Jan. 28, 2026
10th EUV-FEL Workshop

Development of Next-Generation Semiconductor Process Technologies for EUV and BEUV under Japan's "K Program" by JST

Junji Yumoto

Department for Accelerating the Development of Advanced Priority Technologies
Japan Science and Technology Agency (JST)

The University of Tokyo

Program Overview: K Program

- **Key and Advanced Technology R&D through Cross Community Collaboration Program**
- Launched under the leadership of **the Cabinet Office**, **MEXT***, **METI**** and other government ministries.

  * MEXT: the Ministry of Education, Culture, Sports, Science and Technology
  **METI: the Ministry of Economy, Trade and Industry

- It aims to **enhance economic security** and **advance the research and development of critical technologies** in 5 domains of
  - **Maritime**,
  - **Aerospace**,
  - **Cyberspace**,
  - **Biology**, and
  - **Transversal Technology**

  10-20 programs in each Domain

Program Dynamics (evolving Portfolio)

Maritime domain

Realization of comprehensive maritime security for ensuring maritime rights such as utilization of maritime resource, for maintaining the peace and stability of Japan as a maritime nation, and for securing the lives, bodies, and properties of Japanese.

■ **Improvement of ocean observation, survey and monitoring capabilities (wider range and enhanced mobility)**

- Unmanned and manpower-saving transportation, injection, and collection technology for autonomous unmanned vehicle (AUV).
- AUV airframe performance improvement technology (small scale and lightweight).
- High-precision navigation technology in the sea (non-GPS environment) using state-of-the-art technology such as quantum technology.

■ **Improvement of ocean observation, survey and monitoring capabilities (securing communication networks)**

- Undersea wireless communication technology that enables drastic unmanned and efficient underwater work(*).

■ **Improvement of ocean observation, survey and monitoring Capabilities（continuous operation）**

- Spatial observation technology from the sea surface to the sea floor using advanced sensing technology.
- Technologies for extracting, analyzing, and integrating useful information from observation data.
- Innovative underwater sensing technology using state-of-the-art technologies such as quantum technology.

■ **Better use of ship data which has not been utilized**

- Next-generation data sharing system technology that advances the current Automatic Identification System (AIS).

■ **Ensuring stable marine transportation**

- High-performance next-generation ship development technology using digital technology(*).
- High-resolution and high-precision environmental change prediction technology that contributes to stable marine transportation(*).

Aerospace domain

Achieving **independent space utilization** that secures superiority in space utilization, and development of **safe and convenient** air logistics and aircraft uses.

■ **Drastic enhancement of satellite communication and sensing capabilities**

- Low-earth-orbit Inter-satellite optical communication.
- Satellite constellation network system technology capable of automatic and autonomous operation.
- High performance small satellite technology.
- Compact and highly sensitive multi-wavelength infrared sensor technology.
- High-resolution and continuous remote sensing technology using high-altitude unmanned aircraft(*).
- Optical antenna technology for realizing super-high-resolution and continuous observation(*).

■ **Expansion of the use of unmanned aerial vehicles (UAV) for commercial and governmental use**

- Small UAV technology that enables long-distance flight.
- Flight safety management technology covering small UAVs.
- Highly reliable information communication technology with small UAVs.
- UAV technology for long-distance cargo transport(*).

■ **Developing new UAV technologies that will lead to technological superiority**

- Autonomous control/distributed control technology for small UAVs.
- Detection technology for small UAVs to improve airspace safety.
- Wind condition observation technology for flight paths of small UAVs.

■ **Developing cutting-edge technologies in the aviation**

- Advanced technology for aircraft development and manufacturing process using digital technology.
- Advanced material technology for aircraft engines (composite material manufacturing technology).
- Supersonic element technology (low-noise airframe design technology).
- Hypersonic element technology (Engine design echnology with a wide operating range).

■ **Capacity building for functional assurance**

- Refueling technology that contributes to extending the life of satellites(*).

Cyberspace domain

Building a foundation to ensure safety and security through a cross-domain fusion system of cyberspace and real space.

- Addressing Cyber-AI security challenges.
  - Detecting malfunctioning of systems (firmware/software/hardware).
  - Development of basic infrastructure for hybrid cloud usage.
  - Strengthening advanced cyber defense functions and analysis capabilities(*).
  - -Cyberspace situational awareness and defense technology(*).
  - -Encryption technologies that support secure data distribution(*).
- Disinformation analysis technology(*).
- Fundamental digital technology such as for transmission of human operation realizing effective transfer of know-how(*).

Biology domain

Building a crisis management infrastructure for emergencies such as infectious diseases and terrorism.

- Advanced research analysis equipment and technology such as biomolecular sequencers.
- Rapid and highly accurate multi-gas sensing system technology that enables detection and identification of various substances(*).
- Hemostatic agent manufacturing technology for emergencies(*).
- Advanced technology for high-precision Brain-Tech using brain waves and other noninvasive measurement(*).

Transverse domain

- Next-generation battery technologies that can be installed in new motilities.
- Advanced imaging technologies such as innovative positioning system and 3D imaging technologies that use cosmic ray muons.
- Cutting-edge manufacturing technology for complex-shaped and/or high-performance products responding to diverse needs.
  - -Advanced metal laminate shaping system technology(*).
  - -High-efficiency, high-quality laser processing technology(*).
- High-performance metal materials with less or no rare metal.
  - -High-performance, rare-metal-saving technology for heat-resistant superalloys(*).
  - -High heat resistance and high magnetic force technology for heavy rare earth-free magnets(*).
- Adhesion technology for composite materials. that realizes innovative structures for such as transport aircraft(*).
- Next-generation semiconductor materials and manufacturing technology.
  - -Next-generation semiconductor super-microfabrication process technology(*).
  - -Material technology for high-voltage-output, high-efficient power devices/high-frequency devices(*).
- Next-generation storage battery technology suitable for isolated and extreme environments(*).
- Fundamental superconducting technology that enables application to various devices and systems(*).

(*) denotes 23 key technologies selected in R&D vision of 2nd version on 28/AUG/2023. The other 27 technologies were selected in R&D vision of 1st version on 16/SEP/2022.

AI　Quantum　Robotics (drone)　Advanced sensor technology　Advanced energy technology

Leading Projects in 5 Domains

Maritime

- Ocean observation, survey and monitoring
- Stable marine transportation

Aerospace

- Satellite communication and sensing capabilities
- Unmanned aerial vehicles (UAV)

Cyberspace

- Cyber-AI security
- Encryption technologies

Biology

- Biomolecular sequencers
- highly accurate multi-gas sensing

Transversal Technology

- **Semiconductor process technology**
- Battery technologies
- 3D imaging technologies
- Superconducting technology

A total budget of JPY 500 B (approximately USD 3B) was allocated for K Program.

Next-Generation Semiconductor Process Technology for EUV and BEUV

- **Semiconductors as the Critical Infrastructure Backbone of the Digital Society: 5G, AI, IoT, DX**
  - Designated as **Specified Critical Materials**
- **National Challenge**
  - Enhancing Japan’s global competitiveness in the semiconductor sector
  - Japan’s Strengths: Materials and processing technologies
- **Strategic R&D Focus**
  - Development of energy- and space-efficient laser and mirror technologies
  - Acceleration of R&D on next-generation semiconductor process technologies
  - Innovation in related fields, including materials and metrology
  - Industry collaboration for practical implementation

Clear pathway from advanced technological development to industrial implementation.

Next-Generation Semiconductor Process Technology for EUV and BEUV

1 Development of energy- and space-efficient lasers for EUV lithography

- Development of driver lasers. In particular, development of laser oscillators, preamplifiers, amplifiers, and energy propagation measurement and control techniques.

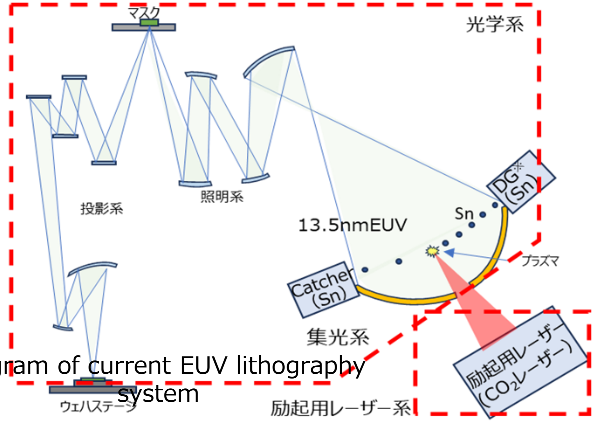

Diagram of current EUV lithography system

2 Mirror development for EUV lithography

- Development of ultra-fine polishing technology, film technology, and ultra-precision mirror characteristic measurement technologies required for EUV mirrors.

3 Development of next-generation microfabrication process for chip mounting process

- Development of database on multi-scale microfabrication, development of AI technology for high-speed condition generation, etc.

