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Source for extreme ultraviolet lithography by the tabletop storage ring MIRRORCLE

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Abstract. Advances of electron storage rings to beam currents of above 1 A and tabletop sizes make possible the development of a synchrotron-based source for EUV lithography (EUVL) at ~13.5-nm wavelength. The MIRRORCLE storage rings can provide on average 3-A electron beam current, 1-min lifetime, 15-ms radiation damping, and beam size ~3*3 mm^2. MIRRORCLE-20SX, MIRRORCLE-6X, and MIRRORCLE-CV4 store electrons with energies of 20 MeV, 6 MeV, and 4 MeV, respectively. These machines can emit EUV from a tiny target, hit by the circulating beam, via transition radiation or diffusive radiation. Using a multilayer microelectromechanical system (MEMS) target allows enhancement and spectral purification of the emitted EUV. Aligning many such MEMS along the electron beam orbit and radiation collection by only one quasi-elliptical EUV mirror can provide EUV satisfying the joint requirements for an EUVL source. *© 2008 Society of Photo-Optical Instrumentation Engineers.* [DOI: 10.1117/1.3040017]

Subject terms: EUV lithography (EUVL) source; electron storage ring; MIRRORCLE; target; EUV mirror.

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1 Introduction

The main problems for advancing EUV lithography (EUVL) at ~13.5-nm wavelength to production level are in the development of the source and the resist.[1] At present, the sources are based on the plasma processes laser produced plasma (LPP) and discharge produced plasma (DPP).[2] The use of these sources for manufacturing is hampered, however, by contamination from the Sn plasma and too high vacuum ultraviolet/deep ultraviolet (VUV/DUV) radiation.[3,4] These lead to fast amortization of the collector optics and unacceptable deposition of carbon, decomposed by oily hydrocarbons, onto the mask and the wafers. Therefore, a need for development of a clean, narrow band, and forward-radiating second-generation EUVL source has been acknowledged.[5]

Synchrotrons can satisfy these requirements but have not been used as EUVL sources, mostly due to their relatively low beam currents and large sizes.[6,7] This situation is changing, however, as a result of the production of the tabletop electron storage rings MIRRORCLE with beam currents of more than 1 A. MIRRORCLE can emit EUV satisfying the joint requirements for an EUVL source.[2] In this paper, are describe our concept for an EUVL source based on MIRRORCLE.

2 Light Sources Based on the MIRRORCLE Storage Rings

2.1 *Evolution of Storage Rings*

The concept of developing storage rings with progressively reduced sizes has been introduced and implemented under the leadership of Professor Hironari Yamada at Ritsumeikan University, Kusatsu, Japan.[8–10] This evolution is illustrated by photos of the first such ring AURORA and the new ring MIRRORCLE-6EUV (Fig. 1).

The range of the MIRRORCLE storage rings is shown in Fig. 2. It includes the rings MIRRORCLE-20SX, MIRRORCLE-6X, MIRRORCLE-CV4, and MIRRORCLE-CV1, which store electrons with energies of 20 MeV, 6 MeV, 4 MeV, and 1 MeV, respectively. The MIRRORCLE rings are manufactured by Photon Production Laboratory Ltd[11] to satisfy industrial demands for small synchrotron light sources with large electron beam currents. MIRRORCLE-20SX is used for materials analysis, x-ray absorption fine structure (XAFS), and EUV applications; MIRRORCLE-6X is used for absorption spectroscopy; MIRRORCLE-CV4 is used for nondestructive testing; and MIRRORCLE-CV1 is used for nondestructive testing, x-ray microscopy, submicron computed tomography (CT), and medical diagnostics.

