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AUTHOR(S): R. D. Fulton, J. Abdallah, J. C. Goldstein, M. E. Jones,
D. P. Kilcrease, J. M. Kinross-Wright, S. H. Kong, and
D. C. Nguyen

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Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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A Debris Free, Electron Beam Driven, Lithography Source at 130Å

**R.D. Fulton, J. Abdallah, J.C. Goldstein, M.E. Jones, D.P. Kilcrease,
J.M. Kinross-Wright, S.H. Kong, and D.C. Nguyen
Los Alamos National Laboratory
P.O. Box 1663, Mail Stop D410
Los Alamos, NM 87545**

Introduction

Most of the proposed extreme ultraviolet lithography (EUVL) sources utilize the interaction of some high energy density source, i.e. a laser, electron beam, or arc discharge, with a solid target. EUV can be efficiently generated by these techniques, but debris from the interaction region impacting on the reflective optics can substantially degrade the performance of the condenser system. Los Alamos and Grumman are cooperatively investigating a debris free source^{1,2} for EUV lithography. This source utilizes the predicted anomalous energy loss^{3,4} of a short pulse electron beam in a preformed plasma to heat and ionize the ions to a charge state where efficient radiation at 130Å occurs. Accelerators⁵ developed for the free electron laser program at Los Alamos are used as the electron bunch source. These accelerators use a laser driven photocathode to produce 15 psec electron bunches containing 4 nC of charge with an energy of 15.5 MeV. These micropulses are produced at a repetition rate of 108 MHz and continue for the length of the rf macropulse energizing the accelerator cavities, typically 1-10 µsec. The weakly ionized preformed plasma is created by purely classical collisional ionization caused by the initial few electron micropulses within the macropulse. When a critical electron density is reached, $n_e \approx 1.6 \times 10^{15} / \tau^2 \text{ cm}^{-3}$, where τ is the FWHM, in psec, of the electron bunch, the plasma responds collectively to the electron micropulse generating a large amplitude plasma wave. The plasma wave efficiently slows the high energy electron beam while heating the background plasma electrons. The initial electron population rapidly heats and then equilibrates with the bulk ion and electron populations in a few 10's of picoseconds. With neon as the dominant ionic species, an efficient filamentary radiator of line radiation near 130Å is created.

The above scenario requires an initial neutral density of 10^{19} cm^{-3} to efficiently transfer the energy deposited in the initial 10^{16} cm^{-3} electron population to ionic

excitations. The required electron bunch length to couple to this initial electron density is 0.65 psec. A time-of-flight electron buncher which utilizes the energy spread created in the acceleration process is now under development to compress the initial 15 psec bunch to 0.65 psec. A proof-of-principle experiment has been completed to demonstrate the anomalous energy loss process and benchmark theoretical calculations at the much lower densities appropriate to the existing 15 psec electron bunches. We will discuss calculations and experiments in the low density, long pulse regime that our apparatus will currently access and then present calculations relevant to the high density, short pulse regime required for a lithography source.

Low Density Experiment and Calculation

Initial experiments are ongoing at the Advanced Free Electron Laser (AFEL). The unmodified electron bunch length is 15 psec which implies a critical electron density of $7 \times 10^{12} \text{ cm}^{-3}$. We create a target plasma of this density by injecting a string of 1-10 micropulses, each containing 4 nC. A target cell containing 200-500 mTorr of argon is collisionally ionized by the first few micropulses to the 0.1% ionization level required to produce the critical electron density for this pulse length. The electron density is determined by means of a 94 GHz microwave interferometer. The plasma target is isolated from the ultra high vacuum accelerator structure by 1 μm thick parylene windows.

Figure 1. Calculated fractional energy loss for 15 psec pulse

Calculations of the response of the atomic systems indicate that extremely long timescales are required for the plasma to recombine at the low fill pressures needed for the 15 psec bunches. This means that subsequent micropulse bunches will interact with different plasma conditions and require time resolved diagnostics to measure the energy loss at each electron density. Some modifications of the photocathode drive laser and beam diagnostics were made to support this mode of operation. The laser pockel cells

were modified to slice one to ten laser pulses out of the mode-locked train thereby producing one to ten electron bunches per rf macropulse. The gain was increased on the spatial and temporal beam monitors to enable visualization of a single pulse. Finally, a new electron energy spectrometer was created by utilizing the beam position monitor downstream of the existing spectrometer bending magnet. The beam position monitor measures⁶ both transmitted current and the beam spatial centroid. Calibrating this position as a function of energy with no plasma creates an accurate spectrometer that is not sensitive to the angular scatter induced in the transmitted beam by the plasma target.

Simulations with ISIS, a 2 1/2 dimensional, cylindrically symmetric, particle-in-cell code, of the interaction of the high energy electron bunch with the initial plasma have been carried out⁷ for the low density regime and indicate approximately a 2.5% mean energy loss for a 10 cm long target plasma. Figure 1. shows the predicted energy loss as a function of target plasma length at an electron density of $6.7 \times 10^{12} \text{ cm}^{-3}$. Figure 2. shows the measured fractional energy loss in a 10 cm cell for two different fill conditions: 200 and 500 mTorr of argon. The 500 mTorr data illustrates the effect of damping of the electron plasma wave due to electron neutral collisions on the energy loss efficiency.

Figure 2. Measured fractional energy loss for two neutral fill pressures

High Density Calculations

We are designing a buncher to install on an existing lower energy accelerator previously used in the Los Alamos FEL program. The accelerator/buncher combination is designed to provide 8 MeV, 3 nC electron bunches with a 0.65 psec temporal width. The energy was chosen so that activation by the electron beam would not be an issue for a commercial system. Numerical calculations similar to those described above were completed for this case with the dramatic result that an energy loss of 80% is predicted for an interaction length of 2.5 mm. These results indicate that a subpicosecond electron beam can strongly heat a plasma. Numerical calculations of the spectrum produced by an initial population of

10^{19} cm^{-3} neutral neon atoms are performed assuming that the initial electron distribution is thermal containing the energy deposited by the high energy electron micropulse. A time integrated spectrum for the first 100 psec after the interaction is shown in Figure 3. The appearance of several strong lines in the range of 10-20 nm indicates a significant population of Ne^{+6} .

Figure 3. Time integrated spectrum from Neon target

Conclusions

Los Alamos and Grumman are developing a debris free extreme ultraviolet source suitable as a lithography source. Initial experiments to verify the anomalous energy deposition process have been completed. Experiments to demonstrate a prototype device will commence soon. This work was performed under the auspices of the U.S. Department of Energy. A portion of the results presented in this paper have been generated in the course of a LANL CRADA with Grumman, No. LA93C10102.

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