, substantial number density and scale length of free electron are necessary. If all free electrons are supplied by only emitting ion, the emission becomes optically thick easily. If some part of free electron is supplied from other ions and emitting power from the ions is small enough, optical thickness of required emission can be reduced. The ion of lowest radiation loss in EUV range is hydrogen. But hydrogen can supply only one electron. If stannane (SnH$_4$) with liquid hydrogen can be delivered as target material, a most efficient target for long pulse YAG could be realized. Hydrogen’s ionization potential is 13.6 eV, i.e., lowest among all ions. From the number of supplying electron, SnF$_4$ is another candidate. Fluorine is nearest neighbor of oxygen in the periodic table and SnF$_4$ is stable composite. But handling halogen might be another difficulty from engineering point of view.

4. Conclusions

We have studied why high conversion efficiency from YAG laser of 10 ns pulse duration to EUV light of 13.5 nm of 2 % bandwidth is achieved by using tin oxide, while the conversion efficiency is reduced into about 1 % by using simple tin target. Number density of free electron per one tin ion in tin oxide plasma becomes 2 times larger than that in tin plasma. As a result, optical thickness of required emission reduced at corona region. To realize the enhancement, emissivity of additional ions is required to be small compared to the ion which emits required EUV emission.

Acknowledgment

This work is performed under the auspices of Leading Project promoted by MEXT (Japanese Ministry of Education, Culture, Sports, Science and Technology).

References

[1] Nishihara K, Sasaki A, Sunahara A, Nishikawa T 2005 Conversion Efficiency of LPP Sources 
EUV Sources for Lithography ed V Bakshi (Bellingham, Washington: SPIE Press) chapter
11 pp 339-370

[2] Okuno T, Fujioka S, Nishimura H, Tao Y, Nagai K, Gu Q, Ueda N, Ando T, Nishihara K, 
Norimatsu T, Miyanaga N, Izawa Y, Mima K, Sunahara A, Furukawa H, Sasaki A 2006 
Appl. Phys. Lett. 88 161501

[3] Fujioka S, Nishimura H, Ando T, Ueda N, Namba S, Aota T, Murakami M, Nishihara K, Kang 
Y, Sunahara A, Furukawa H, Shimada Y, Hashimoto K, Yamaura M, Yasuda Y, Nagai K, 
Norimatsu T, Miyanaga N, Izawa I, Mima K 2006 Proceedings of SPIE 6151 61513