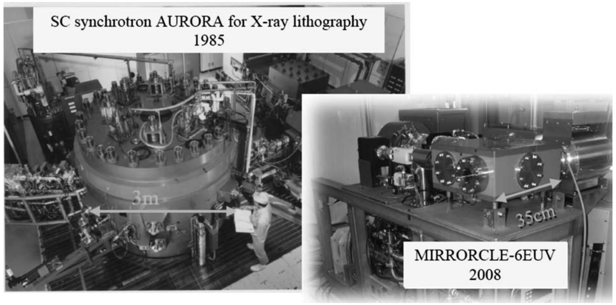

Fig. 1 Photos of our first storage ring AURORA and the new ring MIRRORCLE-6EUV.

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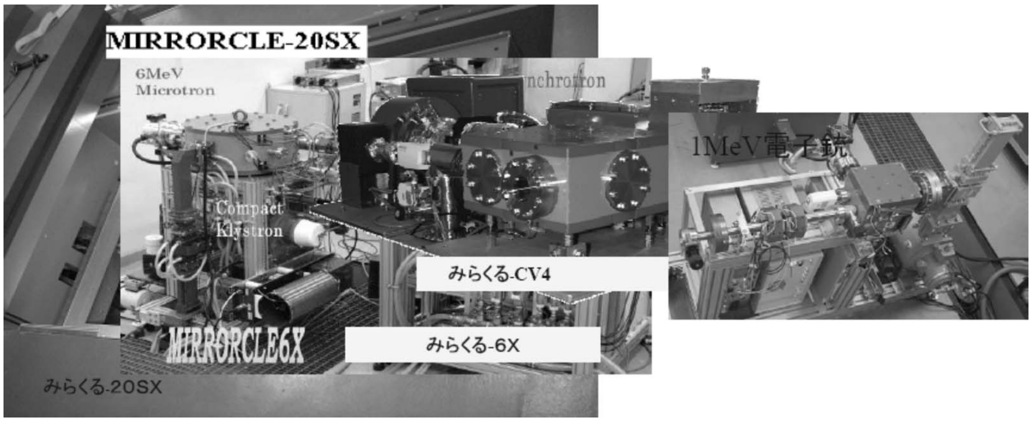


Fig. 2 The range of MIRRORCLE storage rings includes MIRRORCLE-20SX, MIRRORCLE-6X, MIRRORCLE-CV4, and MIRRORCLE-CV1. These store electrons with energies of 20 MeV, 6 MeV, 4 MeV, and 1 MeV, respectively.

The variety of applications of MIRRORCLE-20SX and MIRRORCLE-6X is represented in Fig. 3, depending on the spectrum of the light beam.

2.2 *Principles of Electron Dynamics and Photon Emission from MIRRORCLE*

In MIRRORCLE, a microtron generates and injects electron pulses with a peak injected current $I_P \leq 130$ mA, injection pulse time $T \leq 150$ ns, and injection rate $R \leq 400$ Hz into the storage ring. Advanced technology solutions allow obtaining a large stored beam current and a small beam cross section. The machines work at relatively high vacuum pressure $\sim 1 \times 10^{-5}$ Pa, resulting in significant residual gas ionization in the beam region that forms a positive ion trap there. Combined with energy supplied by the radio frequency (RF) cavity, this increases both the beam stability and the beam lifetime and speeds up the radiation damping. Therefore, MIRRORCLE can provide on average 3-A electron beam current, 1-min lifetime, 15-ms radiation damping, and beam size $\sim 3*3$ mm^2 (Ref. 12). The process of radiation damping is demonstrated, by comparing successive thermography photos of the electron beam, and exemplified in Fig. 4.

The electrons circulate many times in MIRRORCLE, radiating mainly infrared photons. When a tiny target is fixed within the electron beam, the circulating electrons hit it many times, emitting mostly EUV and x-ray photon beams (Fig. 5).

The main mechanism for generating predominantly EUV and soft x ray is transition radiation (TR). TR is emitted when an accelerated electron passes through the interface between two materials, as a result of a velocity change of the electron there. For relativistic electrons, the TR emission is directed forward and has a conical shape with emission intensity maximum at $\theta_{\max} \cong \Delta\theta \sim 1/\gamma$, where θ, $\Delta\theta$, and γ are the angle between the directions of the electron and the emitted photon, the angular half-width of the radiation, and the relativistic factor (Fig. 6).

