Mass limited laser plasma cryogenic target for 13 nm point x-ray sources for lithography

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ABSTRACT

We propose the use of mass-limited, line emitting cryogenic targets for SXPL, which permit a continuous supply of targets without the problem of particulate debris and excessive heating of multilayer optics by an intense x-ray flux in wavelength regions outside the multilayer bandwidth. In preliminary experiments we measured the oxygen line emission in the vicinity of 13 nm. The x-ray emitting plasma was produced by using a laser intensity of 2×10^{12} W/cm^2 on the surface of an ice target. From the observed crater on target we can deduce that clusters are also ejected from cryogenic targets.

1. INTRODUCTION

At the present time, it appears that the most likely source to be used for soft x-ray projection lithography is a high repetition-rate (about 1200 Hz) laser plasma source[1]. The design of this kind of sources is usually envisaged as comprising a compact high repetition-rate laser and a renewable target system capable of operating for prolonged periods of time. For a production-line facility, this would imply uninterrupted shot cycles of $>3 \times 10^9$ shots. Current cost scenarios of the complete irradiation system suggest that the unit shot cost must be in the vicinity of \$$10^{-6}$ per shot[2]. These stringent requirements press the boundaries of current technologies. Moreover, recent studies of the particulate matter ablated from solid and tape targets under laser irradiation conditions similar to those deemed optimum for 13 nm soft x-ray generation, suggest that these types of targets will be unsuitable[3]. The levels of neutral clusters of particulate matter and of high velocity ions are many orders of magnitude above those that can be tolerated in an environment requiring the long-term preservation of expensive, high-reflecting multilayer collecting optics. Thus, it is our viewpoint that considerable progress must be made in the design of efficient soft x-ray-emitting laser plasmas for them to satisfy the needs of projection lithography.

We introduce a new concept of a high repetition-rate soft x-ray laser plasma source for projection lithography, that is, the mass-limited cryogenic target. We commence with the premise that the optimum target for minimum debris production is one whose mass is limited to that of the minimum number of ions required for efficient x-ray generation. This precondition implies target masses as small as about 50 ngm per shot for typical laser and x-ray conversion factors. If the target were configured as a disc, for instance, with a diameter of about 100 μm it would have thickness of <500 nm, equivalent to the plasma ablation depth. To configure this small mass as an isolated solid target and locate it precisely in the focal region of the laser beam under the required cost and operating conditions is technologically difficult. According to our recent experimental results we expect not only a serious debris problem from high Z solid targets but also excessive heating of x-ray optics in the case of broad band emitters. The emission is centered around 13 nm but exceeds the required bandwidth several times. The distortion of the expensive multilayer x-ray mirror caused by the off-band heating was considered as a serious danger for the x-ray collecting system, and we predict the same heating for the first multilayer mirror of lithography optics. The target we propose in this paper emit narrow spectral limits in the vicinity of 13 nm and reduce the heat load on the first x-ray mirror.

A mass-limited cryogenic gas target that emits strong line emission as a laser plasma target of a high repetition rate x-ray source for a production line soft x-ray lithography system will circumvent the principal problems associated with current configurations[4]. The notion of using cryogenic Xe ($Z = 54$) or Kr ($Z = 36$) as a laser plasma target for x-ray generation for lithography in the 0.5 - 1.0 nm wavelength (1.2 - 2.5 keV) range was first introduced by Mochizuki et. al[5,6]. They suggested that this approach might eliminate the problem of laser sputtering of laser target material on optical surfaces, and showed that the broadband x-ray emission of Xe at wave-lengths shorter than 0.8 nm was as expected when compared with that of other materials at 531 nm wavelength laser pulses (1 ns) at an intensity of 10^{14}W/cm^2.

A target mass-limited to the minimum number of radiating ions will eliminate the generation of high-velocity particulate projectiles. This will remove the primary threat to expensive state-of-the-art high reflectivity x-ray mirrors used to focus the soft x-ray emission onto the reflective mask. The plasma ions that are generated (~ 10^{16} ions) can then be impeded in their ballistic trajectories from the plasma by collision with a background gas, or deflected to benign locations with the aid of electric or magnetic fields.

