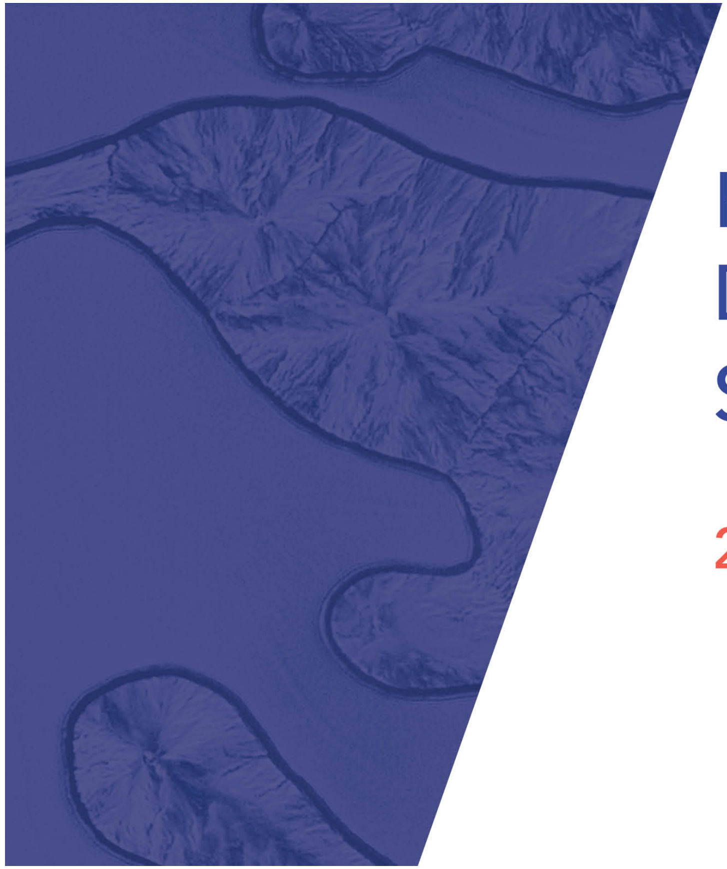
Welcome to Today's Webinar!



HIGH-HARMONIC SOURCES FOR MATERIAL DEVELOPMENT AND METROLOGY IN THE SEMICONDUCTOR INDUSTRY

24 March 2021 • 10:00 EDT (UTC -4:00)

OSA

Short Wavelength Sources and Attosecond/High Field Physics Technical Group

Technical Group Executive Committee

Giulio Vampa, chair
NRC Canada & University of Ottawa

Eric Cunningham
SLAC National Accelerator Laboratory

Hanieh Fattahi
Max Planck Institute for the Science of Light, Erlangen

Benjamin Webb
Laboratory for Laser Energetics, University Of Rochester

Zhiyi Wei
Institute of Physics, Chinese Academy of Sciences

OSA Short Wavelength Sources and Attosecond/High Field Physics Technical Group

About the Color Technical Group

Our technical group focuses on all aspects related to short wavelength sources and attosecond/high-field photonics.

Our mission is to connect the members of our community through technical events, webinars, networking events, and social media.

Our past activities have included:

- CLEO special session on “attosecond nanophotonics”
- CLEO reception on “Lasers for attosecond 2.0”
- Weekly manuscript feed (FB & LinkedIn)
- Webinar on the frontiers of QED science
- Poster prizes at Ultrafast Phenomena

OSA Short Wavelength Sources and Attosecond/High Field Physics Technical Group

Connect with our Technical Group

Join our online community to stay up to date on our group's activities. You also can share your ideas for technical group events or let us know if you're interested in presenting your research.

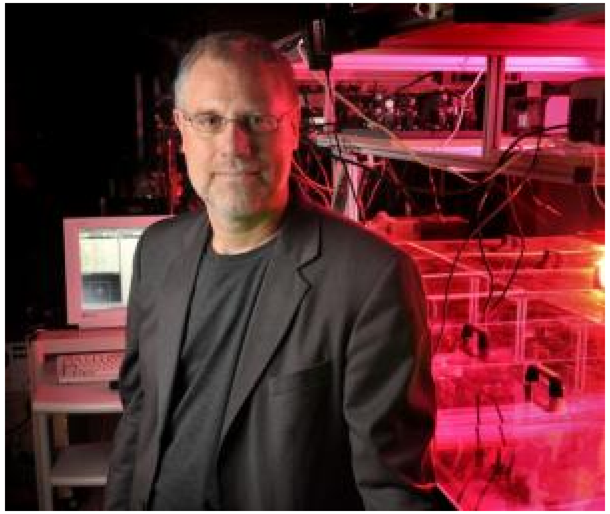
#OSAOH

Ways to connect with us:

- Our website at www.osa.org/oh
- Email us at TGactivities@osa.org

OSAShortWavelengthTG

Today's Speakers



Henry Kapteyn

Dept. of Physics & JILA
University of Colorado
CTO, KMLabs Inc.

Short Bio:

- most known for the development of x-ray and short-wavelength lasers and for lasers capable of producing < 10 fs pulses
- OSA Adolf Lomb's medal (1993) and APS Ahmed Zewail Award in Ultrafast Science and Technology (2009)
- Fellow of OSA, APS, AAAS and the American Academy for Arts and Sciences.

