DESIGN OF HIGH BRIGHTNESS LIGHT SOURCE BASED ON LASER-COMPTON UNDULATOR FOR EUV LITHOGRAPHY MASK INSPECTION

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Abstract

We will present a design of high brightness light source for EUV lithography mask inspection. The required system parameters are minimum brightness of 2500W/mm^2/Sr at 13.5nm/2% bandwidth. Our design consists of superconducting DC RF-gun as a radiator and 10.74nm CO_2 laser stacked in an optical cavity as a laser undulator. Recent achievements of each component technologies, which is 1.3GHz SC-RF-gun, 10kW average power short pulse CO_2 laser, and laser storage optical super-cavity, indicate the feasibility of producing required brightness based on laser Compton undulator. Design parameters of high brightness EUV source, the technological gap of the present component technologies and required further developments will be resented at the conference.

INTRODUCTION

Extreme ultraviolet lithography (EUVL) is the next generation technology for integrated circuit fabrication at 22nm half-pitch mode and beyond, to start its full implementation from 2011. Most critical technical component has been the high average power EUV light source, at 13.5nm/2% band width of average power in several hundred Watt, in almost one decade. The basic technology has been established recently to satisfy the requirement, by high repetition rate (50-100kHz) laser produced tin (Sn) plasma, driven by a short pulse (<10ns), high average power (>10kW) CO_2 laser [1]. Remaining technological task is implementation of defect free EUVL masks, in which metrology tool to characterize the defects of masks is an urgent subject [2]. The required light source is characterized by high brightness as more than 2500W/mm^2-Sr at 13.5nm with 2% band width [3]. This requirement is closely satisfied by a high average power (>100W) EUV light source of laser produced Sn plasma for high volume manufacturing, but more dedicated light source is desirable for this specific application.

Laser-Compton X-ray source is an emerging technology for imaging applications, characterized by a quasi-monochromatic beam of stable and low Etendue number, from a compact and contamination free source. It was already discussed in a session of 2006 International Symposium on Extreme Ultraviolet Lithography, on the possibilities of laser-Compton X-ray method as a candidate for EUV light source for lithographic applications. The authors presented in the source workshop on the conceptual design of EUV source as "Development of pulsed laser stacking cavity for EUV source" [4]. We present an overall evaluation of the classical laser-Compton method to apply to this specific metrological requirement in this paper. Basic characteristics of the X-ray generation are reviewed and a conceptual design is presented in the following section. Each component technologies are evaluated, on 10kW average power, short pulse CO_2 laser, super conducting DC RF gun at 1.3GHz repetition rate of 77pC bunch charge, and optical super cavity of 600 enhancement factor at 10.6μm wavelength. It is discussed in each section on the technological gap of the present component technologies and required further developments.

CONCEPTUAL DESIGN OF EUV SOURCE

We first show the schematic of our design of EUV source for mask inspection in Fig. 1 and the design parameters in Table 1. Small spot and continuous laser-Compton interaction between electron beam and CO_2 laser provide a high brightness EUV light. In the forward direction, laser-

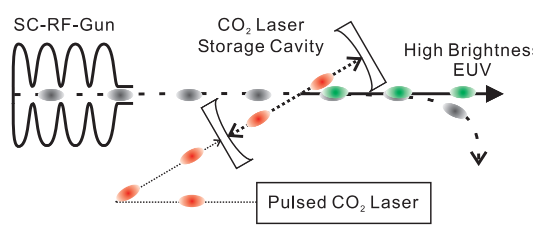

Figure 1: Schematic of EUV source.

Table 1: Electron Beam and CO_2 Laser Design Parameters

Electron		Laser	
Energy	7.2MeV	Wavelength	10.6μm
Charge	77pC	Energy	20mJ
Rep.	1.3GHz	Rep.	1.3GHz
Size	15μm	Size	15μm
Bunch Length	400fsec	Pulse duration	20psec
Current	100mA	Power	26MW
Collision angle		10degrees	

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Compton scattering photon spectrum has a peak at a wavelength [5]

$$\lambda_p = \frac{\lambda_L(1+K^2/2)}{2\gamma^2(1+\beta\cos\phi)} \tag{1}$$

where γ and β is Lorentz factor, λ_L the laser undulation period, *i.e.* laser's wavelength, K the K parameter of the undulator which is equivalent to the laser intensity parameter, and ϕ the colliding angle. The spectrum depends on the angular distribution; the wavelength λ is emitted at an angle

$$\theta = \frac{1}{\gamma}\sqrt{\frac{\lambda-\lambda_p}{\lambda_p}} \tag{2}$$

Now we found the higher γ can produce smaller diverging light. Target EUV wavelength is now relatively long of 13.5nm. In order to make EUV source small divergence *i.e.* make electron beam energy higher, we employed CO_2 laser for a photon target. According to the Eq. 1, 7.2MeV electron will produce 13.5nm EUV light through the laser-Compton interaction with 10.6μm photon target at an angle of 10deg.