A limited mass cryogenic target system could, in principle, function continuously at a cost commensurate with the required unit shots costs. This offers distinct advantages over target assembly approaches that use solid targets or tape-drive targets, which would require periodic system deactivation for target replacement. It has also been shown that these target system approaches will have difficulty meeting the single shot costs required[3]. On the other hand, cryogenic targets can be configured with continuous automatic target fuel replenishment permitting unimpeded x-ray source operation on the production line. With the use of inexpensive gases, this concept should also be able to provide targets at a unit cost attractive for soft x-ray projection lithography.

2. CONSERVATIVE REQUIREMENTS FOR A HIGH REPETITION-RATE LASER PLASMA SOFT X-RAY SOURCE

In the following, we discuss the minimum number of ions required to produce enough x-ray flux and the maximum mass build-up that can be tolerated from a laser-plasma x-ray source designed for continuous operation on a production-line lithography facility.

2.1. Minimum number of laser plasma ions

Considering the implications of the first premise of the concept of the mass-limited cryogenic target, we believe that the optimum target mass is the mass of the minimum required number of atoms to radiate, when ionized, at the desired wavelength. A 1200 Hz source operating with a soft x-ray conversion efficiency of 1% of the total laser energy (about 1 J) into a 3% spectral bandwidth around 13 nm, the wavelength of current choice for soft x-ray projection lithography will provide a total flux of 10 mJ per pulse of useful x-rays (6.3×10^{14} photons of energy 100 eV), with a total useful x-ray power output of 12 W. Using an f/2.0, double mirror collector optical system each of reflectivity 60%, a flux on the mask is implied to be 0.0675W (or 3.5×10^{12} photons per pulse). On the assumption that all the laser energy is absorbed in the plasma, and that the mean temperature of the plasma is about 100 eV, then the minimum mass required is about 50 ngm. Were this target configured as a thin disc, for example, with a diameter of 100 μm, the optimum thickness would be <500 nm.

2.2. Maximum tolerable number of ions emitted from the target.

We now consider the maximum tolerable number of ions emitted from the target that can be deposited on an x-ray mirror surface during the course of regular operation in a high repetition-rate projection x-ray lithography illuminator. Assume that the total number of target shots (N) that the mirror must be exposed to without replacement or repair is 10^{10} shots (a 1200 Hz source operating for 100 days, 24 hours a day).

The principal effect of the high energy ions emitted from the target is to coat the mirror surface with a layer of target material. It is assumed here that the ions do not seriously deteriorate the integrity of the multilayer mirror itself[7]. This coating will introduce an additional x-ray absorbing material in the path of the x-rays from the target, and thereby reducing the x-ray flux illuminating the mask. Thus the maximum layer thickness of target material that can be allowed to build up on the mirror depends on the target material used. High Z materials will be greater x-ray absorbers than low-Z materials. As an approximation, assume that the maximum buildup of material of density on a mirror situated a distance of r (r = 20 cm) from the target over the operating period is ds = 10 nm. Then the maximum mass of particles per shot, dm emitted from the target that can reach and stick to the mirror is

$$dm = 4 \pi r^2 (ds / N) \rho = 5 \times 10^{-13} \rho \text{ gm}$$

where ρ is the density of the material.

From this we can calculate the maximum number of ions emitted from the target that would lead to a buildup of ds on the mirror. This is

$$N_i = dm N_o / m_o$$

where N_o is Avagadro's Number and m_o is the atomic weight. This gives a value of N_i about 10^{11} for the parameters chosen. This implies that only one in every 10^6 ions emitted from the limited mass target that we have specified above must be allowed to stick on the mirror.