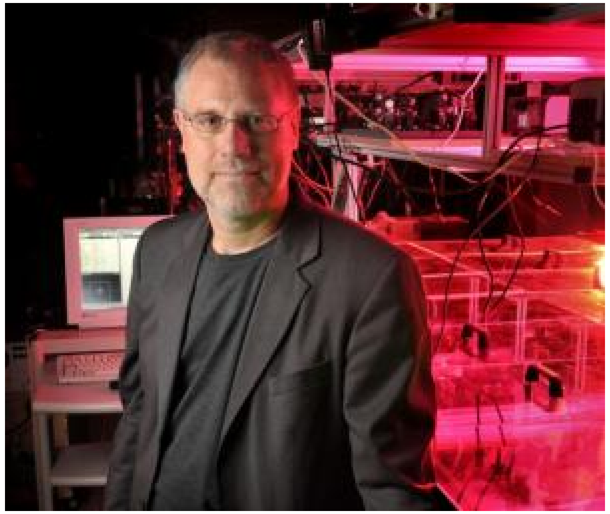
Today's Speakers

John Petersen &
Paul van der Heide
IMEC

Short Bio:

- Co-leaders of *Attolab*, a new ultrafast chemistry and physics lab at IMEC, Belgium
- Leaders in the investigation of the physical and chemical interaction between lithographic systems and the imaging materials and their interfaces.
- John is a SPIE fellow and former fellow of SEMATECH.

High-harmonic sources for material development and metrology in the semiconductor industry

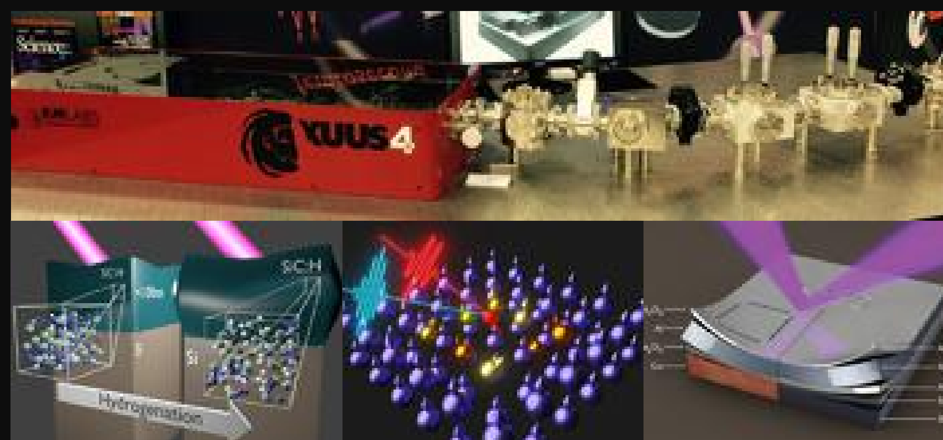


Henry Kapteyn
Dept. of Physics & JILA
University of Colorado
CTO, KMLabs Inc.

John Petersen &
Paul van der Heide
IMEC

Applications of Tabletop Extreme-Ultraviolet Laser Sources in Nanotechnology and Advanced Manufacturing

Michael Tanksalvala, Yuka Esashi, Nicholas Jenkins, Josh Knobloch, Ting Liao, Margaret Murnane ***(JILA)***
Henry Kapteyn, Clayton Bargsten, E. Rinard, R. Ward, S. Cousin, Daisy Raymondson, Matt Harada ***(KMLabs)***
K. M. Dorney, F. Holzmeier, E. W. Larsen, T. Nuytten, D. P. Singh, M. van Setten, P. Vanelderen, S. Böttcher, O. Dyachenko, R. Kremzow, M. Wietstruk, G. Pourtois, P. van der Heide, J. Petersen ***(imec)***



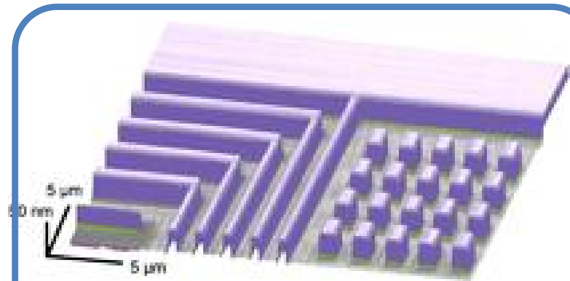
JILA NIST CU — STROBE — KMLABS inc. LEADING IN ULTRAFAST — imec

Outline

- Introduction to coherent “x-ray laser” light sources based on high harmonic generation (HHG)
- New nanoscale imaging and dynamic characterization capabilities
- Industrial relevance of HHG for EUV lithography
  - Proposed TEAMS microscope for EUVL masks
  - ATTOLAB KMLabs/IMEC project: **John Petersen, imec**

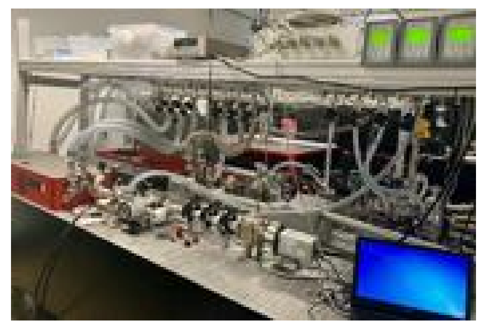
Unique capabilities of high harmonic sources: ”sculpting” light

Science ***364****, 9486 (2019); Nat. Photon.* ***13****, 123 (2019); Science Ad.* ***2****, e1501333 (2016); PNAS* ***112****, 14206 (2015); Science* ***336****, 1287 (2012); Science* ***350****,1225 (2015)*



Complex Phase Imaging Reflectometry: Nondestructive nanoscale composition

Optica ***4****, 1552 (2017)*
Science advances 7, eabd9667 (2021)

