Microelectronic Engineering 23 (1994) 211–214
Elsevier

Issues of laser plasma sources for soft x-ray projection lithography

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Results of optimization of an excimer laser-induced plasma x-ray source for projection lithography in the range λ=13-15 nm are reported. A conversion efficiency of >0.7% in 2% BW has been achieved with high-Z target materials. Two methods of reducing contamination of optical elements by target debris have been tested: usage of a thin target layer (for Ta 1 μm was found to be optimal) and of a heavy buffer gas. The effect of the use of Ta-tape target and Kr buffer gas has been measured by determining the reflectivity of a Mo-Si multilayer sample after 10^5 shots.

INTRODUCTION

The rapid development of excimer lasers providing high average power increases the potential of laser plasma x-ray sources for soft x-ray projection lithography (SXPL) [1-3,7]. In relatively compact KrF and XeCl laser systems power levels as high as 300-400 W have been achieved at repetition rates 300-500 Hz [4]. Efficient utilization for SXPL of lasers of this new generation assumes solution of the problem of target debris for materials with highest efficiency of conversion of laser energy into narrowband x-ray radiation energy.This paper focuses on measurements of conversion efficiency of different target materials and on methods of suppression of debris.

EXPERIMENTAL ARRANGEMENT

1. Laser

The laser LPX350i cc used in this study has been designed for generating plasma soft x-ray radiation. It provides laser pulse energy (1-1.5 J) comparable to that of above mentioned lasers, but has a lower repetition rate (50 Hz). A non-planar cavity optics is used to achieve a lower beam divergence and consequently better focusing conditions. The laser consists of two heads which were assembled in this work as an injection-locking system: a narrow, low divergent beam from the oscillator was injected into the amplifier, resulting after triple pass amplification in a 1 J pulse with a divergence of 0.07×0.13 mrad. The pulse duration was 27 ns at FWHM, the maximum power amounted was 42 W at 50 Hz.

2. Laser plasma source

The laser beam was focused with a 10 cm aspherical lens in a vacuum chamber (Fig.1) on a thin (tape) target, moving by a computer-controlled mechanism, or on a massive target. Thin foils of different metals as well as (sub)micron layers of materials deposited on 25 μm plastic or copper substrates were investigated. The tape target system enables continuous operation in sessions of up to 10^6 pulses per tape. The vacuum chamber contains a CCD microscope for the control of laser beam focusing and target surface, multi-

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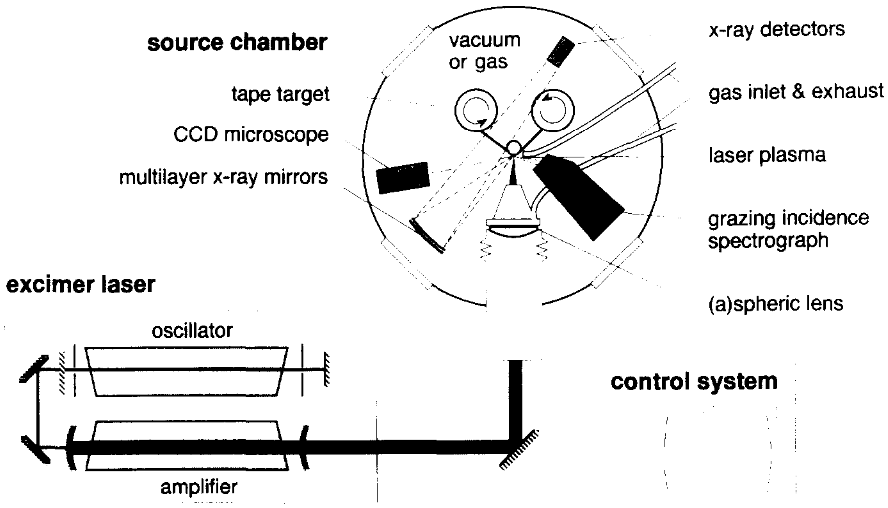

Fig. 1. Essential parts of the experimental facility

layer-based radiometric channels for x-ray intensity measurements; a compact grazing incidence spectrograph, used in this work for the range $\lambda \approx 12.5$-15 nm, and spherical multilayers coupled with a two-dimensional x-ray detector for plasma imaging. The chamber is equipped with a system enabling a gas flow near the target.