To make an estimation of the number of ions that will reach the mirror and attach to it depends on a large number of factors. These include a knowledge of the velocity distribution of the ions emanating from the plasma, the pressure of any background gas included in the chamber to slow the progress of the ions, the efficiency of the pumping system in extracting the ablated mass and the sticking factor of the mirror surface materials. One and two-dimensional hydro-dynamic plasma codes can be used to estimate the ion velocity distributions, and the effects of background gases and pumping speeds can be calculated. Those ions that are not stopped by collisions with the gas will hit the mirror surface. The sticking factor of these ions is dependent on their ion state and velocity at the surface of the mirror, and the materials from which it is made.

3.CRYOGENIC TARGETS FOR A HIGH REPETITION-RATE PLASMA X-RAY SOURCE

There are several distinct advantages to the use of mass-limited cryogenic targets as the x-ray source for soft x-ray projection lithography. Firstly, targets that are in the solid phase at low temperature allow that clusters or particulate matter from the target region can be in the gaseous phase, thereby pose less danger to x-ray collection optics and are more likely to be extracted by efficient pumping. Thus it is possible to achieve high x-ray conversion efficiency with solid cryogenic targets while at the same time, reduce the impact of debris to x-ray optics. Secondly, some of the cryogenic targets that we are proposing here consist of molecules of low Z elements (H_2O and CO_2). Soft x-ray radiation from these targets arises mainly from highly ionized states and contain narrow intensive lines as opposed to the broadband emission that is emitted from high Z solid material such as Sn. This can be very important in reducing the off-band heating to the x-ray mirror. Lastly, it will be possible to construct a cryogenic target system that runs continuously and therefore will not require periodic interruption of its operation for target change and maintenance.

3.1. Candidate cryogenic gases.

The principle gases being considered as materials for a high repetition rate limited-mass laser-plasma target system for projection lithography at a wavelength of 13 nm are shown in Table 1. The gases Kr and Xe have previously been considered as laser plasma target materials for x-ray sources in the 0.5 - 1.0 nm range for proximity print lithography[5,6]. Both these gases and Ar have also been suggested as broadband x-ray source materials for soft x-ray projection lithography systems[4]. Target materials that emit strong x-ray lines in the vicinity of 13 nm are oxygen and fluorine. The latter has several practical and environmental disadvantages. He- and Li-like oxygen emits strong soft x-ray lines in the vicinity of 13 nm (n = 3 to n = 2 transitions for He-like and n = 4 to n= 2 transitions for Li-like oxygen , respectively). As a constituent of either solid or liquid carbon dioxide or water, it could be a practical high repetition rate target material.

Table 1.Candidate Cryogenic Gases

	Melting Temp. (^{o}K)	Boiling Temp. (^{o}K)
Kr	116	120
Xe	161	165
Ar	84	87
CO_2	216(@5atm.)	195
H_2O	273	373

3.2 Reduction of off-band x-ray heating to x-ray multilayer mirror

The broadband soft x-ray radiation from high Z solid targets exceeds the multilayer mirror bandwidth many times and could cause a decrease of the its reflectivity. The multilayer mirrors used in the collecting and imaging systems for projection lithography have high reflectivity within a bandwidth of only 0.3 - 0.4 nm centered at 13nm. Most of the x-ray radiation from high Z targets falls outside of this bandwidth. The radiation from the target that is not reflected by the first collecting mirror is absorbed by its multilayer coating. For a high repetition-rate system this so-called off-band heating of the mirror can result in the thermal distortion of the mirror surface, distortion or change of the layer spacing of the multilayer mirror layers, and even physical damage of the mirror.

A temperature rise in the multilayer mirror by thermal loading may cause a phase change of the mirror materials, which, in turn, would affect its reflectivity. For a Mo/Si multilayer, which is mostly used for 13 nm projection lithography, Mo is usually the top layer. If the absorption in this layer to off-band radiation is 10%, the energy absorbed by this layer is $6\text{x}10^{-3}$ mJ/pulse/cm^2, i.e., 1.5×10^{-6} cal./pulse/cm^2. For a 3.6 nm thick upper Mo layer, the mass aerial density is 3.7×10^{-6} g / cm^2. Since the specific heat of Mo is ~ 0.065 cal./g °C, the heat capacity of this layer is therefore 4.8×10^{-8} cal./ °C. Thus the temperature rise of the top Mo layer would be about 6 °C/ pulse.