4 Development of Innovative Fundamental Technologies for Beyond EUV

- Development of elemental technologies for the development of **new high-performance light sources** for EUV lithography. In addition, feasibility studies of measurement technologies that go beyond existing EUV lithography technologies.

Schedule and Current Status

- **Current Status:**
  6 projects are selected.
- **Total Budget:**
  JPY 13.5B (approximately USD 100M)
- **Start Date: April 2025**
- **Duration: 5 years**

Selected 6 Projects (PIs and Key Words)

1. **Dr. Katsumi Midorikawa (RIKEN*)** — Laser | Mirror | LMP#
   – LD-Pumped Drive Lasers, EUV Mirrors, Chip Assembly Process Technologies
2. **Prof. Yosuke Honda (KEK**)** — Laser
   – Free-Electron Laser for Next-Generation EUVL
3. **Prof. Ryo Yasuhara (NIFS***)** — Laser
   – Solid State Drive Lasers at 3 - 4 μm Range
4. **Prof. Takahiro Kozawa (Osaka University)** — Material
   – Photoresist Science for BEUV
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   – Nonlinear Optical Crystals at 170nm for Inspection Equipment
6. **Prof. Takeo Ejima (Tohoku Univ.)** — Mirror | Metrology
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*RIKEN: The Institute of Physical and Chemical Research
**KEK: High Energy Accelerator Research Organization
***NIFS: National Institute for Fusion Science
#LMP Laser Material Processing

K. Midorikawa (RIKEN)

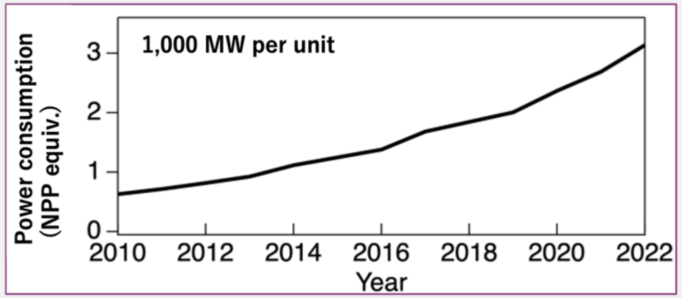
Strategic Challenges for a Sustainable Semiconductor Ecosystem

① Higher-Power EUV	② Higher NA Mirror	③ Advanced Packaging

① Higher-Power EUV

Power required for EU generation

NA 0.55 : 500 W → 2.2 MW
NA 0.77 : 1000 W → 4.4 MW



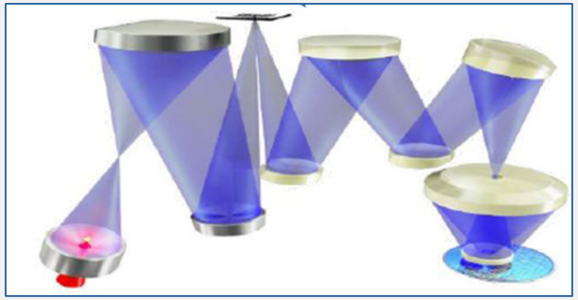
TSMC Power Consumption (Nuclear Power Plant Eqv.)

The existing CO_2 laser technology cannot be scaled effectively.

2-μm solid-state laser technologies to reduce energy consumption

② Higher NA Mirror

The high precision requirements and increasing size of EUV mirrors lead to higher costs.

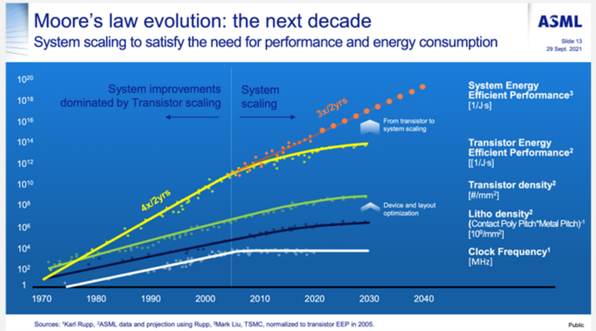


Conventional manufacturing approaches result in mirror production significantly increasing the cost of the optical system.

Processing technologies to reduce manufacturing costs

③ Advanced Packaging

Chiplet integration combining front-end and back-end is needed.



The transition from organic substrates to a glass-based ecosystem is a key challenge.

Versatile laser-based microfabrication technologies for glass

Development of next-generation key technologies to address global challenges in semiconductor processing

① Higher-Power EUV (1)

Drive Laser Technologies for EUV Lithography

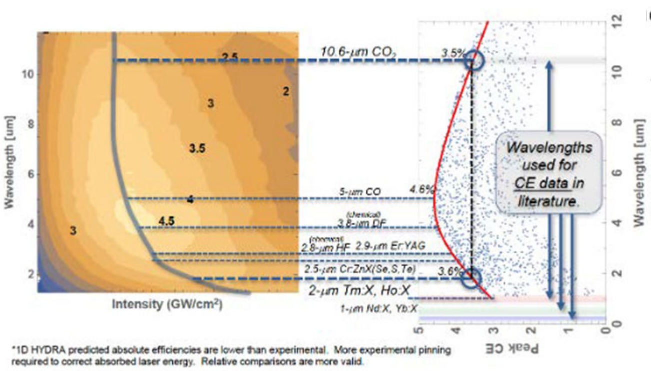
Requirements for EUV driver lasers in the near future

- High wall-plug efficiency
- Laser power scalability (100-kW class)
- Compactness

→ key technology: **Energy-saving, high-average power laser**

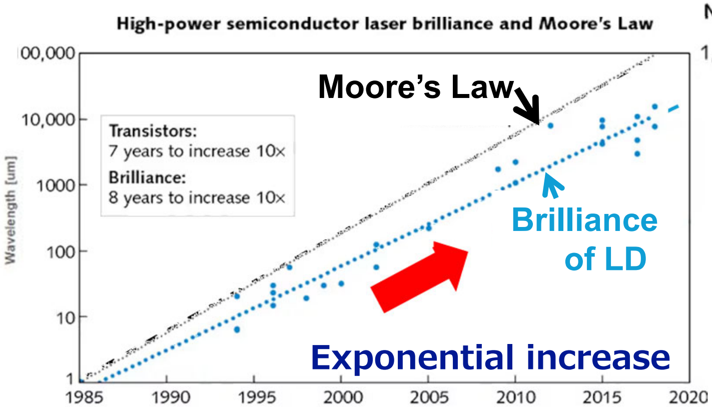
Energy efficiency of EUV driver lasers

EUV Conversion efficiency

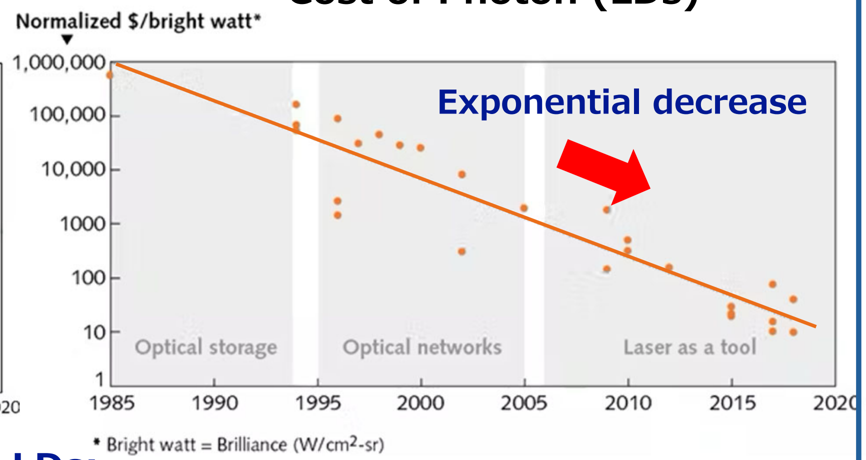


A wavelength of 5 μm would be ideal, but no high-power laser technology is currently available.