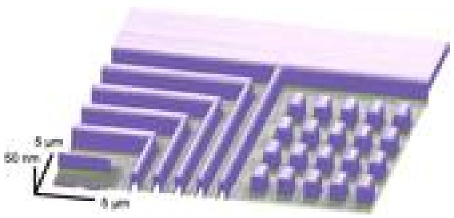


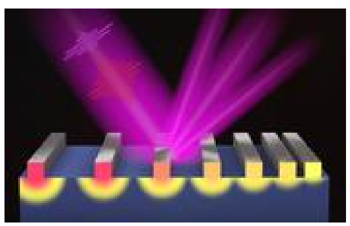
ATTOLAB: KMLabs high harmonic XUUS™ system installed at imec

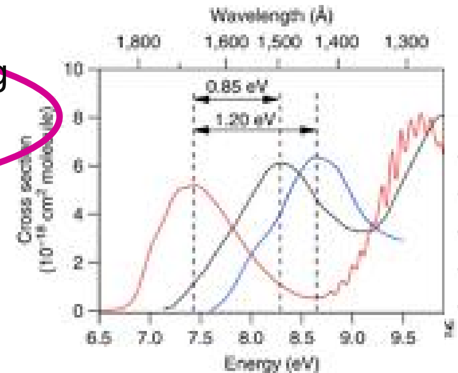
The power of coherent EUV and X-ray light

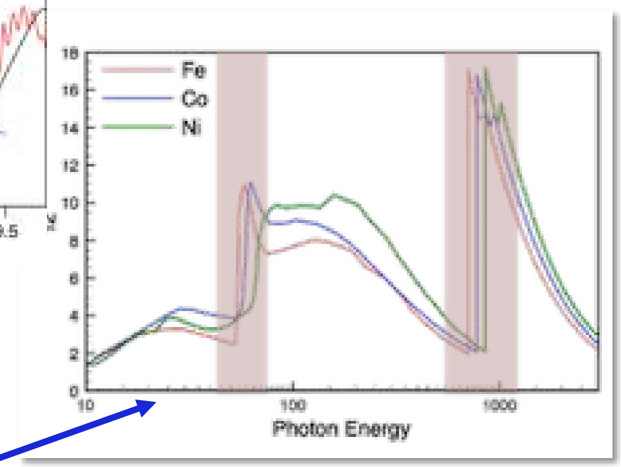
- Elemental, chemical, magnetic specificity
- Non-destructive, diffraction-limited nanoimaging
- Capture dynamics relevant to function (<fs)