The most feasible electron gun which could produce 7.2MeV, high current is a superconducting photo-cathode RF-gun (SC-RF-gun) with 3.5-cells (See Sec. 3). As a photon target, we have to produce high repetition, short pulse, and high pulse energy CO_2 laser target, which will exceed 26MW average power. We employed a high power CO_2 laser system with pulse storage super-cavity for enhancing laser power in the optical cavity (See Sec. 4). Concerning the bandwidth of EUV light, we can obtain the desired bandwidth to collimate the light in forward direction according to Eq. 2. The design bandwidth of the required light source was 2% which corresponds to within 14mrad scattered angle. Now we can calculate the EUV flux based on Table 1. As a result, 2.3×10^{14} photons/sec/2% b.w. will produce by designed EUV source. This value corresponds to 3.4mW/2% b.w. average power. Dividing by the source size and diverging angle, the designed brightness of this EUV source will be achieved 30kW/mm^2/Sr/2% b.w.

DC ELECTRON GUN

Recent progress of superconducting acceleration cavity technology enables us to produce a short bunch, continuous, high average current electron beam. Especially, a SC-RF-gun is the most feasible candidate for this EUV light source. Only a 3.5cells SC-RF-gun cavity can accelerate up to 9.4MeV [6][7]. Forschungszentrum Dresden-Rossendorf (FZD) have already succeeded in generating an electron beam continuously with 3.5cells SC-RF-gun [8]. Now the electron beam status is 3MeV, 77pC/bunch, 1.3MHz repetition, 4psec length, $2\pi\times10^{-6}$mrad emittance. The energy of electron beam is not enough compared with their design, however they will improve SC-RF-gun cavity to achieve the designed electron beam in the near future [9]. This will provide us a possibility to achieve design parameter electron source shown in Table 1. On the other hand, the other candidate of electron source is DC-gun and superconducting linear accelerator. This scheme is considering or operating for the injector of Energy Recovery Linac (ERL) [10][11]. Recently, JAEA group succeeded in operating DC-gun at 500kV for more than 8h [11]. This could be helpful us to use an extreme low emittance, high current electron beam generated by DC-gun and SC-Linac.

LASER UNDULATOR

We have been developing pulsed-laser storage in an optical super-cavity for laser-Compton X-ray source [12]. In our recent studies, the enhancement in optical cavity of 600 and waist of 60μm (2σ) super-cavity was stably achieved using 1μm Nd:VAN mode-locked laser [13]. Figure 2 shows the schematic of super-cavity. In order to adopt this

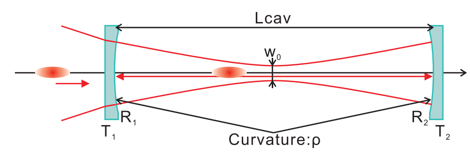

Figure 2: Schematic of super-cavity system.

super-cavity storage technique to CO_2 laser, we first considered the super-mirrors for super-cavity. As described in [13], higher finesse cavity provides higher enhancement in the cavity. Particularly, the loss, which including both absorption and scattering, on the reflection coating is critical issue for storing a high power laser. Such a high quality optical mirrors was difficult for far infrared wavelength, however, there are now some products which usable for super-cavity mirrors [14]. Using R$\sim$99.7% mirror as an input and R$\sim$99.9% mirror as an output, we expect to achive more than 600 enhancement. For super-cavity, the precision of cavity length adjustment is one issue for stable operation. In CO_2 laser storage, this requirement is one-order relaxed due to the wavelength, thus the stable operation with enhancement of 600 and more can be easily achieved from our experiences in 1μm laser storage.