Brightness (LDs)



Cost of Photon (LDs)



Continuous improvements in LDs:

- Efficiency
- Power
- Photon cost

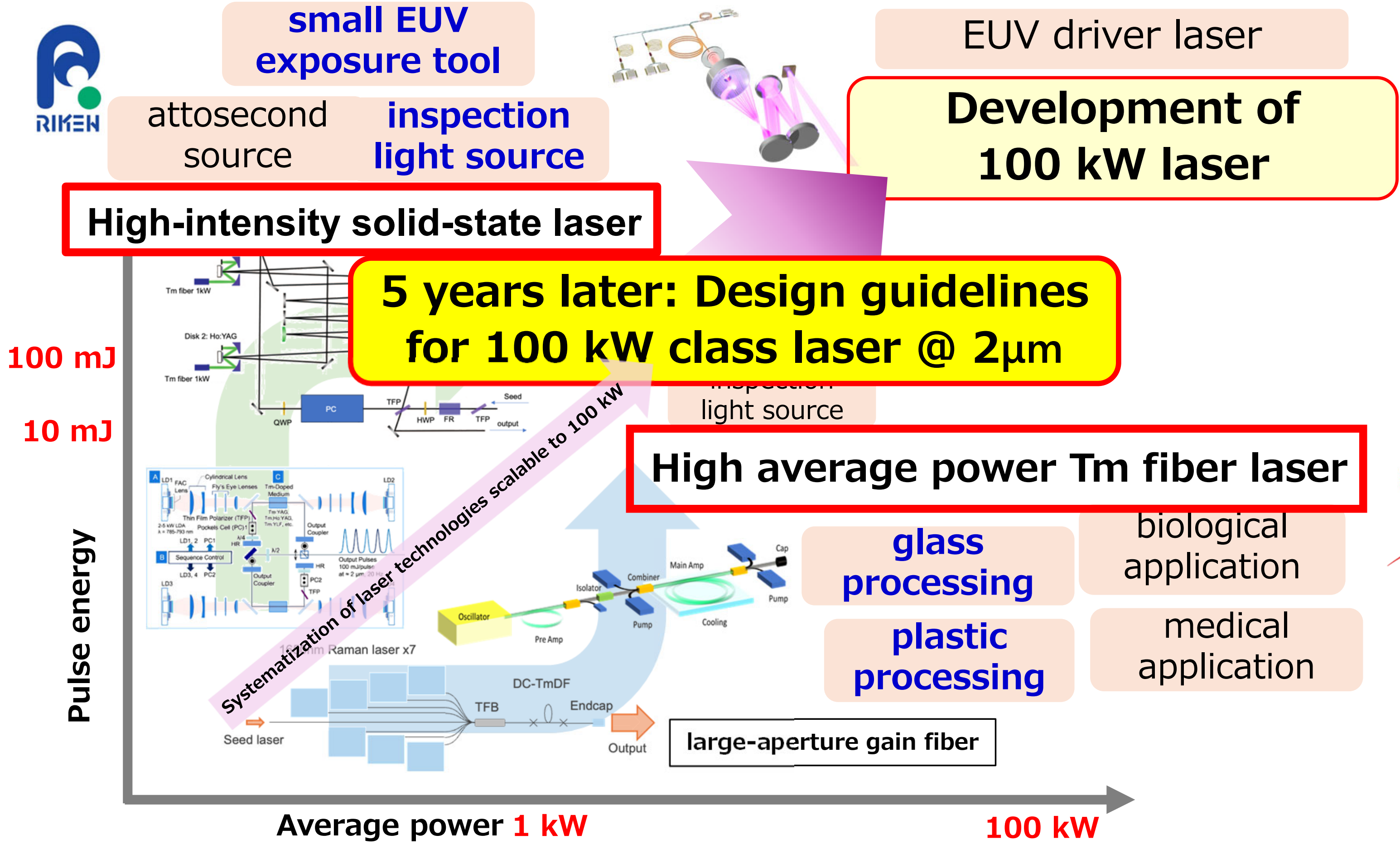
⇒ LDs will significantly advance EUV drive lasers and are also expected to revolutionize lasers in industrial and scientific applications.

① Higher-Power EUV (1)

Future Development Roadmap for Our Drive Laser System

Pulse energy (RIKEN) and average power (Univ of Tokyo, AIST, Furukawa)

RIKEN



UTokyo

産総研 (AIST)

FURUKAWA ELECTRIC GROUP

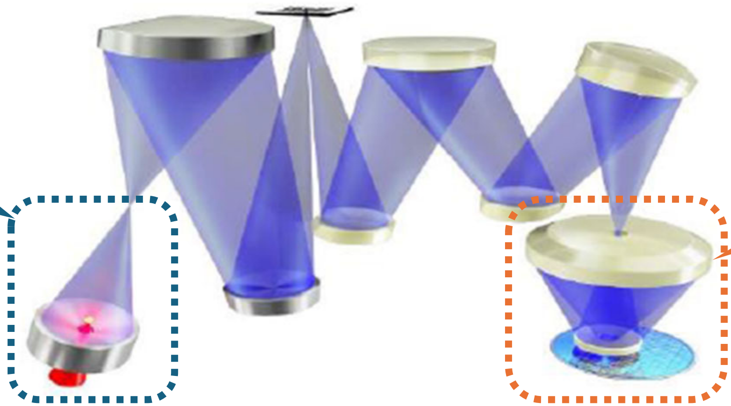
EUV generation and LPP simulation (Kyushu Univ, Hokkaido Univ, Osaka Univ.)

EUV collector mirror and projection mirror

EUV collector mirror

- ➢ Collect EUV light
- ➢ Diffuse infrared drive laser

- Low surface roughness≦0.2nm RMS
- Grating to diffuse drive laser light
- Graded multilayer coatings
- Integrated cooling capability
- Diameter > 1m



EUV Projection Mirrors

- ➢ Extremely high precision mirrors are required

- Ultrasmooth surface
- Long and mid wavelength error <0.1nm RMS
- (Meet Marechal Criterion for 6 mirrors)
- (Mirror Diameter > 1m (NA0.55))

Carl Zeiss Optics of 0.55NA
Ref: 2024 EUVL Workshop and Supplier Showcase @LBNL 06 June 2024
Status and outlook of EUV optics at ZEISS

Challenge:
- Frequent replacement due to plasma contamination
  - ⇒ Results in high costs and reduced chip manufacturing efficiency

Approach:
- Developing low-cost manufacturing technology
- Facilitate technology transfer to manufacturers
  - ⇒ Including EUV mask testing equipment vendors

Challenge:
- High polishing cost due to interference between figure and mid-/short-wavelength errors

Approach:
- low-cost, high-precision polishing for EUV/BEUV optics
- Demonstrate via pilot application to synchrotron optics

RIKEN(Y.Yamagata), Univ. of Tokyo (H.Mimura), Univ. of Osaka(K.Yamauchi), KOGEI Tokyo Polytech.Univ. (M.Toyoda)
AIST(Y.Bito), ISSP, U.of Tokyo(T.Kimura)

Development of Low Cost EUV collector mirror

Strategy:

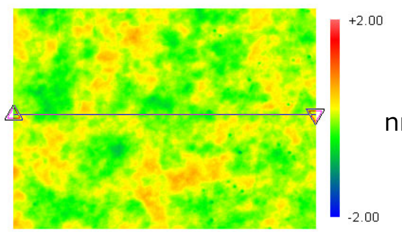
- **Aiming for next-generation excitation laser (2μm) and larger diameter collect mirrors**
- **Collect mirror manufacturing for LPP EUV source**
- **Introduction of replication process and segmented mirror system for achieving overwhelming low cost**

Ultraprecision Replication Technology

UTokyo

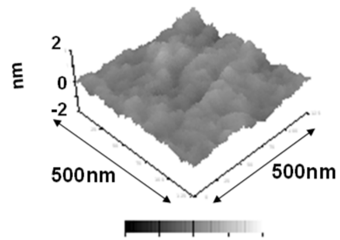
Low cost manufacturing by Replication

- **Excellent surface roughness using direct replication without lift-off layer**
- Room temperature electroplating condition for good replication figure accuracy



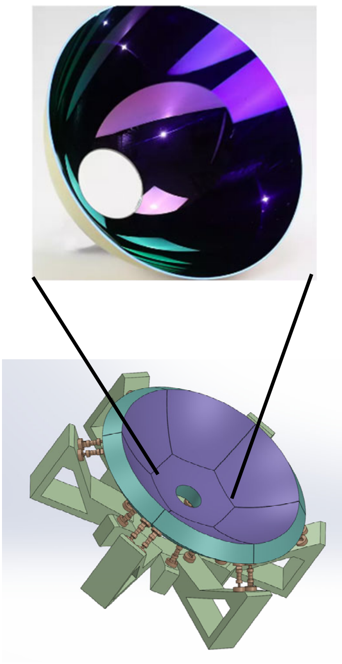
P-V: 1.760nm Rms: 0.222nm

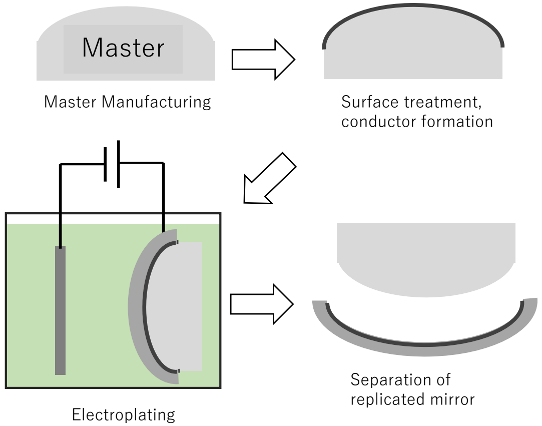
Phase shift interferometer microscope 64μm×48μm