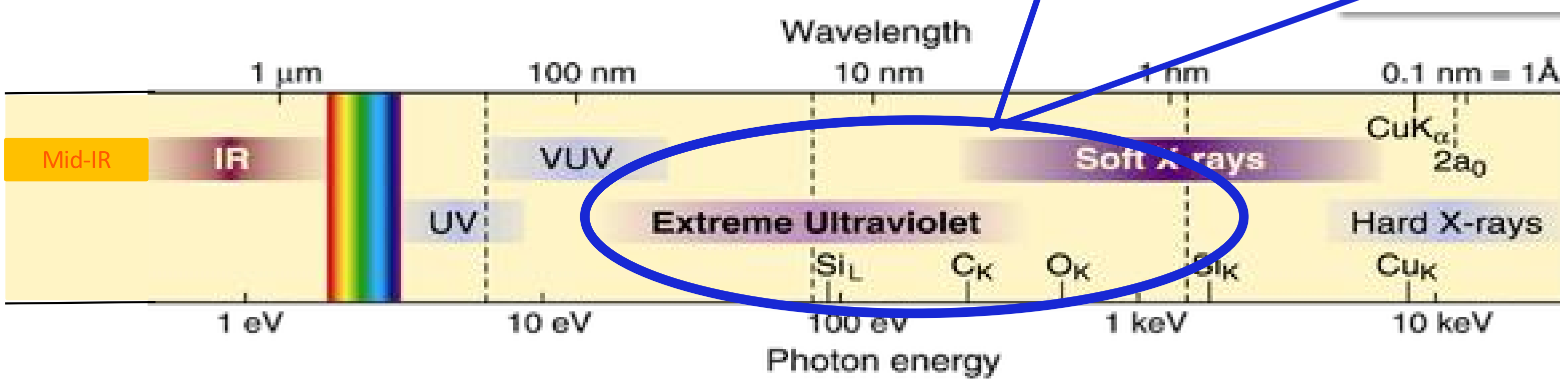
Requires coherence





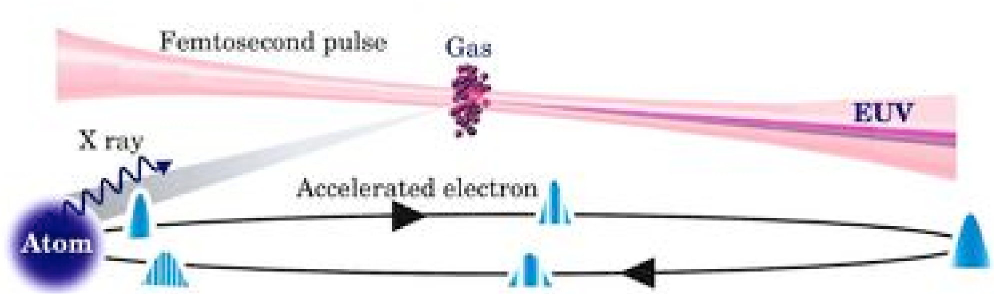


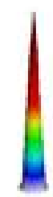




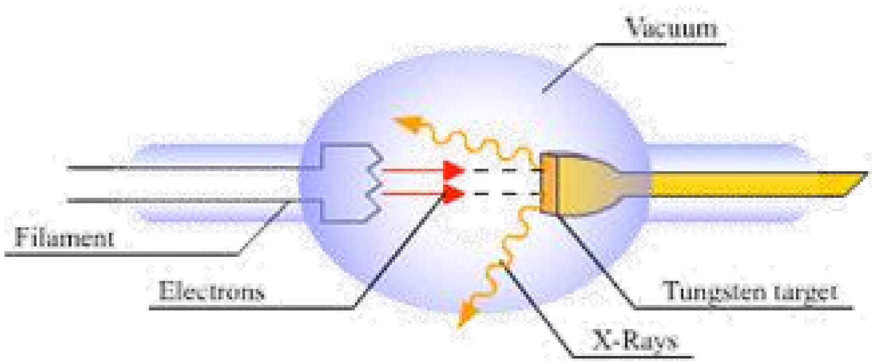
High Harmonic Generation:
Practical coherent upconversion of intense femtosecond lasers

- HHG: “High Harmonic Generation”
  - requires very fast, femtosecond laser



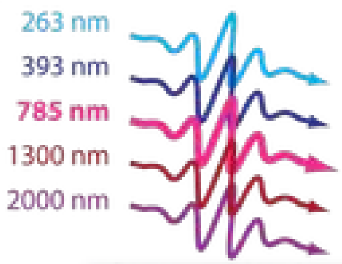


- Laser-driven version of the Röntgen X-ray Tube



1895

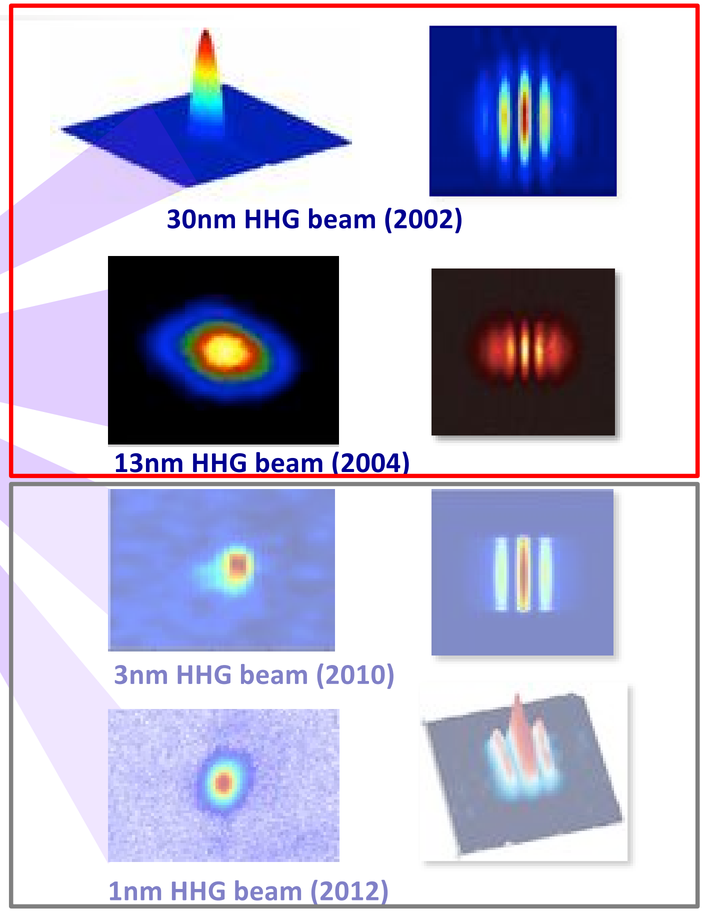
High Harmonic Generation: full temporal and spatial coherence in a new spectral region



4000 nm

Gas filled waveguide

Commercial



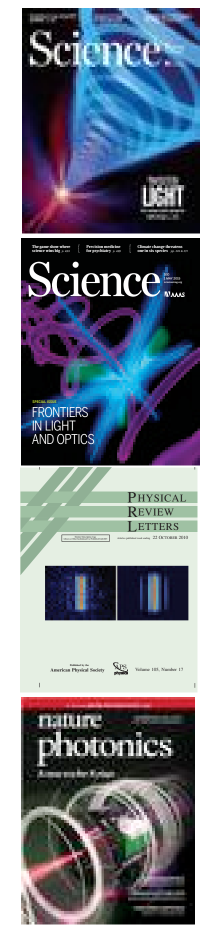
30nm HHG beam (2002)

13nm HHG beam (2004)

3nm HHG beam (2010)