For a Sn target irradiated by the laser conditions referred to above, we can estimate the thermal loading of the first mirror. We assume that the total x-ray conversion efficiency is ~30% and that 50% of this energy is absorbed by the mirror. If it is located 20cm from the source, then the soft x-ray power density on the mirror will be ~75mW/cm^2. For a mirror of one inch in diameter, the total thermal loading would be ~480mW.

Thermal loading can cause distortion of the multilayer mirror surface. This distortion will result in the decrease of a multilayer reflectivity by shifting the phase of the wavefront reflected from different layers. Hawryluk[8] et. al. calculated a maximum permissible x-ray power of 62.5mW to a SXPL optic having an aspect ratio of 4:1 and thermal properties similar to ULE(ultra low-expansion material from DuPont) by assuming that the maximum tolerable thermally induced distortion coefficient δ on the mirror to be ~0.1 nm. The dependence of δ on the loaded power is[8]

$$\delta = 1.6 \times 10^{-3}\ (\text{nm/mW})\ q\ (\text{mW})$$

where q is the thermal power. From this expression, we estimate a value of 0.8 nm for a Sn target operating as an SXPL source.

There are hence advantages to be gained from using low Z laser plasma targets for reducing the level of off-band heating. The use of line radiation from He-like and Li-like ions which have narrow spectral bandwidth(~1A) would accomplish this.

The best emitter of this radiation in 13 nm spectral region is oxygen. Configured as a solid CO_2 or H_2O, these targets would reduce the off-band x-ray flux on and the heating to the x-ray optics.

3.3. Reducing the damage effect of debris

Reduction of the debris level of the target is a very important issue in the application of the laser produced plasmas as a source for soft x-ray projection lithography. The major damage to the x-ray optics resulting from the use of high Z targets (such as Sn and W) could be coating of these materials to the multilayer. This coating will introduce an additional x-ray absorption as well as a phase shift in the wavefront, and thereby reduce the reflectivity of the multilayer mirror. On the other hand, cryogenic gas of low Z material such as hydrogen and oxygen will produce debris that will be vaporized in a short time and can be pumped out of the vacuum system before they hit the x-ray optics. Even if this material reaches the x-ray optics, it will eventually be vaporized, causing no change to the reflectivity of the mirror.

The multilayer x-ray mirror can also be damaged by high velocity particles ejected from the target. These particles have very high momentum and damage the mirror physically and permanently by transferring their momentum rapidly to the mirror. Recent studies[9] on the debris characteristics indicated qualitatively that the velocity distribution of the debris particles may not depend strongly on the target material, since the atomic weights of hydrogen and oxygen are 1% and 10% of that of tin we can therefore expect that the momentum of the debris from the ice target would be much less than tin. The use of an ice target will therefore reduce the chance of physical damage to the mirror.

3.4. Reduced the cost of the operation

The unit cost limitation of operating the target system for SXPL were estimated[2] to be $\sim\$10^{-6}$/shot. Water is the cheapest substance for the target selection and the cost of the freezing water system in practical lithography system will also be low. Thus it is possible to meet the unit cost requirement by choosing ice as the target material for soft x-ray projection lithography. The water freezing system can be made such that it can operate continuously, thereby deminating the need to interrupt the system operation for target change.

