OPTIMIZATION OF HIGH AVERAGE POWER FEL BEAM FOR EUV LITHOGRAPHY APPLICATION *

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Abstract

EUV source community is interested in evaluating an alternative method based on high repetition rate FEL, to avoid a risk of the potential source power limit by the plasma based technology. Present SASE FEL pulse (typically 0.1mJ, 100fs, 1 mm diameter) has higher beam fluence than the resist ablation threshold, and high spatial coherence which results in speckle and interference patterns, and random longitudinal mode spikes of high peak power micro pulses, which is not favourable to resist chemistry. This paper discusses on the required technological assessment and lowest risk approach to construct a prototype, based on superconducting linac and cryogenic undulator, to demonstrate a MHz repetition rate, high average power 13.5nm FEL equipped with specified optical components, for best optimization in EUVL application, including a scaling to 6.7nm wavelength region.

INTRODUCTION

Extreme Ultraviolet Lithography (EUVL) is entering into the high volume manufacturing (HVM) stage, after intensive research and development of various component technologies like Mo/Si high reflectivity mirror, chemically amplified resist, and especially high average power EUV source from laser produced plasma at 13.5nm. Semiconductor industry road map requires a realistic scaling of the source technology to 1kW average power, and further wavelength reduction to 6.7nm. It is recently recognized by the community of the necessity to evaluate an alternative approach based on high repetition rate FEL, to avoid a risk of the source power limit by the plasma based technology.

It is discussed by several papers on the possibility to realize a high repetition rate (superconducting) FEL to generate a multiple kW 13.5nm light [1,2]. We must notice that the present SASE FEL pulse (typically 0.1mJ, 100fs, 1 mm diameter) has higher beam fluence than the resist ablation threshold [3], and high spatial coherence which results in speckle and interference patterns in resist, and random longitudinal mode beat which leads to high peak power micro spikes. The interaction of the SASE pulses with chemically amplified resist is not known, because the typical EUV (13.5nm) pulses from Tin plasma has a characteristics of continuous spectrum of 2% bandwidth with 10ns pulse width. The emission is fully non coherent, and the pulse energy is typically mJ level at 100 kHz repetition rate.

This paper discusses on the scaling of the FEL technology to kW average power level, optical technology to optimize the FEL beam for lithography application, and scaling to 6.7nm wavelength region.

SCALING TO KW AVERAGE POWER

We start to evaluate a general perspective of high average power 13.5nm generation by SASE mode from recent typical operational parameters and future projects like LCLS2 etc. Genesis calculation was performed to estimate available single shot pulse energy by the electron beam and undulator parameters shown in the table 1.Pulse length was assumed as 100fs and 200fs to evaluate the difference of the output pulse energy depending on the pulse lengths. The calculation result is shown in the Figure 1, which indicates the saturation distance is nearly 20m with 0.1mJ pulse energy for short and long pulse lengths. The average power is 100W level with MHz repetition rate, and 1kW is obtained by 10MHz repetition rate with cryogenic superconducting linac and undulator. There are indeed various engineering challenges for this operation ahead.

Table 1: Parameters for Genesis Calculation

Charge	300pC
Emittance	1mm•mrad
Energy Spread	10^{-4}
Bunch Length	100fs/200fs
E-beam Energy	331.13MeV
Undulator Period	9mm
K Value	1
EUV Wavelength	13.5nm

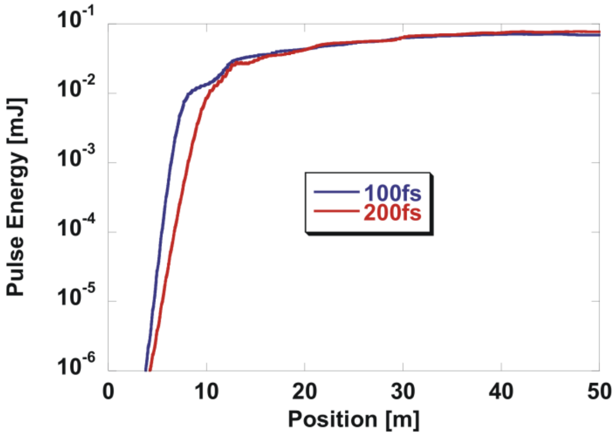

Figure 1: FEL pulse energy growth along Undulator.