Concerning a small waist achievement, our source requires 30μm waist (2σ). The waist of super-cavity is described as

$$\omega_0^2 = \frac{\lambda}{\pi}\frac{\sqrt{L_{cav}(2\rho-L_{cav})}}{2} \tag{3}$$

where λ is wavelength of laser, Lcav cavity length, ρ curvature of cavity mirror. While high enhancement will be easier, small waist cavity is hard for 10.6μm laser as described in Eq. 3. However the two-mirror, Fabry-Perot cavity would be difficult to achieve small waist due to the cavity structure is confocal, we are developing a concentric, four-mirror super-cavity [15]. This technique can reduce the mirror alignment requirements as two order magnitude. We believe that 30μm waist can be achieved using four-mirror super-cavity.

As a seed of super-cavity, we need high average power, psec pulse, CO_2 laser. Multi atmospheric discharge is required to amplify short pulse in ps region due to the band width requirement. Higher repetition rate operation is practically not useful for a multi atmospheric discharge device, due to the limitation of fast gas flow and strong electrical and mechanical stress. Recent achievement of 10kW average power, short pulse CO_2 laser technology was driven by the strong requirement from semiconductor industry for EUV lithography [16][17]. The system is based on commercial high average power CO_2 laser modules as amplifiers, with RF-excitation in conduction cooled slab/waveguide and axial flow configurations, and achieved the output power to 13kW in an experiment of single 10P(20) line amplification. The critical issue is an adjustment of the bandwidth limited pulse length to the ps region. CO_2 laser gain comes from the rotational-vibrational structure of CO_2 molecules. Rotational band width is given by the following formula [18],

$$\Delta\nu = 7.58(\Phi \mathrm{CO_2} + 0.73\Phi \mathrm{N_2} + 0.64\Phi \mathrm{He}) \times P(300/T)1/2 \tag{4}$$

where Φ indicates the ratio of each gas component, P is the total pressure in torr, and T is the gas temperature. It is given as $\Delta\nu$=424MHz for gas ratio as CO_2:N_2:He=1:1:8, total pressure= 100 torr, and temperature= 450 K. Band width limited pulse length is given as $\Delta t \sim 1$ ns in this operational condition. Active control of the CO_2 laser oscillator is required to stabilize the temporal and spectral structure of the pulse. A nonlinear method was employed to generate broad band, short pulse to cover the full bandwidth of one vibration band. The seeding experiment was performed for a CO_2 laser regenerative amplifier with a multi line generation successfully. Quantum cascade laser (QCL) is an emerging new seeding source in the CO_2 laser gain region with higher controllability. There are several approaches to realize an efficient pulse compression of CO_2 laser pulse from ns to ps region. One candidate is backward stimulated Raman scattering, similar to the scheme demonstrated in KrF laser technology in late 70s [19]. The other promising approach is optically pumped NH3 as a high gain amplifier of 10P(34) radiation of ps CO_2 laser pulse [20]. Pumping is 9R(30) wavelength of ns CO_2 laser from high average power, high repetition rate amplifiers. High amplification gain was reported in the literature with pumping fluence more than 10MW/cm^2, which is a realistic parameter from the established short pulse CO_2 laser technology. Figure 3 shows a block diagram of the ps CO_2 laser system composed of pumping 9R(30) 10 ns laser of 20kW average power at 100kHz repetition rate, and short pulse amplifier of a seeder of 10 ps QCL at 10P(34) wavelength and 6 atmosphere NH_3 amplifier with N_2 buffer gas.

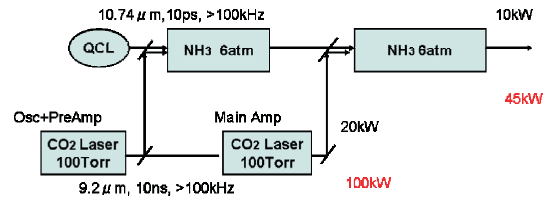

Figure 3: Block diagram of optically pumped ps CO_2 laser system.

CONCLUSIONS

We designed and calculated a high brightness EUV source for mask inspection. Laser undulator radiation is the most feasible because of its low Etendue number. Our design is 7.2MeV electron accelerator using SC-RF-Gun and 10.6μm CO_2 laser with super-cavity. The required specifications of each source are hard in order to produce 2500W/mm^2-Sr at 13.5nm with 2% b.w. EUV light. We discussed the technological gap of the present component technologies and required further developments. As an electron beam, SC-RF-gun and DC-gun have the possibility, the required parameter is almost same with ERL electron source. Thus, we believe that it will be realized in near future. As laser undulator, the super-cavity for CO_2 laser and high power ps CO_2 have to be demonstrated.

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