The simplest possible TR target is a single foil of a given material. TR is emitted around both interfaces foil/vacuum. Our target design work showed[13] that to emit soft x ray/EUV by TR in MIRRORCLE, such a foil should not be thicker than 500 nm. In this paper, all of the considered TR targets are oriented normal to the direction of the electron beam. Also, all of the included computed results concerning emission of TR from a target are based on data about the complex susceptibility of the target material, taken from the National Institute of Standards and Technology (NIST) database.[14]

Appropriate choice of the foil material and its thickness can result in emission of predominantly EUV (Ref. 15; Fig.

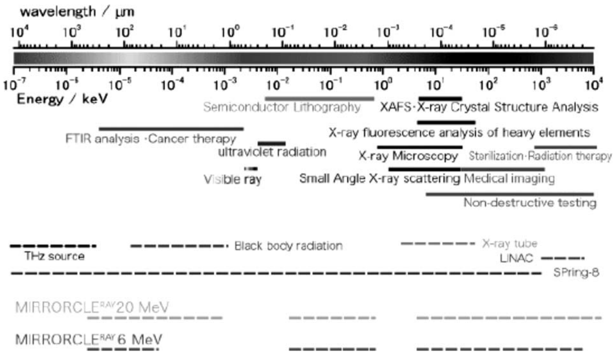


Fig. 3 Spectral regions and areas of application of MIRRORCLE-20SX, MIRRORCLE-6X, and other existing light sources.

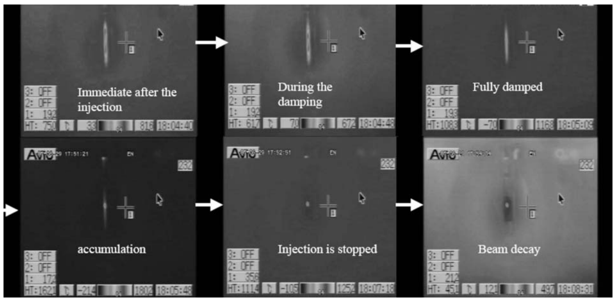


Fig. 4 Successive thermography photos of the electron beam, exemplifying the beam damping. The clock at the bottom right of each of the photos indicates that the beam cross section shrinks for ~15 ms.

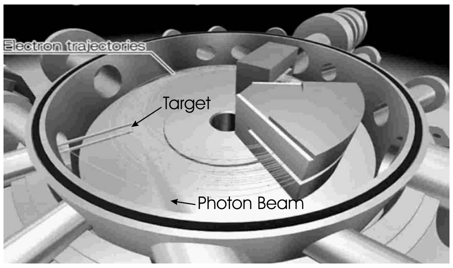


Fig. 5 Electrons circulating in MIRRORCLE hit a tiny target many times, emitting a photon beam.

7). In these conditions and spectral region, the radiation contribution of TR is much larger than that of bremsstrahlung radiation.

3 Experiments on the TR of EUV and Soft X Ray by MIRRORCLE

Several TR experiments were performed for the generation and measurement of EUV and soft x ray in MIRRORCLE. The detector contained a plastic scintillator NE102 with a surface area 3 mm*3 mm and a thickness of 8.5 μm, glued to a quartz substrate; an optical bundle; a photomultiplier H3165-10 (Hamamatsu) operated at 1 kV; and an intermediate frequency (I-F) converter whose output current was recorded in counts. The TR targets represented one foil strip with a width of 2 to 3 mm. The strip was fixed perpendicular to the electron beam, and the central area of the strip was hit by the beam.[16] There was no properly operating RF cavity for recovering energy lost by electrons during their multiple circulation.