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RESIST CHEMISTRY UNDER FEL PULSE IRRADIATION

Chemically amplified resists were first deployed in the mass-production lines of semiconductor devices during the transition of the exposure tool from Hg lamp to KrF excimer laser, and modified to be used by plasma EUV source. After EUV photons are absorbed by molecules, photoelectrons are emitted. The photoelectrons (I_e) with excess energy ($E>E_{th}$) induce further ionization and electronic excitation as shown in Fig.2. The inelastic mean free path of photoelectrons generated by EUV photons is less than 1 nm [4]. Therefore, the ionization and electronic excitation points are distributed narrowly around the photoabsorption point. This is one of the reasons why a higher resolution is expected for EUV lithography than for EB and X-ray lithography, in which the generation of high-energy secondary electrons is a concern. However, the problem associated with the thermalization distance of secondary electrons is the same as that in EB lithography.

One of the remarkable differences of SASE FEL EUV source is its pulse length typically as 100fs, which is 10^5 times shorter than that of plasma source. The EUV photoabsorption / initial ionization and secondary process are regarded as temporally separated under FEL pulses, but this is convoluted in the case of 10ns EUV pulse irradiation. Resist sensitivity is typically 10mJ/cm^2 and the ablation threshold is 10 times higher for the case of 10ns 13.5nm pulses. An experiment by FLASH reported the ablation threshold of PMMA as less than 10mJ/cm^2 with 13.5nm 25fs SASE FEL pulses [5]. It is desirable to make a systematic research on the resist chemistry under such FEL EUV fluence in advance.

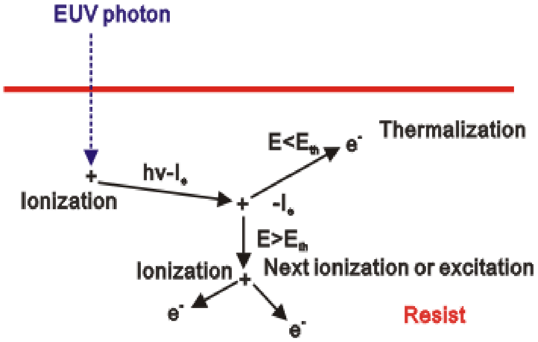

Figure 2: Resist reaction under EUV photon.

SPATIAL COHERENCE

Excimer lasers operating in the Deep Ultra-Violet (DUV) have been used in lithographic systems for over a decade. Their high brightness and limited spatial and temporal coherence make them an attractive source for circuit patterning. However, the wide bandwidth of excimer lasers caused problems in designing DUV photolithographic optics. Line-narrowing processes reduce chromatic aberration in refractive optical systems, but have the disadvantage of increasing coherence and causing problems with interference and speckle. Increased spatial coherence brings problems with interference in conventional beam homogenization systems. Optical modelling of such partially coherent sources was beneficial in the design of efficient beam homogenization techniques, based on micro lens array.

Spatial coherence measurements were reported by illuminating a 10 μm pinhole array with a KrF excimer laser operating at 248 nm. An estimate of the spatial coherence of the source can be taken at a reference level of 50 % visibility, and gave a coherence length of 285 μm. An experimental characterization of the spatial and temporal coherence properties of FLASH at a wavelength of 8.0 nm is reported [6]. Double pinhole diffraction patterns of single femtosecond pulses focused to a size of about 10 × 10 μm^2 were measured. A transverse coherence length of 6.2 ± 0.9 μm in the horizontal and 8.7 ± 1.0 μm in the vertical direction was determined. The mutual coherence function K is given as 0.42, and a measurement of K by a laser plasma source is 3.2x10^{-9}.It is concluded from these measurements that a beam homogenization is required at EUV wavelength by using total reflection optics.

Multi foil optics (MOF) is a EUV optics which consists of two perpendicular sets of very thin reflecting mirrors, where photons are reflected at grazing incidence. Figure 3 shows an example of a MOF focusing element.