P-V: 2.201nm Rms: 0.183nm

AFM image 500nm×500nm



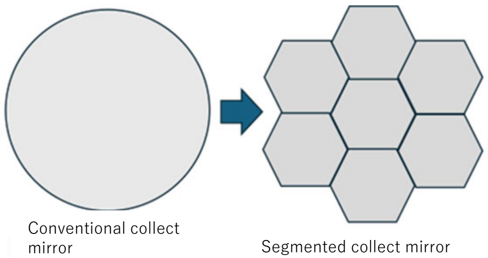


Ultraprecision segmented mirror system

RIKEN 産総研

Lowering cost by segmented mirror

- Precision machining of mirrors with sufficient geometry
- Efficient cooling system
- **High-precision support structure for segment mirror exchange**

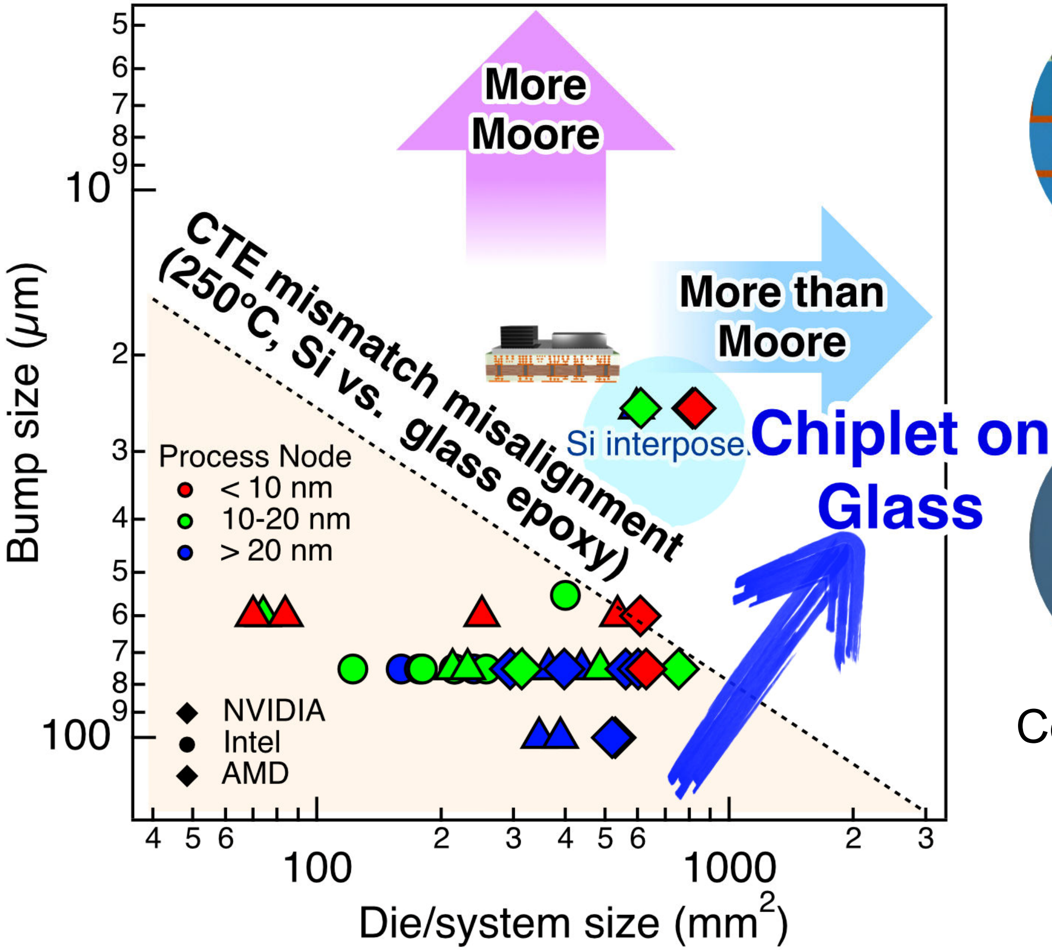


③ Advanced Packaging (2)

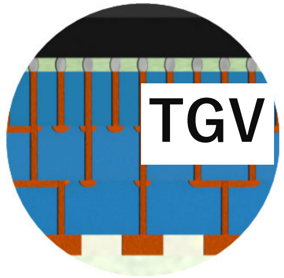
ICs require higher speed, lower power, and lower cost.

Key technologies to be developed

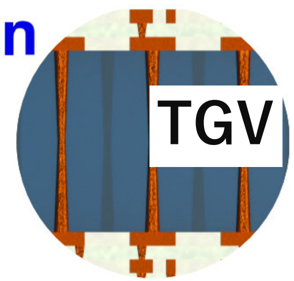
Die size vs. bump size



Key technologies to be developed



Interposer



Core substrate

TGV Challenges

	To date
Shape control	
◆ High aspect ratio	~ 10
◆ Good circularity	~ 0.9
◆ Minimal taper angle	
Process speed	
◆ High throughput	~ 300 vias/s
Environmental impact	
◆ Minimal HF etching	

Zero Pollution Action Plan (EU, 2021)
HF Regulation under TCCSCA (Taiwan, 2021)
HF Regulation under EPCRA and CAA (US)

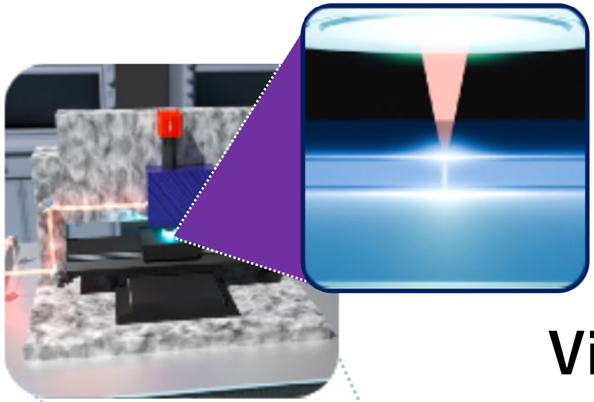
③ Advanced Packaging (3)

Next-Generation Microfabrication Process in Chip Assembly

Output of the Project

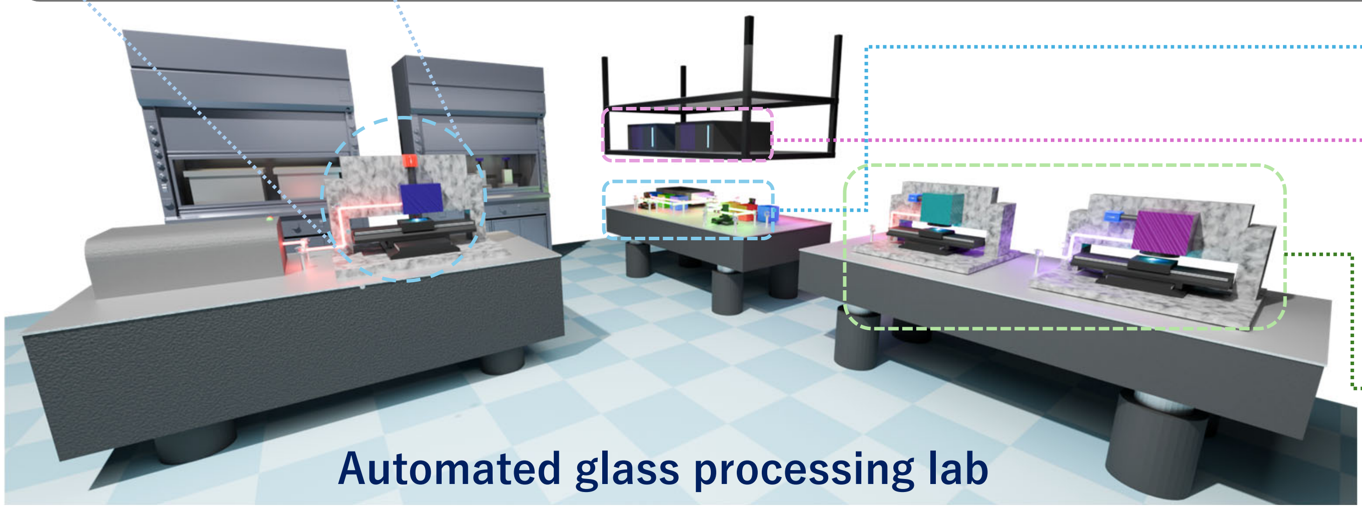
High-speed precision laser processing technology for glass

High-speed & high-precision glass processing technology



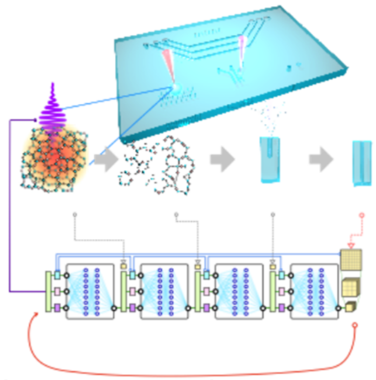
- ✓ Laser direct drilling: no etching
- ✓ High speed
- ✓ High precision
- ✓ High aspect ratio