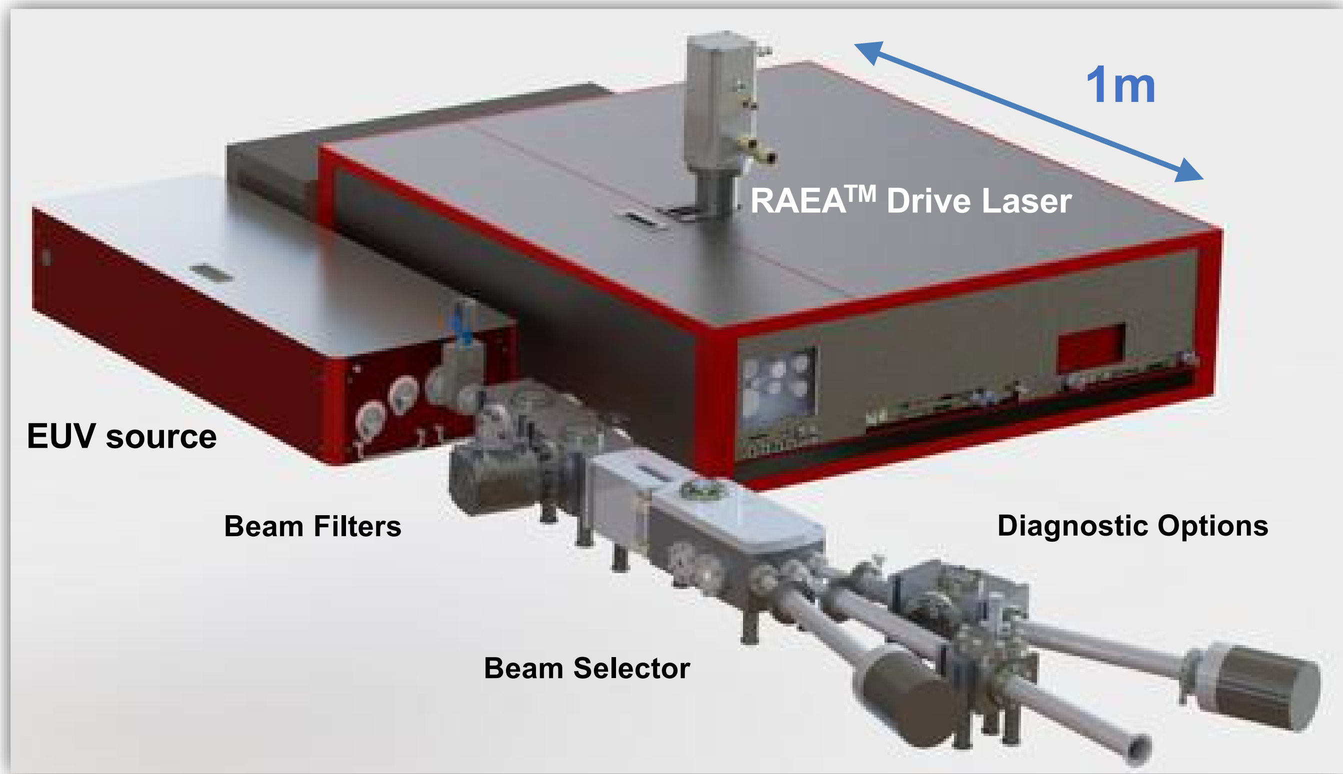
1nm HHG beam (2012)

Experimental- In development



*Science **280**, 1412 (1998); PRL **83**, 2187 (1999)*
*Science **297**, 376 (2002); PNAS **106**, 10516 (2009)*
*Science **336**, 1287 (2012); Science **350**,1225 (2015)*
*Science **364**, 9486 (2019); Nat. Photon. **13**, 123 (2019)*

KMLabs XUUS^{TM} and beamline system: Compact, robust, modular, and *well characterized* setup



Near- EUV (25-50 nm)

- >10^{12} photons/s
- 100-200 meV linewidth
- ~ fs to as
- ~1-2% rms stability
- 5 - 50 kHz rep rate