During our MIRRORCLE-6X experiment, the injected beam current was $I_{Bi}=I_P\cdot T\cdot R=800$ nA, the target was 385-nm-thick Al foil, and one photomultiplier (PMT) output current count corresponded to 10 pA. The measured angular distribution of the radiation is shown in Fig. 8.

In our MIRRORCLE-20SX experiment, the injected beam current was $I_{Bi}=160$ nA, and one PMT output current count corresponded to 1000 pA. Three targets were used representing one strip of 85-nm-thick diamond-like carbon (DLC), 200-nm-thick Al, and 500-nm-thick Al. The measured angular distribution of the radiation is shown in Fig. 9.

The already discussed experiments revealed angular distribution of the emitted radiation typical for TR. The maximum of the TR distribution from MIRRORCLE-20SX is observed at $\theta\approx 25$ mrad $\approx 1/\gamma$, and the respective maximum for MIRRORCLE-6X is at a larger angle. The maximum of the angular distribution for MIRRORCLE-6X corresponds to 60-nA PMT output, while the respective maximum for MIRRORCLE-20SX corresponds to 550-nA PMT output, although with 5 times smaller I_{Bi}.

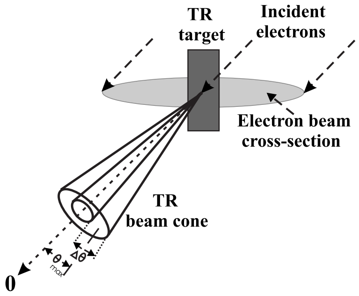


Fig. 6 TR target emits TR with a conical spatial distribution and emission intensity maximum at $\theta_{\max}\cong\Delta\theta\sim 1/\gamma$.

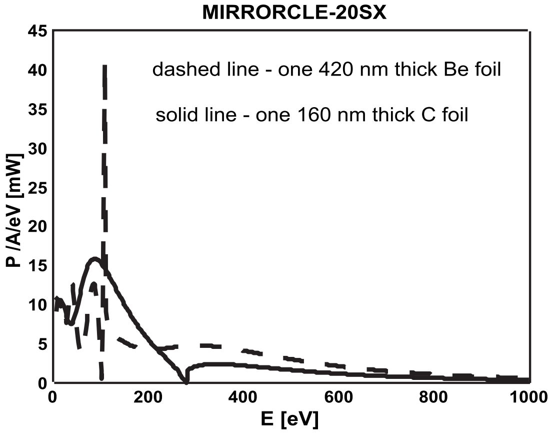


Fig. 7 Calculated emitted power spectra of TR from MIRRORCLE-20SX for 1-A beam current passing through the target. The result is obtained by integration of the TR intensity over the entire spatial angle of emission.

Our next experiment measured the EUV spectrum of TR from MIRRORCLE-20SX with a TR target. Part of the TR around an angle $\theta\sim 1/\gamma$ was reflected by an EUV mirror consisting of 50 Mo/Si bilayers with a period of 6.95 nm and produced by Fraunhofer Institute (Dresden, Germany). The mirror was rotated to provide an angle of incidence of TR with respect to the mirror normal between 5 deg and 35 deg. Part of the reflection from the mirror TR falls onto a calibrated diode SXUV-100Si/Zr (International Radiation Detectors, Torrance, CA). This Si pin diode has an active region with a thickness of only 5.5 μm and an Si/Zr filter absorbing VUV/DUV reflected from the mirror. Since the maximum of the known mirror reflectivity varies with the