Via formation at 10,000 vias/s



Automated glass processing lab

Development of Processing Digital Twin



Fully Automated In-Situ High-Quality Large-Scale Data Acquisition

- High-Density Excited State
- Defect Generation
- Etching Process

Deep-learning-based modelling

Parameter optimization on Processing Digital Twin

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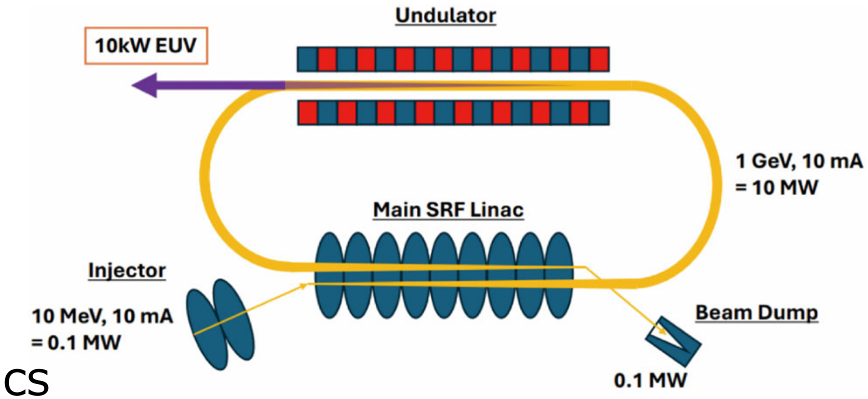
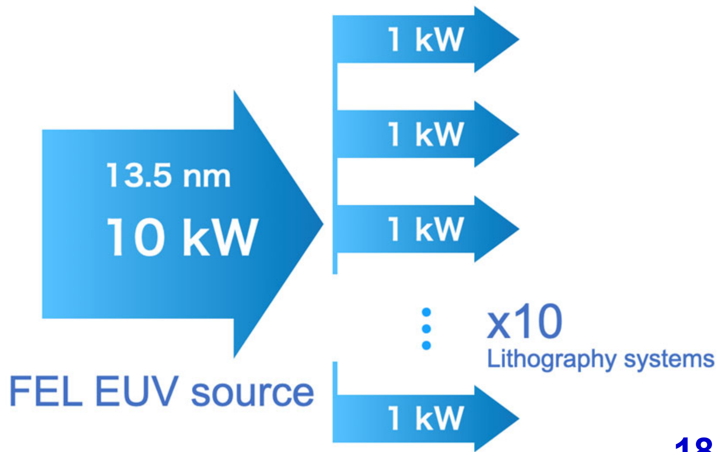
*RIKEN:	The Institute of Physical and Chemical Research	***NIFS:	National Institute for Fusion Science
**KEK:	High Energy Accelerator Research Organization	#LMP	Laser Material Processing

FEL Can Address the Limitations of LPP

- Power output **exceeding 10 kW**
- Power efficiency: **0.5 MW/kW-EUV** (one order of magnitude improvement)
- Supports **high-resolution patterning** with High-NA optics
- **Polarization can be optimized** for specific process patterns
- **Scalable to Beyond-EUV** by increasing e-beam energy using the same scheme
- **Lower maintenance costs** due to absence of mirror contamination

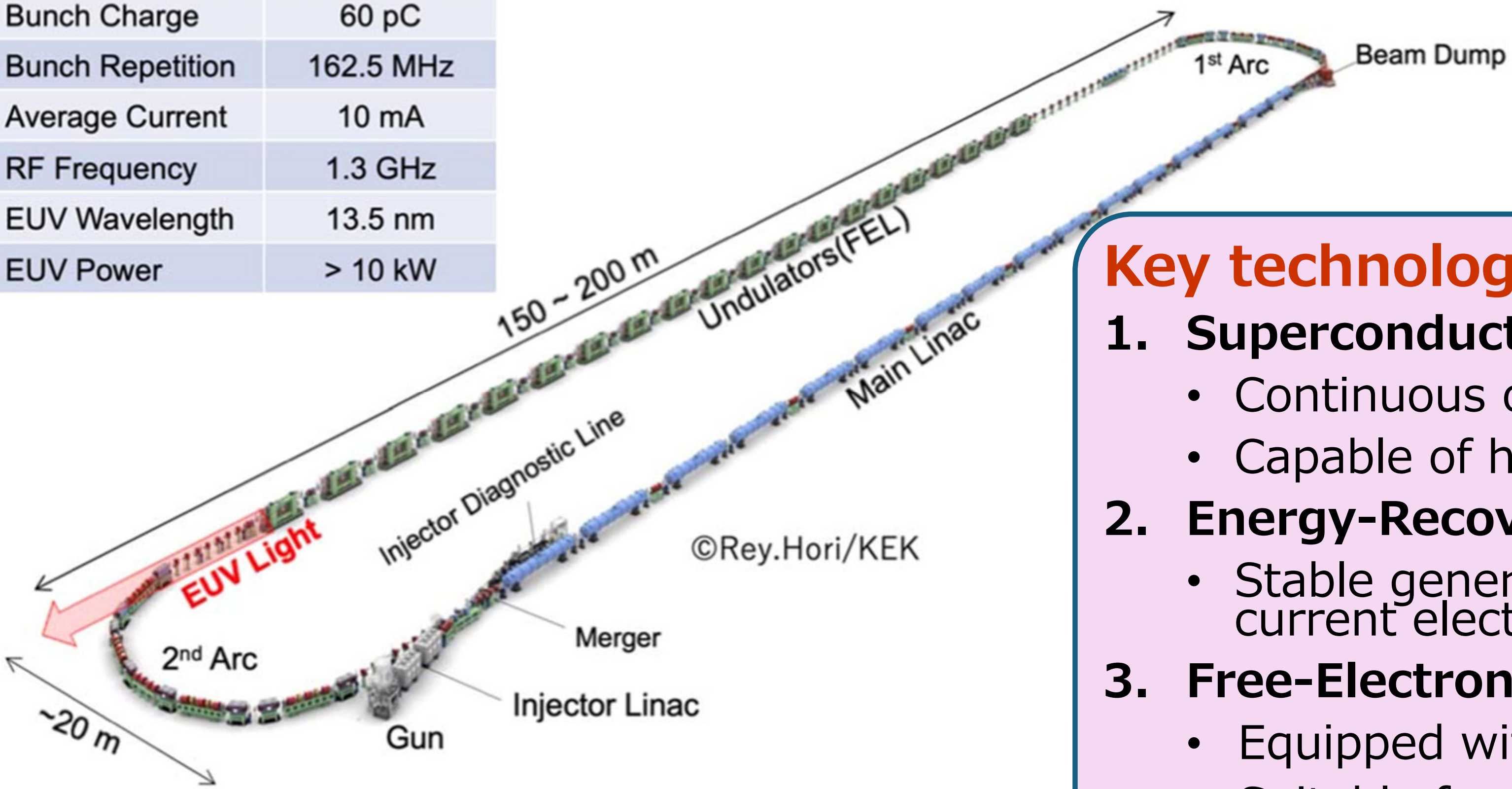




"Fundamental Technology Development for Free-Electron Lasers Toward an Innovative Next-Generation EUV Lithography Light Source"

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

Jpn. J. Appl. Phys. 62, SG0809 (2023)



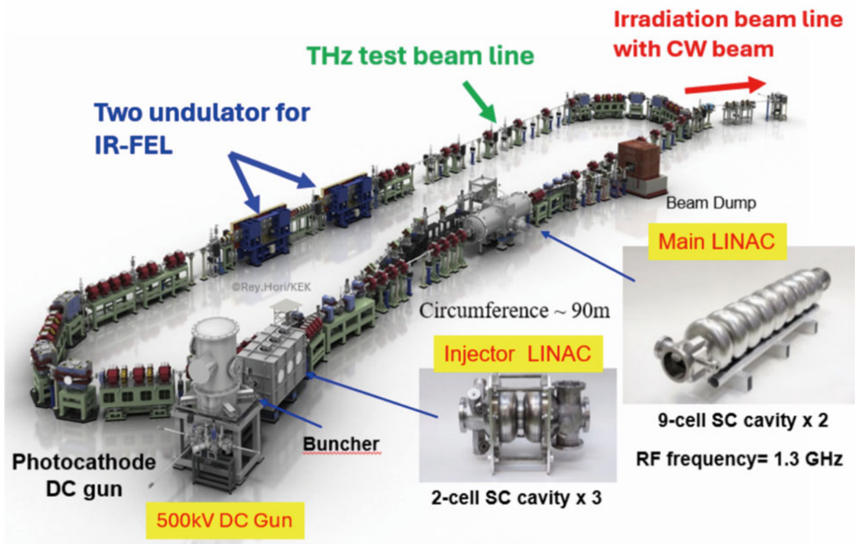
Key technologies:

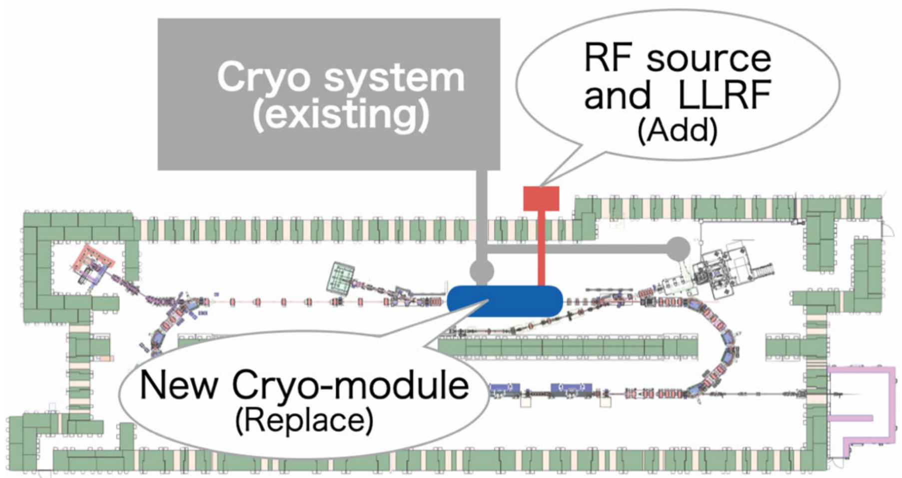
1. **Superconducting accelerator**
   - Continuous operation with low heat load
   - Capable of handling high-current beams
2. **Energy-Recovery Linac (ERL)**
   - Stable generation and circulation of high-current electron beams
3. **Free-Electron Laser**
   - Equipped with undulator
   - Suitable for mass production
   - Advanced beam handling techniques

Fundamental Technology Development for Free-Electron Lasers
Toward an Innovative Next-Generation EUV Lithography Light Source

Development plan in 5-years

1. Utilize existing test ERL accelerator (cERL) to demonstrate beam operation
2. Develop one accelerator module and conduct high-power RF performance test
3. Design and fabricate a prototype EUV undulator based on existing IR undulators.
4. Perform overall machine design





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Development of a High-Efficiency EUV Light Source Driven by High-Power Mid-Infrared Lasers in the 3–4 μm Wavelength Range

Motivation

National Institute for Fusion Science, R. Yasuhara

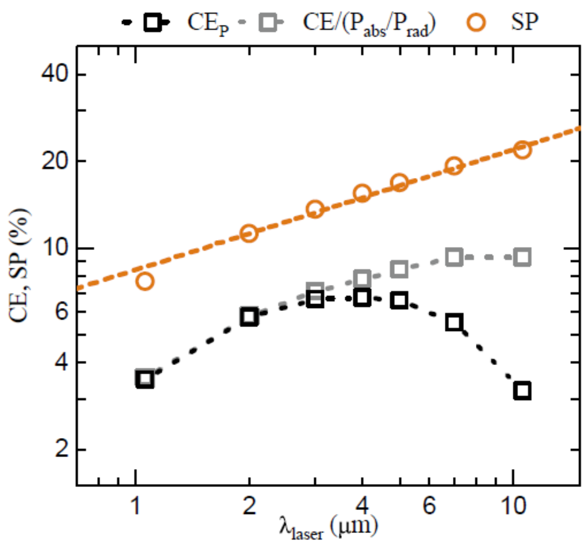


Figure 1 Wavelength dependence of the optical-to-optical conversion efficiency from irradiated laser to EUV light

<D. J. Hemminga et al., Phys. Plasmas 2023>

- **The 3 to 4 μm band has the highest conversion efficiency.**
- **Considering industrial applications, an improvement of EUV power by more than a factor of 20 is highly significant.**

- **Development of high-power mid-infrared lasers**
  - ✓ **Target wavelength range: 3–4 μm**
- **Confermation of high-CE EUV generation**
  - ✓ **For potential application in next-generation lithography**

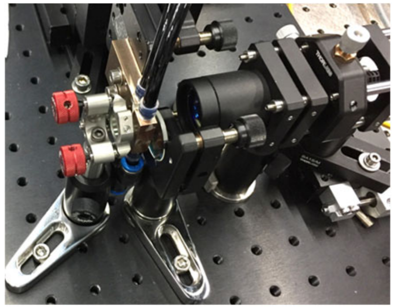
High-Power EUV Drivers Enabled by 3 - 4 μm Solid-State Laser Innovations

■ Diode-pumped 2.9 μm Er:YAP laser

Research Article Vol. 27, No. 9 | 29 Apr 2019 | OPTICS EXPRESS 12213
Optics EXPRESS

2.92-μm high-efficiency continuous-wave laser operation of diode-pumped Er:YAP crystal at room temperature

HIROKI KAWASE[1,4] AND RYO YASUHARA[1,2,3]



- Very compact
- High-efficiency (slope 34%)
- .High thermal conductivity (11W/mK)
- .10 W level

First 2.9μm CW oscillation, highest efficiency of Er:YAP lasers

Further refine cutting-edge technologies toward EUV light sources.

Technical challenges

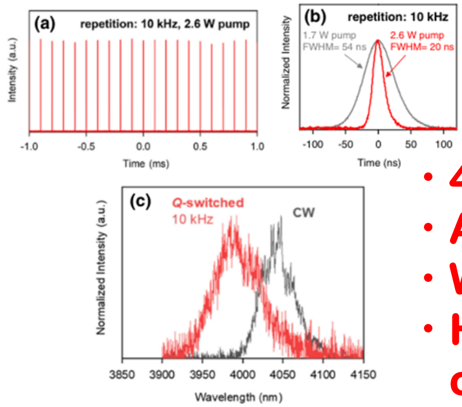
- Efficient thermal management
- High laser damage resistance

■ All solid 4 μm Q switch laser

Optics Letters

40 kHz, 20 ns acousto-optically Q-switched 4 μm Fe:ZnSe laser pumped by a fluoride fiber laser

HIYORI UEHARA,[1,5] TAKANORI TSUNAI,[2] BINGYU HAN,[2] KENJI GOYA,[3] RYO YASUHARA,[1] FEDOR POTEMKIN,[4] JUNJI KAWANAKA,[2] AND SHIGEKI TOKITA[2,*]



- 40kHz
- All-solid state
- Watt-level
- High thermal conductivity (18W/mK)

All solid-state Q-switched 4μm laser

Based on the proponents' previous work at 3 μm and 4 μm wavelengths, developing solid-state lasers capable of generating EUV light at a power density of 10^{10} W/cm²—will be realized.

Selected 6 Projects (PIs and Key Words)

1. **Dr. Katsumi Midorikawa (RIKEN*)** — Laser | Mirror | LMP#
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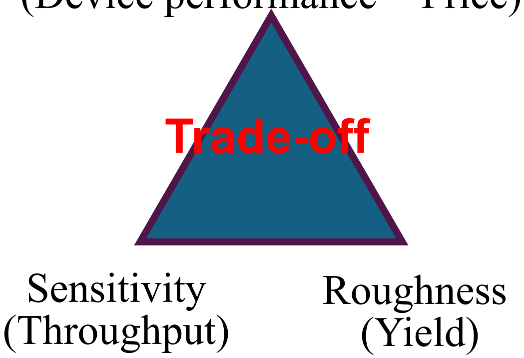
*RIKEN:	The Institute of Physical and Chemical Research	***NIFS:	National Institute for Fusion Science
**KEK:	High Energy Accelerator Research Organization	#LMP	Laser Material Processing

Development of high-performance extreme ultraviolet resist based on reaction system enabling high-sensitivity and high-resolution patterning without chain reactions

T. Kozawa (The University of Osaka) and S. Enomoto (Toyo Gosei)

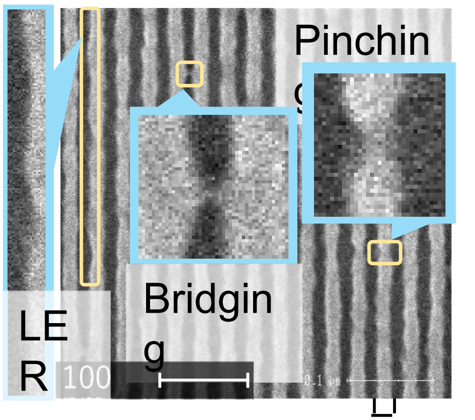
				N7	N5	N3			Ånode		
Year	2001	04	07	16	19	22	24	26	28	30	
Resolution (nm)	130	90	65	22	20	15	14	12	10	8	Target
Roughness (nm)				1.8	1.5	1.3	1.2	?	?	?	
Source (Wavelength)	KrF 248nm	ArF 193nm	ArF immersion (+DP) 193nm		EUV 13.5m			EUV (High NA) 13.5m			
	EB for mask production										