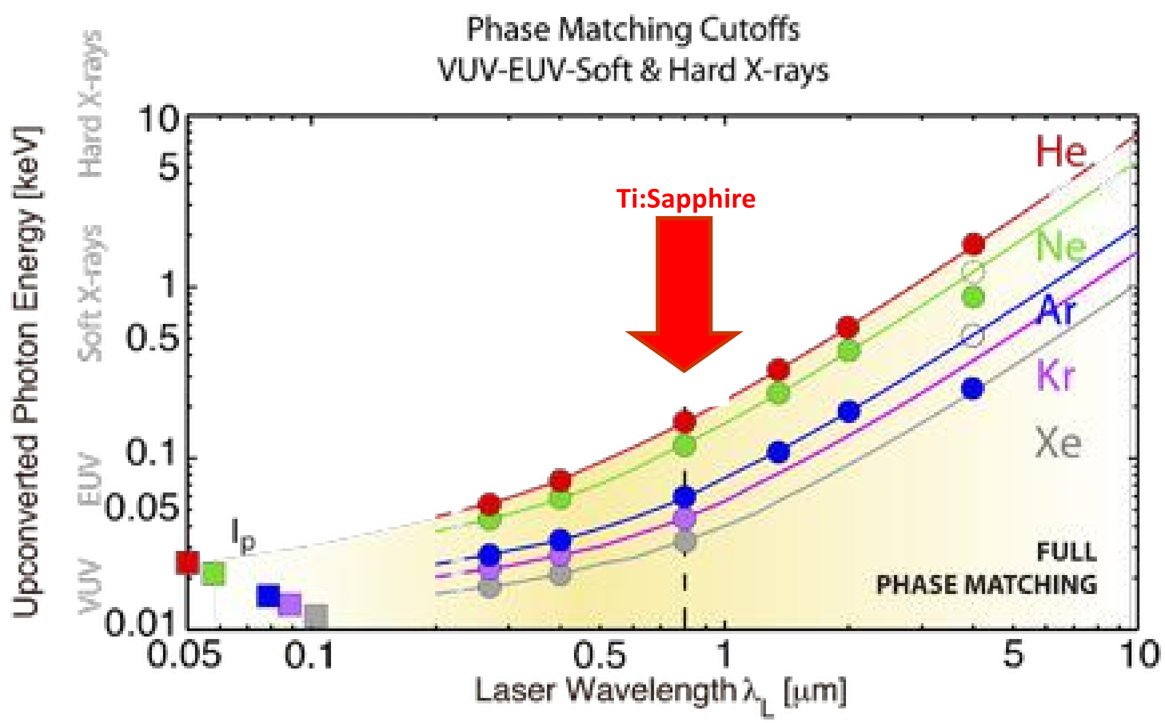
13.5 nm EUV

- 10^{10}-10^{11} photons/s
- Adjustable linewidth
- ~ fs to as

Why Ti:sapphire: 800 nm ideal for EUV 13.5 nm sources

- HHG wavelength related to **laser wavelength**, **gas type** (ionization potential)
  - keV HHG: mid IR lasers
  - EUV HHG: 0.8μm -1 μm lasers

$$E_{max} \simeq I_p + 3.17U_p \propto I\lambda^2$$

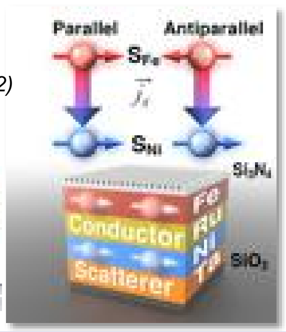


*Science **280**, 1412 (1998)*
*PNAS **106**, 10516 (2009); PRL **105**, 173901 (2010)*
*Nature Photonics **4**, 822 (2010); Science **336**, 1287 (2012)*

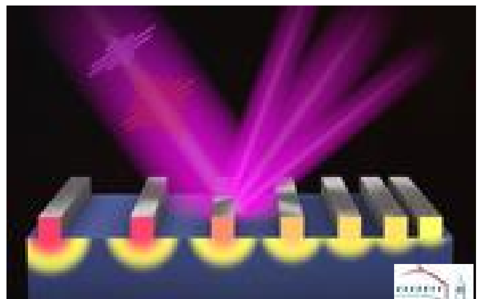
High harmonic quantum light sources → unique new material characterization and metrology capabilities

Spin dynamics, transport

Science Advances, **6**, 1100 (2020)
Science Advances **6**, 8717 (2020)
PRL **121**, 077204 (2018)
Science Advances **4**, 9744 (2018)
PRB, **97**, 024433 (2018)
PRB **94**, 220408 (2016)
PRL **110**, 197201 (2013)
PNAS **109**, 4792 (2012)



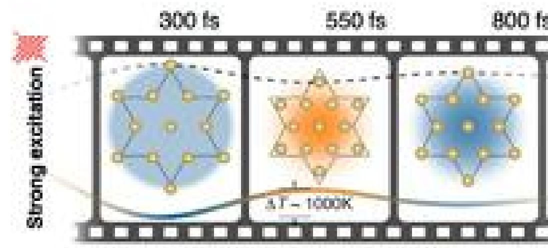
Nanoscale functional properties



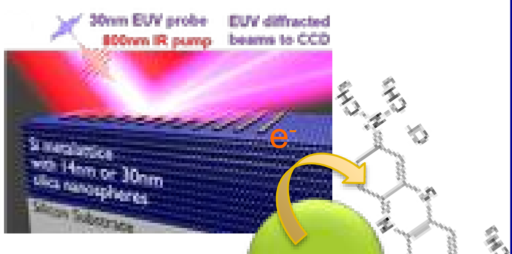
PNAS **112**, 4846 (2015); *Nano Lett.* **16**, 4773 (2016); *Nano Letters* **17**, 2178 (2017)
Science Advances **4**, 4295 (2018); *Phys. Rev. Appl.* **11**, 024042 (2019)
Phys. Rev. Materials **4,** 073603 (2020); *Nano Lett.* **20**, 3306 (2020); Submitted (2020)

Time-Resolved Photoemission

Quantum Materials



Nano-materials

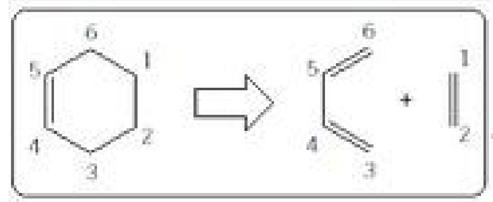


Nano Lett. **13**, 2924 (2013)
ACS Nano **8**, 8810 (2014)
JACS **137**, 3759 (2015)
J. Phys. Chem. Lett. **7**, 609 (2016)
Opt. Express **26**, 11393 (2018)
Nano Lett. **20**, 3306 (2020)

Nondestructive 3D buried layers imaging

Science **348**, 530 (2015); *Ultramicroscopy* **158**, 98 (2015)
Nano Lett. **16**, 5444 (2016); *IQT* **8**, 18 (2016); *Nature Photonics* **11**, 259 (2017)
Optica **4**, 1552 (2017); *Science Advances* **4**, 4295 (2018); *Science Advances* 10.1126/sciadv.abd9667 (2021)