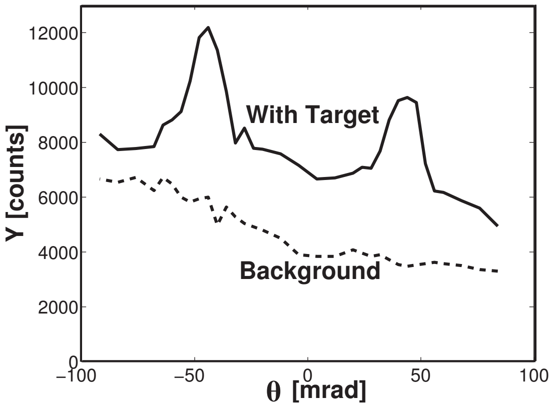


Fig. 8 Angular distribution of TR from MIRRORCLE-6X, measured in Y counts of the output current of the detector. The injected beam current was $I_{Bi}=I_P\cdot T\cdot R=800$ nA, the target was a 385-nm-thick Al strip, and one count corresponded to 10 pA current at the PMT output. The distribution, corresponding to the target emission, represents a difference between the measured distribution with a target and the background distribution without a target.

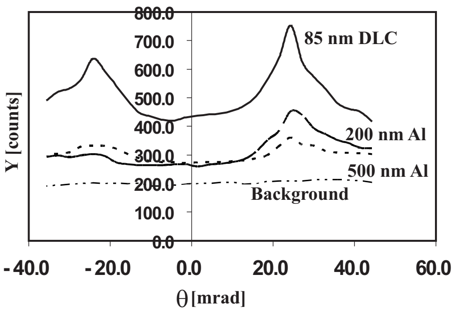


Fig. 9 Measured angular distribution of TR from MIRRORCLE-20SX. The injected beam current was I_{Bi}=160 nA, and one count corresponded to 1000 pA current at the PMT output. Three single-strip targets were used: 85-nm-thick DLC, 200-nm-thick Al, and 500-nm-thick Al. Background measurement, performed without a target, is also included.

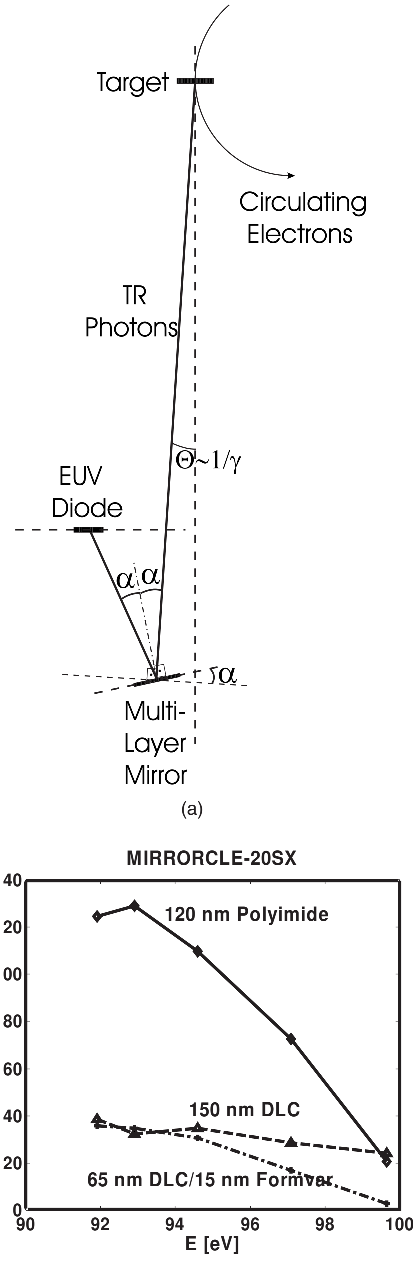
angle of TR incidence, while the reflectivity spectral half-width is ~2%, this measurement setup allows measuring of 2% band EUV spectrum in the vicinity of 13.5 nm (91.837 eV). Such spectra were derived from the measured diode output current, because the responses of all components of the setup are known. The measurement setup and obtained spectra are shown in Fig. 10.