4. CALCULATIONS OF EMISSION SPECTRA.

The characteristics of the spectral emission from a laser produced plasma source depends on the laser parameters, such as laser wavelength, laser intensity ,the laser pulse shape and duration, and also on the target geometry and composition. We use the one-dimensional Lagrangian hydrodynamic code MEDUSA[10] to simulate numerically the plasma conditions (electron temperatures and densities) for different laser and target conditions. A second codes, RATION[11], are used to estimate the ion population and the spectra radiation from the plasma. It takes the plasma parameters as input variables and calculates the ion populations in the different ionization stages, the various excitation and de-excitation coefficients and the resulting emission from Hydrogen-like, Helium-like and Li-like ions at the given plasma condition. Laser-produced plasma has a very high electron temperature and density gradient, the simulation of the radiation spectra from the laser plasma for given laser and target conditions need the integration of the above two codes. We have coupled these two codes and created a new code, called COUPLING, which calculates the time- and space-integrated spectra of the laser produced plasma. In the current version, radiation capture is not included. This code is used to target materials from carbon to iron, which are set by the RATION codes. A typical spectra output from COUPLING for a Nd:Glass laser and an oxygen target is shown on the bottom of the Fig.1.

5. SPECTROSCOPIC CHARACTERIZATION OF ICE & TIN TARGETS IN THE WAVELENGTH REGION 5-20 NM

The experimental facility we have constructed to analyze the x-ray and plasma emission characteristics of these targets is shown in Fig. 2. X-ray emission from the target is currently being analyzed with an array of instruments. These include specially constructed calibrated soft x-ray diode detectors, with double x-ray multilayer/filter combination for wavelength