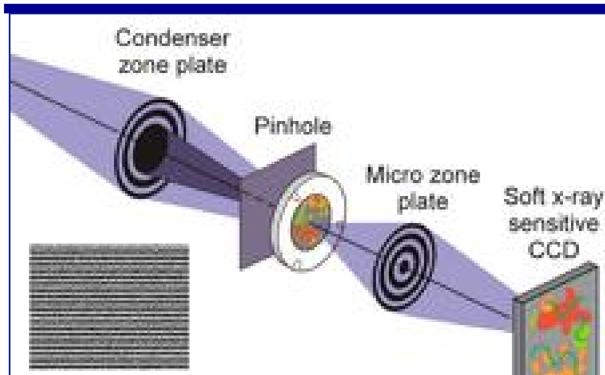
Molecular dynamics, advanced fuels



Retro-Diels-Alder reaction

PNAS **117**, 8788 (2020); *J. Phys. B*, in press, 10.1088/1361-6455/aba2fb (2020)
Science Advances **5**, 4449 (2019); *Science Advances* **4**, 9744 (2018)
PRL **121**, 077204 (2018); *PNAS* **114**, E5300 (2017)
Science Advances **3**, e1602094 (2017)
Science **353**, 62 (2016) ; *Science* **353**, 28 (2016)
Nature Comm. **7,** 12902 (2016); *PRL* **112** , 207001 (2014)
PRB **92**, 041407 (2015); *Nature* **471**, 490 (2011)
Nat. Comm **3**, 1069 (2012); *Rev. Scientific Instrum.* **78**, 083105 (2007)

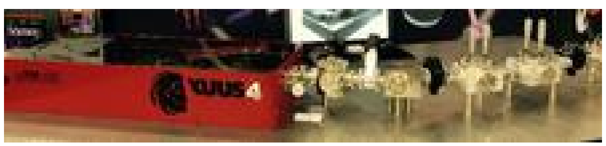
Coherent imaging – a revolution in X-ray imaging

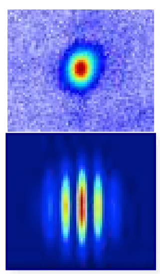


Nature ***435,*** *1210 (2005)*

Traditional X-ray microscopes
- Limited by lossy, imperfect, optics
- ≈7 - 10x diffraction limited imaging

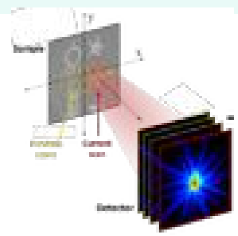
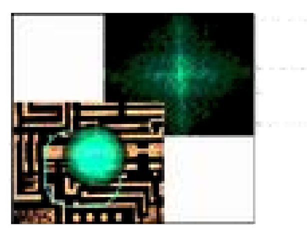
Coherent EUV/SXR sources



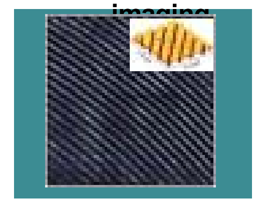
Science ***297****, 376 (2002); Nature Photonics* ***4****, 641 (2010)*

Coherent imaging

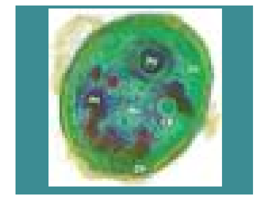
Fundamentally new imaging

2017: 1st sub-λ EUV imaging



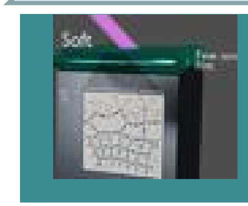
Nat. Photon. **11**, 22 (2017)