4 Concept for an EUVL Source Based on MIRRORCLE

When an appropriate TR target is used, the photon beam can be mostly EUV usable for EUVL. Such a target is named an EUVL target. The calculated power spectra of emission from MIRRORCLE-20SX with one such 60-nm-thick Au foil and of synchrotron radiation from the Ritsumeikan ring AURORA are shown in Fig. 11. It is seen that MIRRORCLE-20SX with 60-nm Au foil can provide $P_{\text{EUVL}} \sim 35$ mW of EUV power, within the 2% band of 13.5 nm, when 1-A electron beam hits the target. This power is significantly larger than the respective power P_{EUVL} from the much larger ring AURORA.

P_{EUVL} can increase when a multilayer TR target is used rather than one foil target.[17,18] If the emitting layers are separated by vacuum spacers (Fig. 12), both the EUV emission from the interfaces foil/vacuum and the EUV transmission through the target are enhanced. In such a case, further enhancement of P_{EUVL} can be achieved by a strict control of the spacers' thickness to ensure a coherent enhancement of the radiation from the individual emitting layers at 13.5 nm while coherently suppressing radiation at other wavelengths. This can be achieved by preparing a MEMS consisting of identical emitting layers separated by identical vacuum spacers.[19] Our estimation shows that using one such MEMS should provide $P_{\text{EUVL}} \sim 150$ mW.

Significantly larger EUV power can be emitted just below the absorption edge of Si from Si/Be MEMS by the mechanism of diffusive radiation.[20] In this case, the alternating layers have different thicknesses, and one such MEMS can provide EUV power ~500 mW in the 2% band of 12.44 nm (Ref. 21). The design and the electron beam behavior of optimized TR targets for the EUVL source based on MIRRORCLE will be the subject of another paper.



(a)

(b)

Fig. 10 Setup for measurement of 2% band EUV spectrum in the vicinity of 13.5 nm of TR from MIRRORCLE-20SX (a) and obtained spectra (b). The injected beam current was I_{Bi}=400 nA.

Stacking of MEMS targets along the stored electron beam trajectory allows simultaneous emission of EUV from each of them. To achieve the required collected power of $P_{\text{EUVL}} \sim 120$ to 180 W for the EUVL source,[2] many such MEMS should be aligned along the stored electron beam. Notably, electron beam current exceeding 1 A passes through each of these MEMS. Radiation emitted from the individual MEMS can be collected using one quasi-ellipsoidal EUV mirror, which provides a collimated EUVL beam at its output.[22] The mirror represents a Mo/Si multilayer structure whose period can be determined using the Lawrence Berkeley National Laboratory (LBL) data-

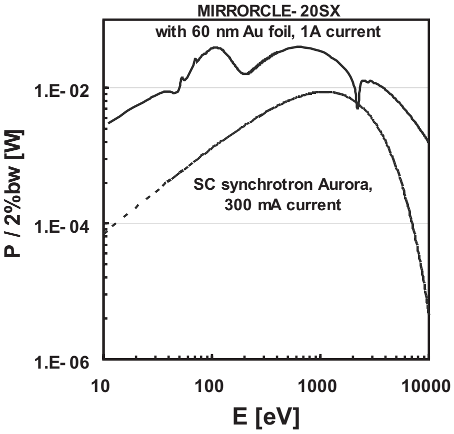


Fig. 11 Calculated power spectra of emission from MIRRORCLE-20SX with one 60-nm-thick Au foil, as well as from the storage ring AURORA. MIRRORCLE-20SX with 60-nm Au foil can provide $P_{\mathrm{EUVL}} \sim 35$ mW of EUV power, within 2% band of 13.5 nm.

base for EUV mirrors,[23] depending on λ, and the angle of incidence. A sketch of the proposed EUVL source based on MIRRORCLE is shown in Fig. 13.