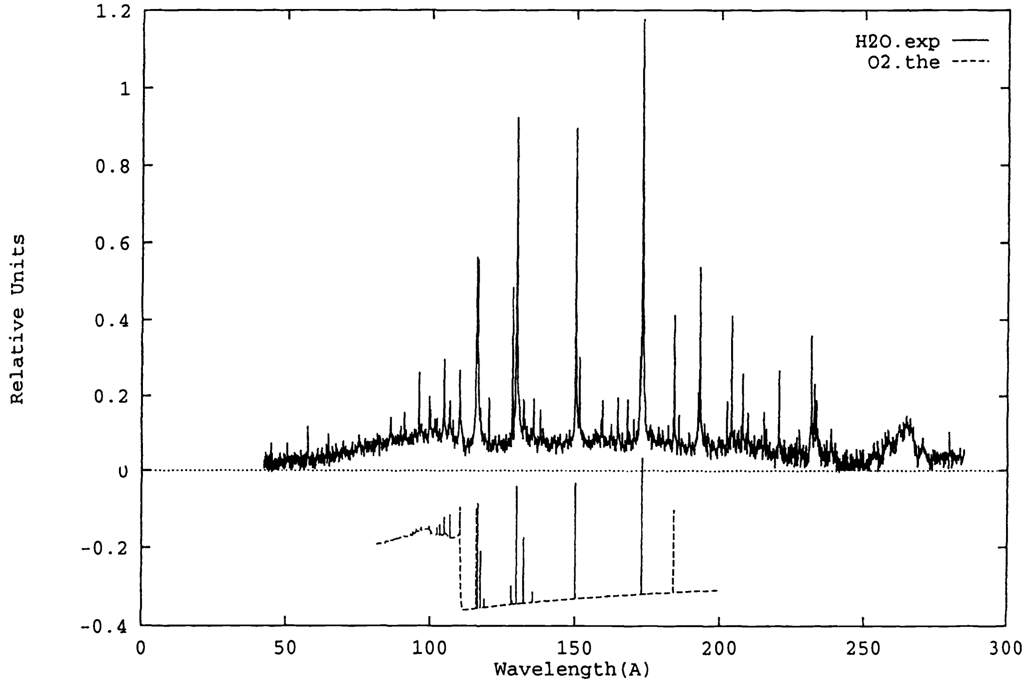

Figure 1. Ice spectra and COUPLING output of He-like and Li-like oxygen

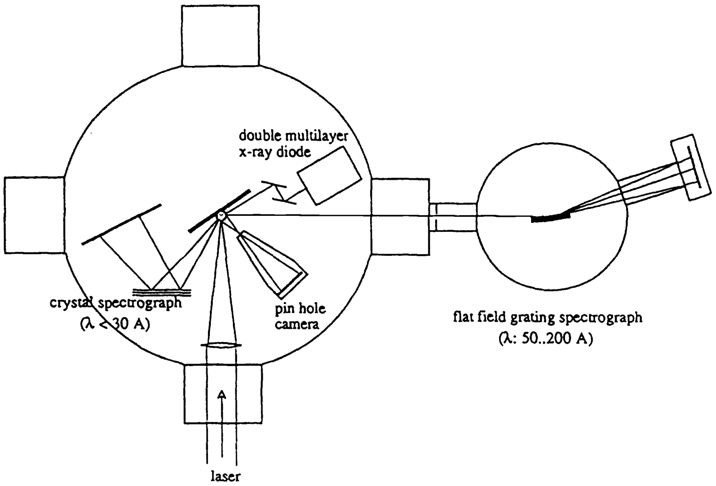

Figure 2. Experimental system for optimizing laser-plasma line emission at 13 nm

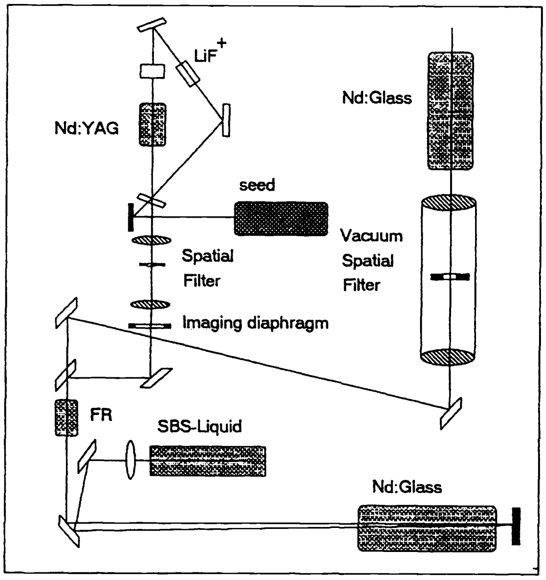

Figure 3. Laser oscillator and Amplifier set-up

selectivity which have sensitivity only within a narrow (0.4 nm) wavelength band in the vicinity of 13 nm. High resolution soft x-ray spectroscopy of the laser plasma x-ray emission is made with a flat-field grating spectrograph[12]. Other x-ray instruments include a crystal spectrograph for plasma diagnostics using He_α, intercombination and Li-like satellite line ratios, an x-ray pinhole camera to photograph the plasma emission region, and filtered PIN-diode detectors (not shown) to determine the time duration of the high energy x-ray emission. In the future it is planned to deploy ion and plasma debris measuring instrumentation to make quantitative measurements of the particulate emission.

A 3 J, 10 ns laser pulse (λ=1.06 μm) was focused with an f=14 cm lens on target. The set-up of the laser oscillator and the amplifiers is shown in Fig. 3. An intensity of ~10^{12} W/cm^2 was obtained within a 200 μm diameter spot. The x-ray emission from the created plasma was analyzed with the FFG spectrograph. Spectra were recorded on KODAK 101-07 x-ray film.

We used distilled water frozen in a petri dish to produce an ice target. Strong x-ray emission was found in transitions to the $1s^22p$, $1s^22s$ states respectively from different excited states of Li-like oxygen. The $1s^22p$-$1s^24d$ transition at 12.98 nm is very bright (see Fig. 1) as it was expected from COUPLING calculations (note: the spectra in Fig.1 is not normalized with the grating efficiency). Several weaker lines around 13 nm were identified as transitions to the 1s2p level in He-like ions. The recorded tin spectrum (upper part of the Fig. 4) shows the expected strong x-ray emission in a broad wavelength band exceeding the required bandwidth of 0.5~1.0 nm at 13 nm many times. From Fig.4, we can also see that the optical density at 13 nm for tin and ice are 1.00 and 0.95 which corresponding, respectively, to 2.5 and 2.2 photons/μm^2[13]. Thus, although the recorded oxygen lines are instrument-limited, since the width of the spectra feature at 13.0 nm has a spectral width of ~0.3 nm, we can say that the ice target is as efficient as the tin target as a 13nm radiation source for SXPL. Although very simple in construction, we found that our ice target was stable over a period of at least 3 hours after evacuation of the target chamber. The thickness of the ice changes only about 0.5mm per hour. Inspection of the crater following the shot indicated that the debris from this target probably consisted of clusters.