Obstacle to EUV litho



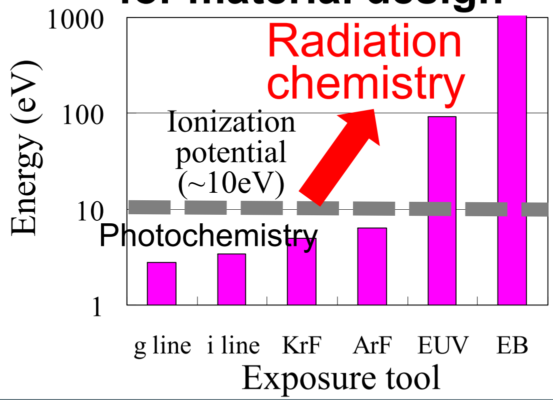
Trade-off relationship between resolution, LER, and sensitivity

Obstacle to High NA



Stochastic defect

Transition of science for material design

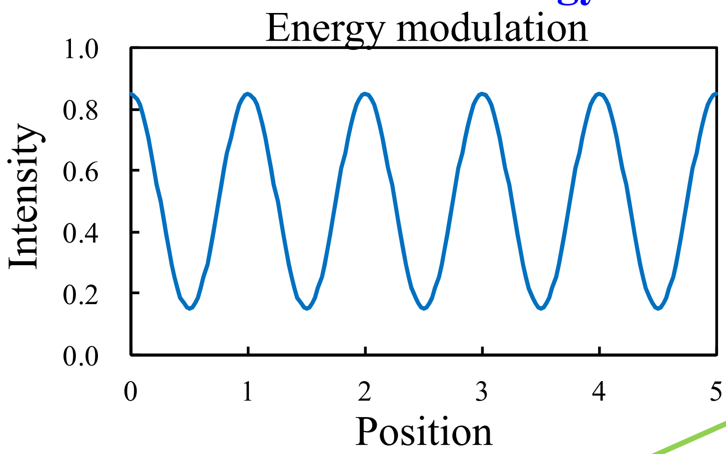


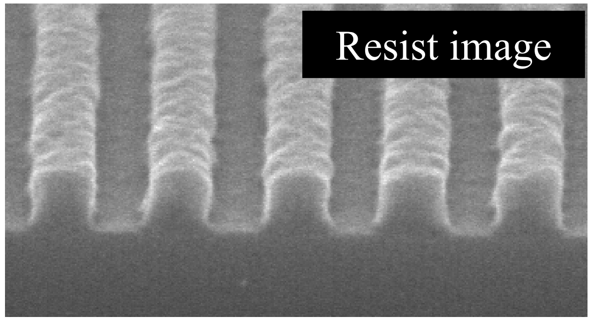
From direct excitation of sensitizer to redox reaction of all resist components

Role of Photon and Resist

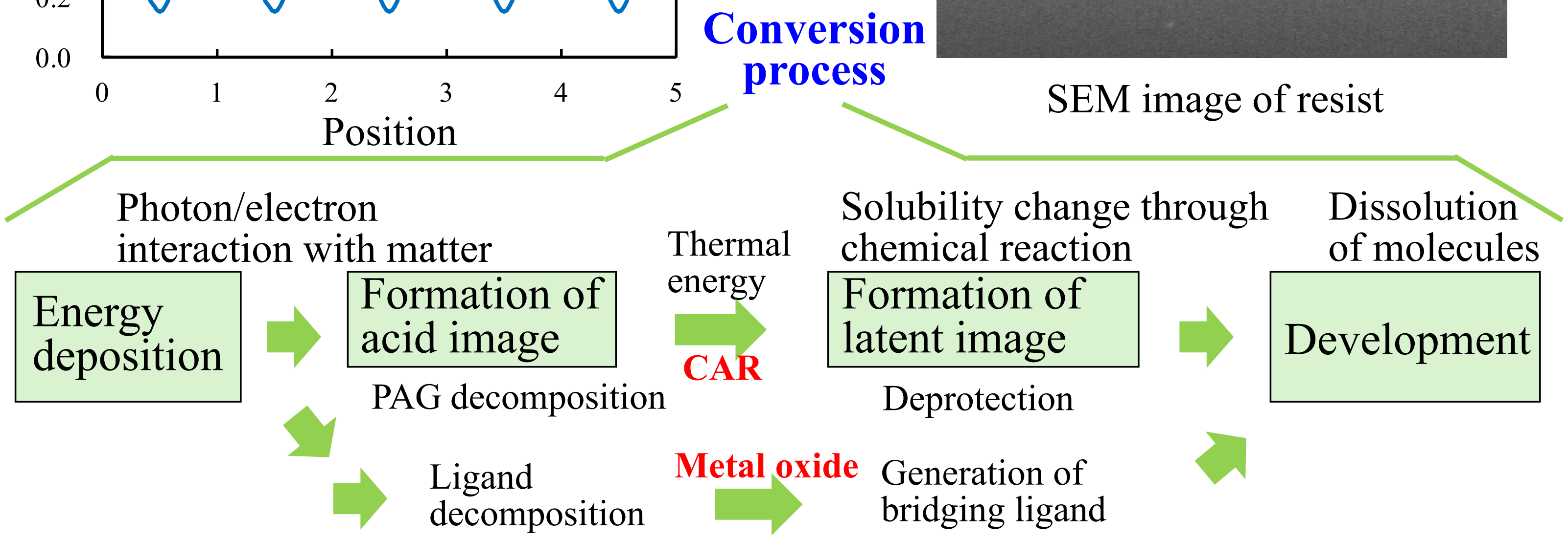
Transfer of information and energy for imaging

Energy modulation to binary image





SEM image of resist



First-Gen. EUV resist: **Improved acid generation and chemical process**

Remaining challenges: **Low photoabsorption and issues in the development process**

Key concepts: **Enhancing photoabsorption, introducing new developer, and re-optimizing chemical process**

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#LMP Laser Material Processing

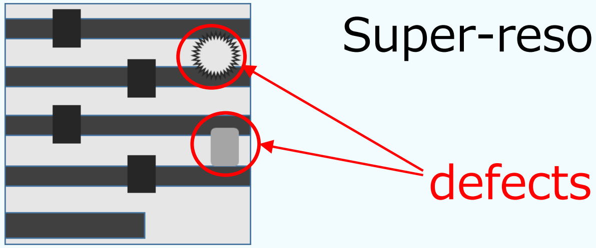
Development of nonlinear optical devices for coherent light generation in the wavelength range of 170nm and their applications

Target application field

PI : Akio Miyamoto

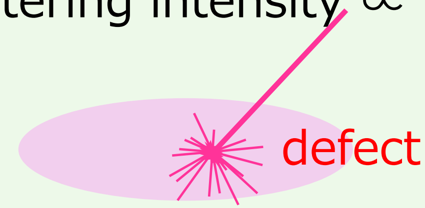
Ultrafine inspection using ***a coherent VUV light source*** for **EUVL era**

Super-resolution $\propto \lambda$



Patterned masks or wafers

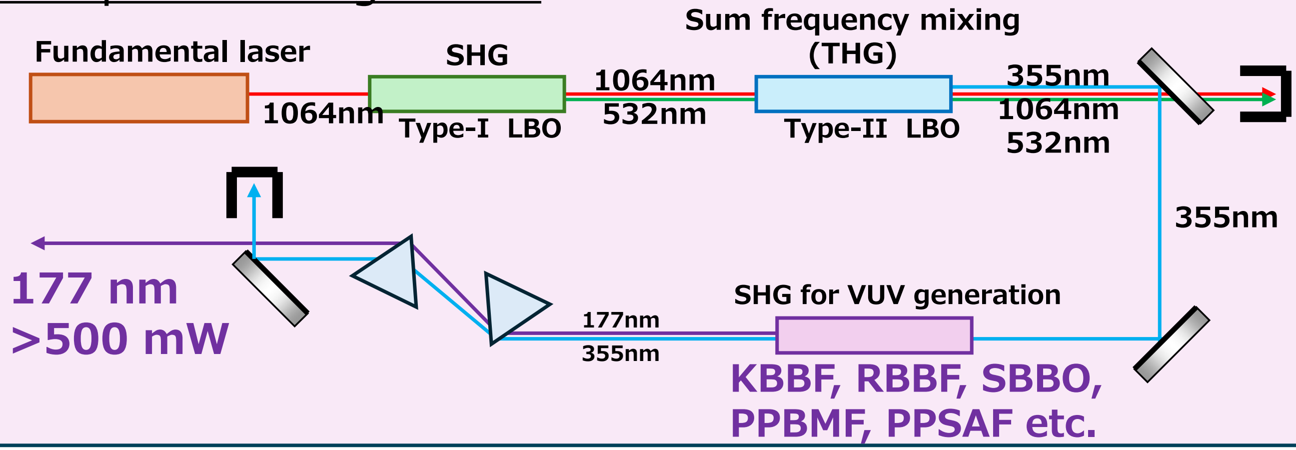
Scattering intensity $\propto \frac{1}{\lambda^4}$



Polished wafers or Mask blanks

Final goal **:**
λ~170nm range
output > 500mW
Coherent source

Example of configuration



Development of nonlinear optical devices for coherent light generation in the wavelength range of 170nm and their applications

OXIDE challenges to achieve the goal by its strong technology

Established in Oct. 2000 as the venture company from NIMS
    Technology transfer under license from NIMS

Provide Material Solution
    A company with most of the crystal growths

Expand business from key materials to laser systems

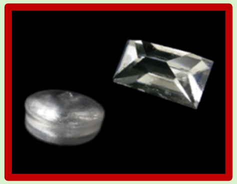
Crystal growth technologies

CZ	FZ	TSSG	VG	DCCZ

UV laser products lineup

266nm CW laser (production model) | **266nm QCW laser (production model)** | **213-257nm CW laser (new product)** | **114nm pulse laser**

Semiconductor Industry Products



nonlinear crystals
BBO/CLBO/LBO

UV lasers
355nm/266nm

image

Used in semiconductor wafer inspection, in operation around the world

Source:
Correction-Notice-of-partial-correction-to-Supplementary-Explanatory-Materials-for-Fiscal-Year-2025-February-Financial-Results.pdf

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Development of BEUV Multilayer Mirrors Using Ion Sputtering with Quantum Ellipsometry-Enabled Precise Thickness Control

PI: EJIMA, Takeo (Tohoku Univ.)

