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EUV-FEL LIGHT SOURCE FOR FUTURE LITHOGRAPHY

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Abstract

A more powerful EUV light source will be required for lithography to overcome the stochastic effects for higher throughput and finer patterning. We have designed and studied a high-power EUV-FEL light source based on energy-recovery linac (ERL) for future lithography. In this paper, we show that the EUV-FEL light source has many advantages such as extremely high EUV power without tin contamination of EUV mirrors, upgradability to a Beyond EUV (BEUV) FEL, polarization controllability, low electric power consumption and cost per scanner, as compared to the laser-produced plasma (LPP) source used in the present EUV lithography exposure tool. Furthermore, demonstration of proof of concept (PoC) of the EUV-FEL is in progress using the Compact ERL (cERL) at KEK. We also briefly present the current state of the PoC of the EUV-FEL.

INTRODUCTION

The lithography resolution R is given by the light source wavelength λ, numerical aperture NA and process parameter k_1 as follows:

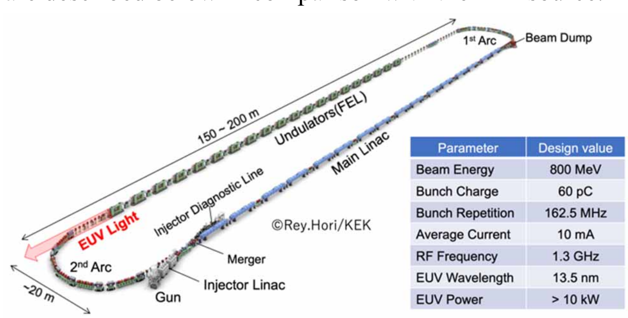
$$R = k_1 \frac{\lambda}{NA}. \quad (1)$$

The light-source wavelength has become shorter to keep Moore's law alive. The wavelength of EUV lithography is 13.5 nm, which is fitted to the reflectivity of Mo/Si multilayer mirrors. In EUV lithography, high-volume manufacturing started using a 250-W LPP source [1]. In the LPP source, tin plasma generated by a CO_2 laser and tin droplets provides unpolarized EUV light for the scanner system with EUV optics. Tin contamination to the collector mirror is an issue of this system. Another issue is stochastic effects. In EUV lithography, the photon number absorbed in resist is much less than those of the excimer lasers at the same dose because of the much higher photon energy [2]. If the dose is insufficient, stochastic pattern defects appear [3]. The EUV power required for mitigating the stochastic effects at the maximum throughput of future high-speed scanners was estimated to be more than 1 kW for the 3-nm node and beyond [4]. EUV Lithography will require a more powerful EUV source in future.

We have designed and studied a high-power EUV-FEL light source based on ERL for lithography since 2015 [5-8]. In Japan, a new firm, named Rapidus, was recently established and invested by eight major companies such as Toyota Motor Corp. and Sony Group Corp. to begin domestic production of next-generation semiconductor chips in the late 2020s [9]. The Japanese government also created a new public body called the Leading-edge Semiconductor Technology Center (LSTC) at the end of 2022 to serve as an open research and development platform for next-generation semiconductors [10]. The LSTC consists of major Japanese research organizations and universities as well as Rapidus. KEK is one of the participating organizations and expected to develop the EUV-FEL light source for future lithography.

EUV-FEL LIGHT SOURCE

The illustration and parameters of the EUV-FEL light source based on ERL are shown in Fig. 1. In this light source, the electron beam with the bunch charge of 60 pC generated by the gun at the bunch repetition frequency of 162.5 MHz is accelerated to ~11 MeV in the injector superconducting (SC) linac and then to 800 MeV in the main SC linac. The electron bunch is compressed by magnetic bunching in the 1st arc to generate the high-power EUV light by the FEL undulators in the recirculation loop. After the FEL lasing, the electron beam is returned back to the main linac, decelerated to almost the injection energy for energy recovery and then dumped. By the energy recovery scheme, the high average current of 10 mA is achieved to provide the high EUV power of more than 10 kW. The conceptual design and related R&D of the main components such as a photocathode DC gun, injector and main-linac cavities, two arc sections, an FEL system and an optical beamline to scanners are described in the references [7, 11-18]. Advantageous features of the EUV-FEL light source are described below in comparison with the LPP source.