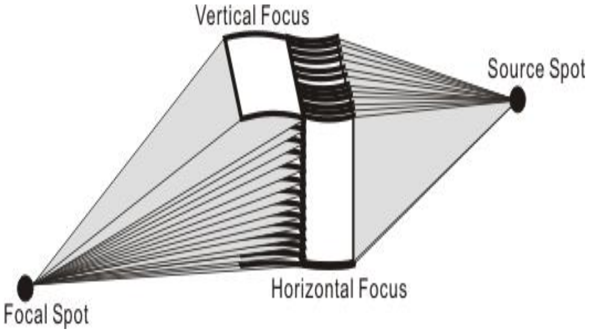

Figure 3: MOF EUV optics to compose FEL beam expander and beam homogenizer.

TEMPORAL COHERENCE AND SPIKE

Temporal coherence was also reported by using a split and delay unit. The coherence time of the pulses produced in the same operation conditions of FLASH was measured to be 1.75fs. The measured coherence time has a value, which corresponds to about 65.5 ± 0.5 wave cycles ($c\tau/\lambda$). It is well known that the SASE FEL pulses are composed of many small spikes and random spectrum due to SASE process. It is reported that the averaged spectrum has a 1.4% bandwidth typically.

LASER TECHNOLOGY FOR HGHG AT MHZ REPETITION

Seeding a FEL with an external coherent source has been studied together with SASE operation to enhance the radiation brightness and stability compared to SASE. An efficient scheme for seeding a VUV-soft x ray FEL uses a powerful, long wavelength external laser to induce on the electron beam coherent bunching at the harmonics of the laser wavelength. When the bunching is further amplified by FEL interaction in the undulator, the scheme is called as high gain harmonic generation (HGHG). A successful demonstration is reported from FERMI as double stage seeded FEL with fresh bunch injection technique [7]. High power seed sources and small electron beam energy spread are at the main limits for direct extension of the HGHG scheme to short wavelengths. The fresh bunch scheme was proposed as a way to overcome these limitations, namely the FEL radiation produced by one HGHG stage acts as an external seed for a second HGHG stage. A 10Hz demonstration is reported by using an electron beam parameters in Table 1 except the beam energy as 1 Gev. The following Table 2 compares the wavelength of the HGHG operation in the case of FERMI FEL-2 and EUV FEL.

Table 2: Comparison of Wavelengths for HGHG Operation in FERMI FEL-2 and EUV FEL

	Fermi FEL-2	EUV FEL
Seed	260nm	324nm
1st FEL	32nm	40.5nm
2nd FEL	10.8nm	13.5nm

The external seed laser was the third harmonic of a Titanium:Sapphire laser with a duration of ~180 fs (FWHM) and up to 20 μJ energy per pulse. Its transverse size in the modulator was made larger than the electron beam size to ensure as uniform as possible the electron beam energy modulation. Once the same laser energy is required for 100W EUV FEL, 20W average power is required for 324nm with 180fs at MHz repetition rate. There are two approaches to generate such laser pulses, the first is based on MHz repetition rate Ti:Sapphire laser with 100μJ level pulses, and the second one is based on OPCPA.

The short pulse, short wavelength laser technology is now advancing due to the new suitable laser configuration as thin disc laser, and efficient wavelength conversion method. Second harmonics of the Yb:YAG thin disc laser is employed to pump the Titanium:Sapphire laser or OPCPA with typically 1mJ pulse energy. It is reported recently that a thin disc multi pass amplifier generated 1.1 kW average power at 800kHz with 1.4mJ pulse energy of 6.5 ps[8]. It was also demonstrated to convert to the second harmonics efficiently with more than 400W average power.

SUMMARY AND CONCLUSION

Discussion is presented in this paper on the EUV FEL perspective to the kW scaling with 13.5nm wavelength with suitable beam characteristics. It is pointed out that the EUV FEL pulse is available with 100W by MHz repetition rate, and kW by 10MHz. Suitable compensation technology is required to overcome the negative effects of the spatial and temporal coherence, and pulse spikes. These are beam expansion and homogenization by reflective optics, and external seeding by HGHG. Advanced EUV optics technology and short pulse high average power laser technologies are the fundamental tools for this research subjects. Wavelength extension to 6.7nm is one of the options of the future EUV lithography, and the plasma source is expected to supply by Gd plasma. The usable mirror has a narrower band width at this particular wavelength, and the resulting lower efficiency is the main problem for the Gd plasma approach. FEL EUV has a possibility to generate narrower band width, 1kW 6.7nm wavelength at relatively comparable source size and cost at this wavelength.

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