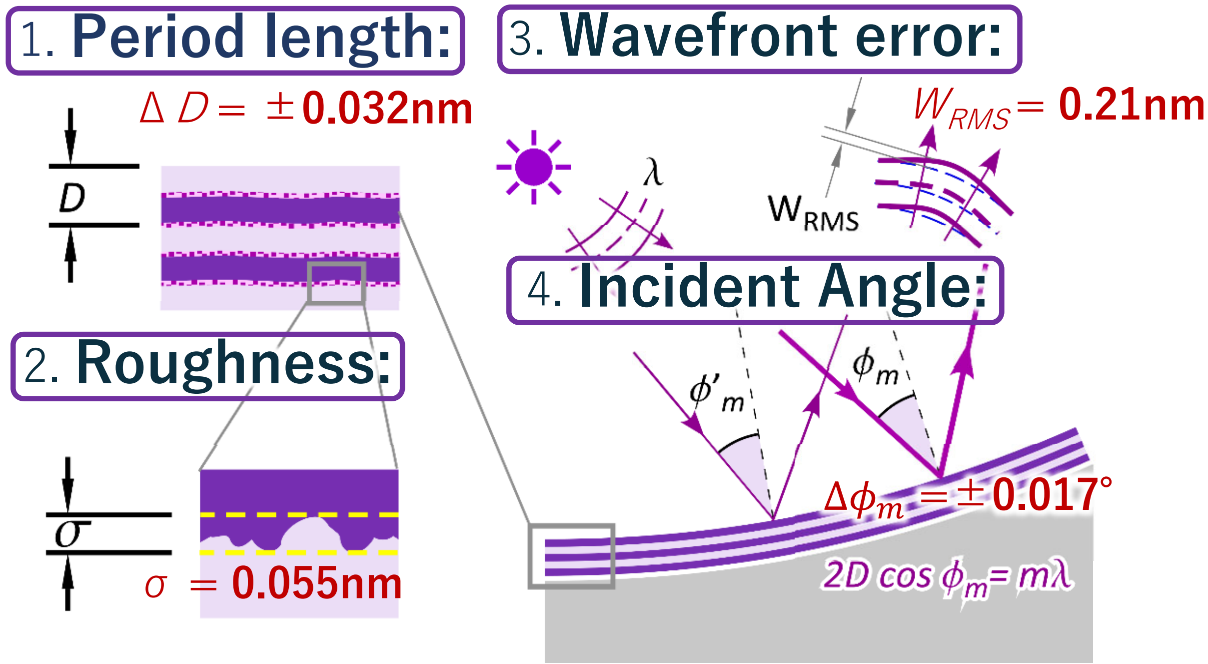
Co-PI: MIZUTANI, Yasuhiro (Osaka Univ.)

- **Present Status of Exposure Tools**
  - λ =13.5 nm
  - NA=0.55@EXE:5000(ASML)
- **IRDS 2023**
  - hyper-NA: **NA ≥ 0.75**
  - BEUV: **λ =6.x nm**

● Targets:

- **Development of reflection multilayers for BEUV reflection mirrors.**
- **Development of BEUV imaging optics using the developed reflection multilayers.**

Tolerance of BEUV Multilayer Mirror for 6.8 nm



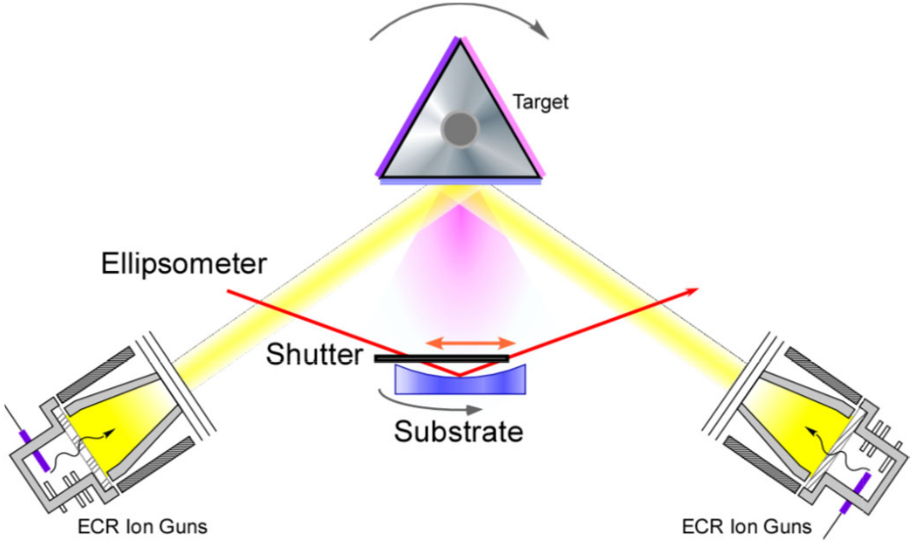
ΔD, σ, W_{RMS}, $\Delta\phi_m$: Estimated values of fabrication errors at **60%** of theoretical reflectance, $\mathbf{R_T}$ assuming that errors contribute equally.

⇕

Achieving $\mathbf{R=0.6R_T}$ requires all fabrication errors within ±**5%** of target values.

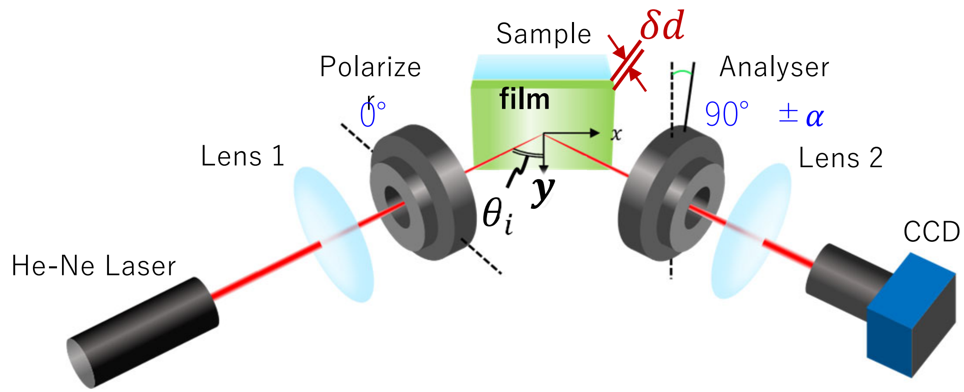
Ion Sputtering and Ellipsometry for the Fabrication of BEUV Reflection Multilayers

Ion Sputtering System with Thickness Monitor and Control of Film Thickness Distribution



- Reducing the deposition pressure by two orders of magnitude 0.2 Pa ⟶ 0.002 Pa
- Enabling seamless switching between reactive and non-reactive sputtering modes
  ⟶ sharply defined interfaces
- Control of Film Thickness Distribution Using a Shutter Mechanism
  ⟶ Fabrication of Imaging Optics in BEUV

Determination of film thickness via the Spin Hall Effect of Light (SHEL)



- With known optical constants of a single-layer film, film thickness δd is represented by the equation:

$$\delta d \sim \frac{2\pi \cos\theta_i}{\lambda\,\mathrm{Im}(\rho)} \delta y$$

using SHEL shift δy, complex reflection ratio ρ ($= r_p/r_s$), incidence angle θ_i, and wavelength λ.

- Film interface roughness is determined by optical constant changes or SHEL spot scanning.

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Final Summary / Take-home Message

- **Addressing challenges across the entire semiconductor value chain**—from EUV light sources and optics to materials, metrology, and advanced integration—**to realize a sustainable manufacturing ecosystem**

- **Recognizing the limits of conventional scaling**, future progress depends on collaboration beyond traditional technological and organizational boundaries

- **Through cross-community collaboration**, Japan's **K Program** aims to build a **resilient and sustainable technological foundation**