5 Conclusion

An EUVL source can be developed, based on a tabletop electron storage ring, with a beam current of above 1 A. The main ring candidates are MIRRORCLE-20SX, MIRRORCLE-6X, and MIRRORCLE-CV4, which store electrons with energies of 20 MeV, 6 MeV, and 4 MeV, respectively. EUV is emitted from a tiny target hit by the circulating electrons. The radiation mechanisms are either transition radiation or diffusive radiation. Resonant multilayer MEMS targets can enhance and spectrally purify the emitted EUV. Alignment of many such MEMS along the electron beam orbit results in multiplication of the EUV power, while a beam current of above 1 A passes through each of the target layers. The emitted EUV can be collected by a single quasi-ellipsoidal EUV mirror. This approach allows providing EUV satisfying the joint requirements for an EUVL source. If a necessity occurs to increase further the emitted EUV power, this could be achieved by increasing the number of aligned MEMS targets, as well as by improving the beam focusing of MIRRORCLE to increase the beam current passing through the targets.

A comparison between the main capabilities of plasma and MIRRORCLE-based sources for EUVL at ∼13.5 nm is shown in Table 1.

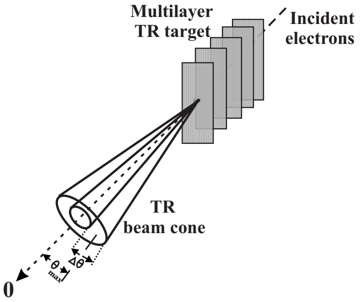


Fig. 12 Sketch of emission from a multilayer TR target consisting of identical emitting layers separated by identical vacuum spacers. The largest possible P_{EUVL} can be obtained when the target represents MEMS, which provides predetermined and constant spacer thickness.

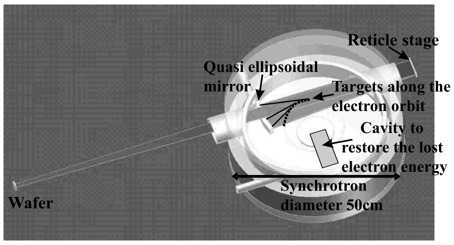


Fig. 13 Sketch of EUVL source based on MIRRORCLE. Radiation from individual MEMS targets is collected by one quasi-ellipsoidal EUV mirror, providing a collimated EUV beam.

Table 1 Comparison between the main capabilities of plasma sources (LPP and DPP) and a MIRRORCLE-based source for EUVL at ∼13.5 nm.

	Power at IF in 2% band, at ∼13.5 nm	Debris problem	Heating problem
LPP and DPP sources	>115 W	Yes	Yes
MIRRORCLE-based source	>115 W	No	No

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Hironari Yamada is a director of the Synchrotron Light Life Science Research Center of Ritsumeikan University. He is an experienced scientist in the field of accelerator physics, synchrotron radiation (SR) instrumentation, and free-electron lasers, as well as nuclear structure physics. He is the first person to propose a scheme to down-size SR by introducing Compton backscattering, bremsstrahlung, and transition radiation using a tiny target in the orbit and a photon storage ring laser scheme with a circular mirror surrounding the electron orbit. He has successfully implemented a tabletop SR of 8-cm orbit radius and observed brilliant far-infrared (FIR), extreme ultraviolet (EUV), and hard x-ray radiations. X-ray flux is reached to the level of second-generation SR. He is also working on many applications such as protein crystallography, extended x-ray absorption fine structure (EXAFS), small angle x-ray scattering (SAXS), FIR spectroscopy, and submicron resolution computed tomography (CT). A 100-W EUV source is the next target of his life work.

Dorian Minkov graduated from Sofia University, Bulgaria, with a specialty in semiconductor physics. His PhD and industrial experience focused on the design and technology of optoelectronic devices—namely, GaAlAs-based LEDs, LDs, and optocouplers. During that time, his main responsibilities included epitaxial growth of the emitting structures and improving the efficiency of light extraction from these structures. During his university employment in South Africa, he developed methods for characterization of thin films utilizing their reflection spectra. These methods are widely used and cited by researchers who characterize optically thin films. At Ritsumeikan University, he is working on design, preparation, and analysis of the performance of targets emitting extreme ultraviolet light in the storage rings of MIRRORCLE synchrotrons.

Biographies and photographs of the other authors not available.