MEASUREMENTS OF PLASMA RADIATION

Absolute spectrally selective measurements of plasma radiation intensity were performed using principles of the technique described in [5]: calibrated semiconductor detectors (XUV-5, UDT Sensors Inc) in combination with Mo-Si spherical multilayer mirrors, reflecting x-rays in a narrow interval ($\Delta\lambda$=0.5 nm) at λ=13.2 nm. The detectors were protected from the laser light and long wavelength plasma radiation by submicron Rh and Mo filters. A narrowband time integrated conversion efficiency $\eta = E_{x\text{-}ray}/E_{laser}$ in 2% BW on a Ta target was found to be η=0.7%. This value was obtained with a focal spot size about 35 μm at a laser power density of 3×10^{12} W/cm^2, At the laser power 42W it corresponds to the average power of plasma radiation 300 mW in 2π sr in 2% BW.

Radiation spectra of many target materials were recorded in the range from 12.4 nm (L-edge of Si) till 15 nm, which is interesting for SXPL systems utilizing Mo-Si multilayer optics. A preliminary analysis of spectra has been done, showing a possibility to increase the efficiency of the source by at least 15% using a Re target.

Measurements of the laser and x-ray power performed with high time resolution (1 ns) have demonstrated an essential drop of the instantaneous conversion efficiency after about 15 ns since the initial moment of the pulse. The efficiency integrated over this interval appears to be approximately twice higher than the value of η for the full pulse duration. This result shows that an optimal pulse duration (obviously within 10-15 ns) is to be considered as an important issue of future laser developments.

MITIGATION OF CONTAMINATION PROBLEM

A critical issue is inevitable ejection from the target of debris particles (atoms,clasters, droplets), having a wide velocity distribution. Contamination of x-ray optics by debris leads to a drastic reduction of reflectivity. We investigated essential elements of two methods to solve the debris problem.

1. Tape target

The first method is the use of mass-limited targets such as thin tapes [6]. Apart from reduction of the total amount of debris, another essential effect is utilized in this case: a large fraction of the material is ejected through the hole, created by the laser pulse, into the volume behind the tape. In initial experiments [6] the use of a 60 μm steal foil resulted in reduction of the number of fast fragments (with energies sufficient for penetration through submicron plastic filters) by two orders of magnitude.

The minimum thickness of a target layer still giving the same x-ray yield as a massive target should in principle be equal to the laser ablation depth. To determine this value we measured the yield at 13.2 nm from plasmas created on samples with different thicknesses of Ta deposited on 25 μm plastic and copper tapes. The other experimental conditions were identical to those described above. The result is presented in Fig. 2. It is seen that the maximum yield , close to that of massive Ta target, requires a Ta layer of 1 μm. For smaller thicknesses the x-ray yield approaches that of the bare substrate. This experimental result is in agreement with estimations of the laser ablation depth using classical models [8,9].

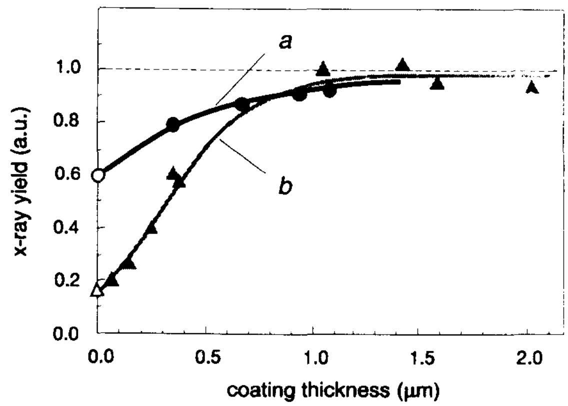

Fig. 2. X-ray yield at λ= 13.2 nm as a function of thickness of Ta layer deposited on a) 25 μm Cu tape, b) 25 μm plastic tape. The yield value 1.0 - for a massive Ta target. Open symbols represent the yield of the uncoated copper and plastic tapes.