Parameter	Design value
Beam Energy	800 MeV
Bunch Charge	60 pC
Bunch Repetition	162.5 MHz
Average Current	10 mA
RF Frequency	1.3 GHz
EUV Wavelength	13.5 nm
EUV Power	> 10 kW

Figure 1: 3-D illustration and design parameters of the EUV-FEL light source based on ERL.

High Power Performance

A start-to-end simulation of the EUV-FEL light source is carried out to demonstrate its high-power performance [8]. Three simulation codes, GPT, GENESIS and ELEGANT, are used for the injector, the FEL system and the other parts, respectively. In this simulation, new optimization of the injector parameters is used to minimize the longitudinal

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emittance in place of the transverse emittance at the injector exit [19]. Longitudinal space charge effects are introduced in the whole light source for more accurate simulation. The tracking particle number is 500 k. In this simulation, at the FEL entrance, the bunch length and energy spread are 39 fs and 0.1 % and the normalized horizontal and vertical emittances are 2.0 and 0.9 mm·mrad.

Figures 2(a) and 2(b) show the simulated FEL pulse energy per electron bunch as a function of the undulator section length and the FEL power spectrum at the FEL exit. The FEL pulse energy with the optimum linear tapering of 4 % is 109.4 μJ at the FEL exit and, as a result, the FEL power is 17.8 kW at 9.75 mA. The EUV-FEL light source can provide more than 1-kW EUV power for ten scanners at the same time. If the bunch repetition frequency can be doubled to 325 MHz, the EUV power is increased to 35.5 kW at 19.5 mA. The FEL spectral width is narrow enough for that of Mo/Si mirror reflectivity as shown in Fig. 2(b). Although the energy spread is increased to 0.34 % after the FEL emission, the electron beam is transported without any beam loss through the beam ducts with typical apertures. Further simulation study is needed for unconsidered effects of beam dynamics and various errors.

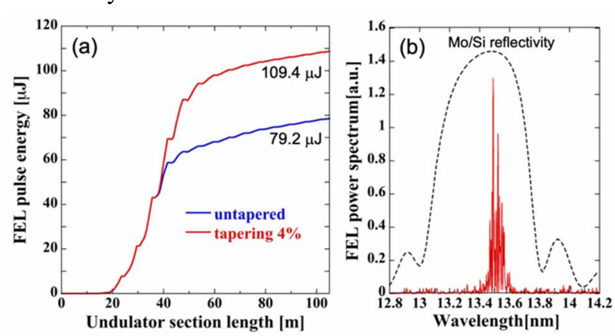

Figure 2: (a) Simulated FEL pulse energies with 0 and 4 % tapering as a function of the undulator section length and (b) FEL spectrum at the FEL exit with the Mo/Si mirror reflectivity curve (a broken line).

Upgrade to BEUV-FEL

Figures 3(a) to 3(c) schematically show three possible upgrade schemes to a BEUV-FEL from the EUV-FEL.

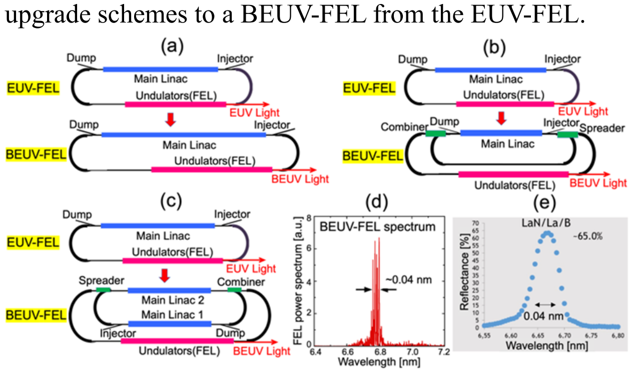

Figure 3: Three possible upgrade schemes to a BEUV-FEL based on (a) single-loop layout and (b)(c) double-loop layout, (d) a simulated BEUV-FEL spectrum and (e) measured reflectivity curve of a BEUV mirror.