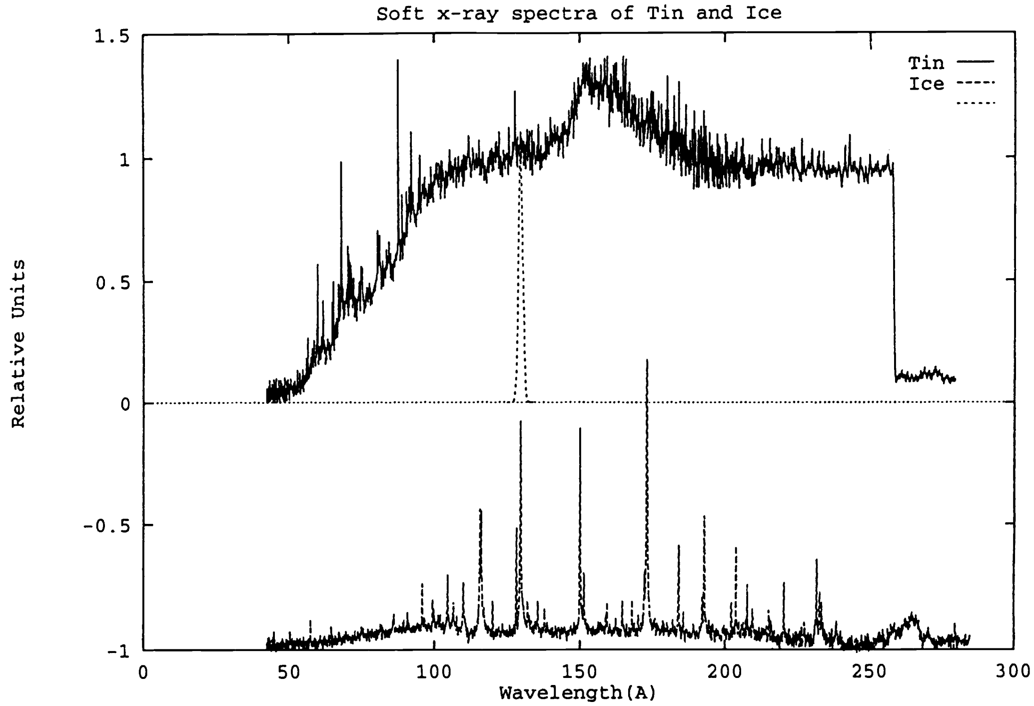

Figure 4. Soft x-ray spectra of tin and ice.

6.SUMMARY

We have discussed here initial results supporting the concept of using mass limited laser plasma cryogenic targets to produce strong line emission at 13 nm as a high repetition rate x-ray source for projection lithography. This approach is promising as a laser target medium for low cost uninterrupted operation over the long time periods required in production environment.

We successfully tested a simple cryogenic ice target and found strong x-ray line emission at 12.98 nm in Li-like oxygen. The first version of the COUPLING code can now calculate the radiation spectra from laser produced plasma. The result shows the very good agreement with the experiment. The observed crater indicated that clusters might be present in the created debris. Further experiments are necessary to optimize the line emission at 13 nm especially to increase emission in He-like ions, and to investigate the debris in more detail. It now seems very likely that even cryogenic targets must be mass-limited to protect lithography x-ray optics from particulate emission.

We have raised the issue of x-ray optics heating due to a very intense x-ray flux observed from broad band emitters like ions of Sn, and suggest that further theoretical and experimental investigation of these topics are necessary.

We expect the eventual target in a production line facility to be a compromise of conversion efficiency and x-ray optics protection, which makes narrow band line emitters a promising candidate.

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