2. Buffer gas.

The second measure to reduce the deposition of debris onto optical components is the use of a buffer gas (usually He [6,7]) in the source chamber. In the previous work with a source of subkilovolt radiation the amount of submicron particles at 77 mm from the target was reduced by a factor of 300 at 1 atm of He. That experience can not be applied directly to the case under consideration because of high absorption of low energy photons at atmospheric pressure. The stopping power of a gas at pressures below 1 Torr, sufficiently transparent for 13-15 nm radiation, is much lower. It can be enchanced by using a gas with a higher atomic weight. In this work we tested Kr as a buffer gas. The average fractional loss of kinetic energy of a heavy target atom (like Ta) in a collision with Kr atom is an order of magnitude higher than with He. This, together with considerably larger scattering angles should result in an improved stopping power. Krypton is relatively transparent for radiation below the $M_{IV,V}$ absorption edge from about 13 nm up to ~20 nm: for 13.5 nm radiation over a distance of 100 mm at a pressure of 0.25 Torr the calculated transmission is 95% (97% for He).

3. Contamination of test multilayer sample

We have studied the degree of pollution of a multilayer sample in a prolonged exposure session of 10^5 laser pulses. Both techniques considered above were applied. A Mo-Si multilayer mirror positioned at 240 mm from the plasma served as a monitor of the debris deposition rate. A Ta-foil with a thickness of 8 μm was used as a target. Krypton was admitted through an inlet pipe near the target (8 cm^3/min), the average pressure in the volume amounted to 0.25 Torr. After 10^5 pulses we measured reflectivity of the monitor mirror to be 82% of the initial value. This corresponds to a deposition rate of 25 ng/sr per shot on the sample at 240 mm, assuming the material is deposited as a uniform layer. Comparing the total mass of the material removed from the tape and the debris deposited on the multilayer we find a reduction of the deposition rate of a factor 150-200.

We found that scattering of debris atoms in Kr under the given conditions has resulted in a considerable reduction of their kinetic energies, i.e. in thermalization of particles. This was concluded from the weak sticking of the debris layer to the multilayer surface. By simple cleaning (flushing the surface with alcohol) we could remove the main part of the debris from the surface and restore the reflectivity up to 97% of the initial value.

These results are not sufficient for desirable technological exposures of x-ray optics of SXPL systems (comparable with 10^9 pulses typical for an excimer laser maintenance period).

An obvious development of the Kr buffer gas technique is to create a sufficiently fast flow (jet) of gas capable to drag thermalized debris atoms out of the acceptance angle of the optics.

CONCLUSIONS

We have demonstrated a high average soft x-ray yield of a laser plasma source driven by a compact, application-specific KrF laser with pulse energies of 1-1.5 J. A conversion efficiency of >0.7% has been measured for 13.2 nm radiation in a 2% bandwidth. The experimental facility including a computer-controlled tape target unit has been tested in long exposures.

An optimal thickness of a high-Z material layer -1 μm of Ta - in a tape target composition has been determined.

The use of Kr as a heavy buffer gas has been proposed as an alternative to He for the spectral range 13-15 nm, perspective for SXPL. The effectiveness of Kr has been tested by monitoring the decrease of reflectivity of a multilayer mirror exposed to debris in 10^5 laser pulses. Over this exposure the reflectivity decreased to 82% of the initial value, but could be restored by simple cleaning.

ACKNOWLEDGEMENTS

This work is part of the programme of FOM (the Foundation for Fundamental Research of Matter) and STW (the Technology Foundation) of the Netherlands. The work is made possible owing to financial support of the Netherlands Government trough NWO (the Netherlands Organization for Scientific Research) and in the framework of EUREKA.

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