The first scheme in Fig. 3(a) is based on a single-loop layout. The beam energy of the BEUV FEL is increased to ~1.14 GeV to shorten the wavelength to ~6.7 nm. The main-linac length is increased by a factor of ~1.4. The other two schemes are based on double-loop layout not to increase the light source length significantly. The beam is accelerated twice by the main linac in Fig. 3(b) and the main linac is separated into two parts in Fig. 3(c). Figure 3(d) shows the simulated BEUV-FEL spectrum [20]. The bandwidth of this spectrum (~0.04 nm) is narrower than that of the measured BEUV mirror reflectivity in Fig. 3(e) [21]. This means that an ERL-based BEUV-FEL is also a promising light source for BEUV lithography.

Polarization Effects and Control

The polarization of the FEL light can be utilized for high-NA lithography. As shown in Eq. (1), higher resolution is achieved by higher *NA* even for the same wavelength. Figures 4(a) and 4(b) show schematic of two plane waves propagating on different paths and the light intensity produced by interference of the two waves on a wafer for the s-polarized and p-polarized modes. In vacuum or air, *NA* is defined by $\sin\theta$, where θ is the incident angle. The s-polarized light fully interferes at $x = 0$ because the electric fields of the two waves are parallel, while the p-polarized light only partially interferes. As a result, the s-polarized light has better performance in intensity and contrast for high-NA lithography. Such polarization effects in high-NA configuration were experimentally demonstrated [22].

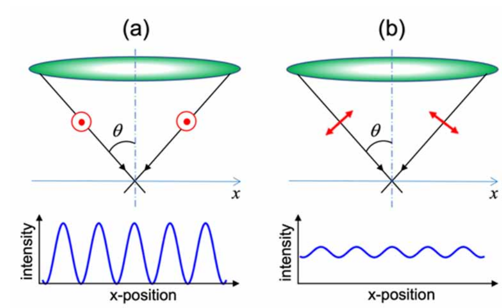

Figure 4: schematic of two plane waves propagating on different paths in high-NA configuration and the light intensity produced by interference of the two waves on a wafer for the (a) s-polarized and (b) p-polarized modes.

Variably-polarizing undulators such as Apple-2 type [23] will be used for the EUV-FEL and BEUV-FEL. In low-NA lithography, all the undulators should be operated in circular polarization mode to have higher FEL gain and power. On the other hand, in high-NA lithography, it is important to make most of the polarization effect described above. A simple scheme of polarization control is to operate all the undulators in the same polarization mode, such as horizontal or vertical linear polarization mode, suitable for generation of the s-polarized light for the lithography pattern. We are also studying another polarization control scheme. In this scheme, some undulators in the upstream are operated in circular polarization mode to obtain a higher FEL gain and the other undulators in the downstream is operated in the polarization mode suitable for generating s-polarized

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light for the lithography pattern. In either way, the polarization of the FEL light from the EUV-FEL and BEUV-FEL light sources can be well controlled for high-NA lithograph, while the LPP source only provides unpolarized light.

Electric Power Consumption and Cost

In the semiconductor society, sustainability of semiconductor technologies and systems is becoming important [24, 25], because CO_2 footprint of semiconductor manufacturing is rapidly rising. From this point of view, since the LPP source consumes most of the electric power in the EUV lithography exposure tool, the electric power consumption of the EUV source should be reduced. Table 1 shows estimated electricity power needed for the EUV-FEL light source. The total electricity power is 7 MW for 10-kW EUV power and hence 0.7 MW per 1-kW EUV power. The electric power of the refrigerator system includes 50 % margin for the stable operation and the electric power of the RF source is estimated with a rather low power-efficiency of 30 %. On the other hand, the LPP source consumes ~1.1 MW electric power for 250-W EUV power [26, 27] and ~4.4 MW for 1-kW EUV power. The EUV-FEL can greatly reduce the electric power consumption per scanner.

Table 1: Electric Power Needed for the EUV-FEL

Item	Electric power [MW]
Refrigerator System	3.2
RF Source	1.3
Other Components	1.0
Infrastructure	1.5
Total	7.0

The cost of ownership is also important. The construction and running costs of the EUV-FEL light source are roughly estimated to be US$400M and US$40M/year for 10-kW EUV power and hence US$40M and US$4M/year per 1-kW EUV. On the other hand, the construction and running costs of the LPP light source are roughly estimated as US$20M and US$15M/year per 250-W EUV power and US$80M and US$60M per 1-kW EUV power by simple linear extrapolation. Especially the running cost of the LPP source is expensive because the collector mirror contaminated by tin debris have to be frequently replaced with a new one. The EUV-FEL light source can also reduce the construction and running costs per scanner.

POC OF THE EUV-FEL

Demonstration of PoC of the EUV-FEL light source is important for industrialization. PoC of the EUV-FEL on ERL can be provided by installing FEL undulators in the cERL for generation of SASE-FEL emission, as shown in Fig. 5. Fortunately, an IR-FEL was constructed in the cERL from October 2019 to May 2020 as a NEDO project for the purpose of developing high-power mid-infrared lasers for highly-efficient laser processing utilizing photo-absorption based on molecular vibrational transitions. Two 3-m undulators were installed with two FEL monitor ports for the IR-FEL. The beam energy is about 17.5 MeV and the undulators cover the FEL wavelength of 10 to 20 µm. The FEL commissioning was carried out in Jun. to Jul. 2020 and Feb. to Mar. 2021. The details of the construction and commissioning of the cERL IR-FEL are described elsewhere [28]. As a result of the commissioning, the FEL pulse energy of the NEDO-project goal was almost achieved, though the FEL was operated in Burst mode without energy recovery. Such significant SASE-FEL emission at the cERL IR-FEL became a very important step of PoC of the EUV-FEL light source.

Toward future high-power FEL operation with energy recovery in CW mode, the cERL dump line was reconstructed in 2020 to greatly improve the energy acceptance for avoiding serious beam loss and then the first beam transport study in the new dump line was done in 2021 [29]. Moreover, the first high-current operation after the IR-FEL construction was carried out with a low bunch charge and no FEL emission in Feb. to Mar. 2022 and, as a result, the maximum current of about 250 µA was achieved with ~100% energy recovery [30].

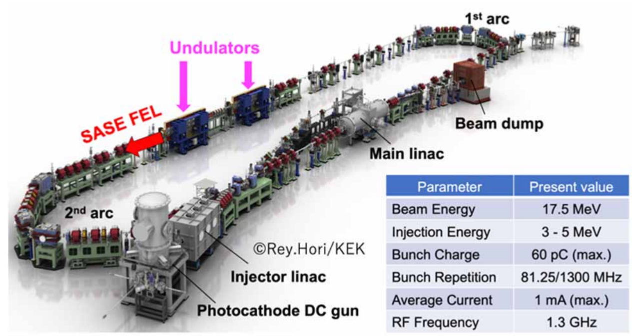

Figure 5: Schematic of PoC of the EUV-FEL light source using the cERL and the cERL parameters.

SUMMARY

The EUV-FEL light source has many advantages in EUV power, upgradability to a BEUV-FEL, polarization control for high-NA lithography, electric power consumption and cost per scanner and so on. Generation of significant SASE-FEL emission at the cERL was achieved as PoC of the EUV-FEL on ERL. The EUV-FEL light source is a most promising light source for future lithography and should be much more promoted for industrialization. KEK has recently participated in the LSTC and we are expecting to speed up developing and industrializing the EUV-FEL light source for lithography.

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