2018: Whole cell imaging



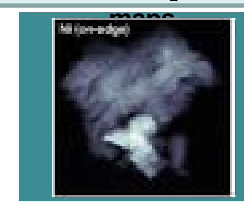
Science Ad. ***4****, 4548 (2018)*

2020: Nano-Mechanical



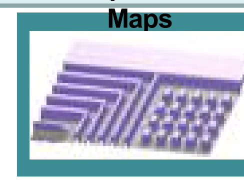
PR Materials ***4****, 073603 (2020)*

2019: Heterogeneous maps



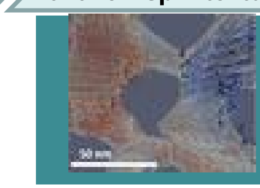
Science Ad. ***5****, eaax3009 (2019)*

2020: Dopant/interface Maps



Optica ***4****, 1552 (2017); Submitted (2020)*

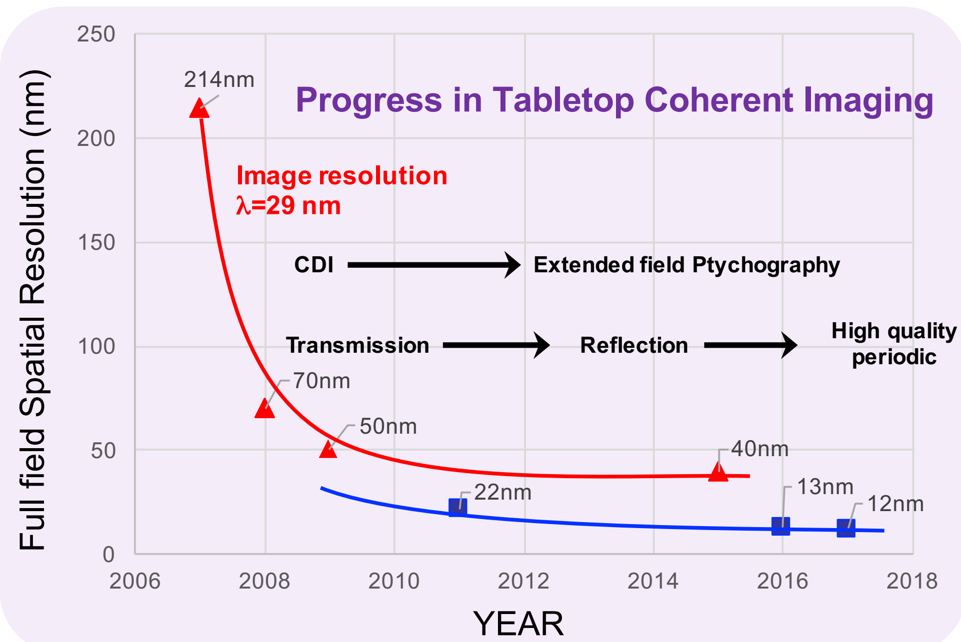
2020: 3D spin texture

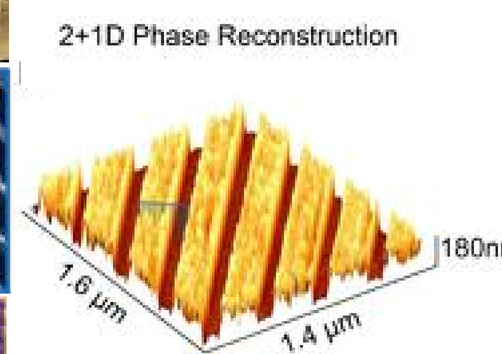


In prep. (2020)

2017: First diffraction-limited sub-wavelength resolution EUV imaging

- First near-perfect (sub-λ) imaging at short wavelengths using ANY light source
- Resolution ~12.4nm at 13.5 nm wavelength
- Comparison: Zeiss AIMS microscope ($500m) ~80nm at same 13.5 nm wavelength

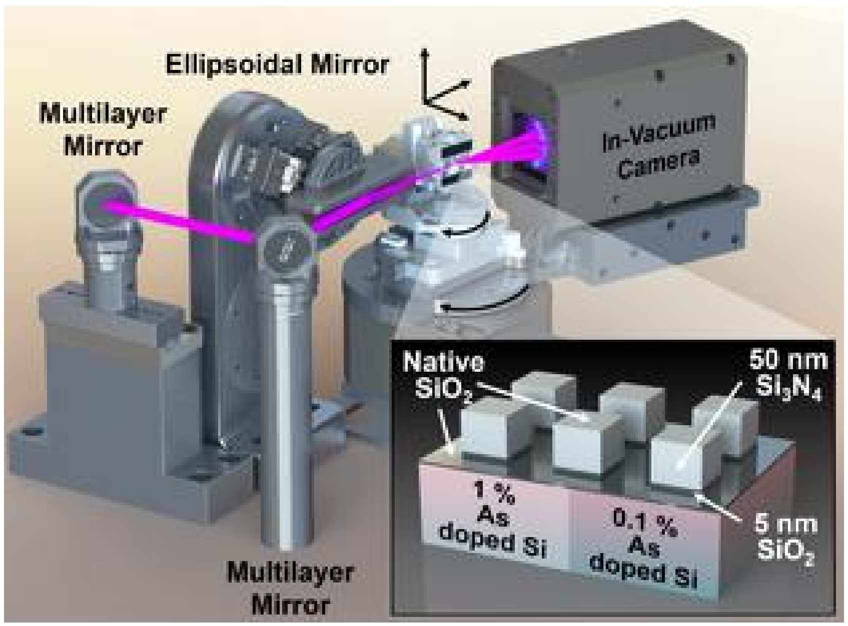


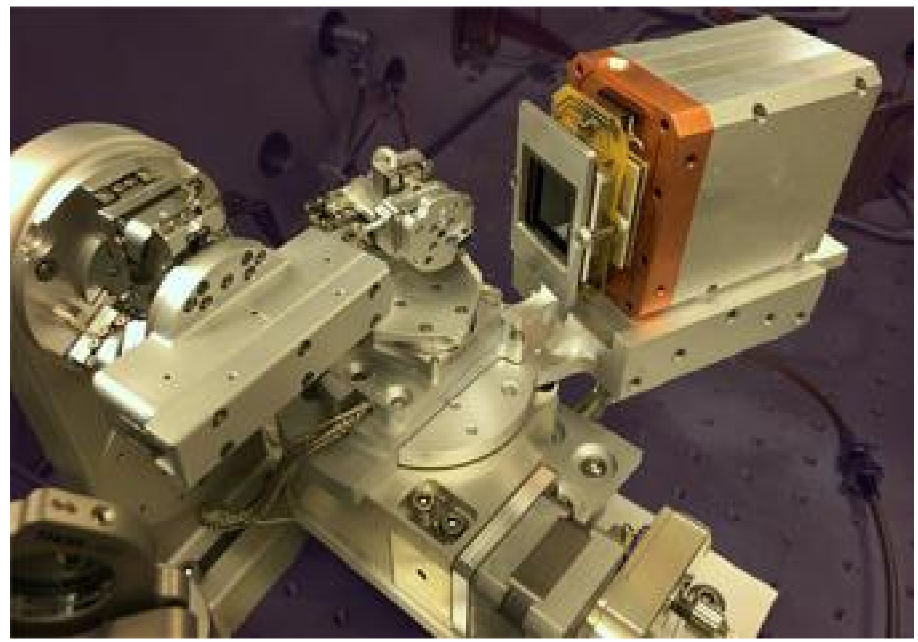


*Gardner et al., Nature Photonics **11**, 259 (2017)*

2020: Complex EUV Imaging Reflectometer: Nondestructive spatial and depth-resolved maps

- Nanostructured dopants, buried interfaces are challenging to measure
- Most approaches are destructive, image small areas, sample preparation can induce interdiffusion
- Most CDI done in transmission





Complex EUV Imaging Reflectometer: Nondestructive spatial and depth-resolved maps

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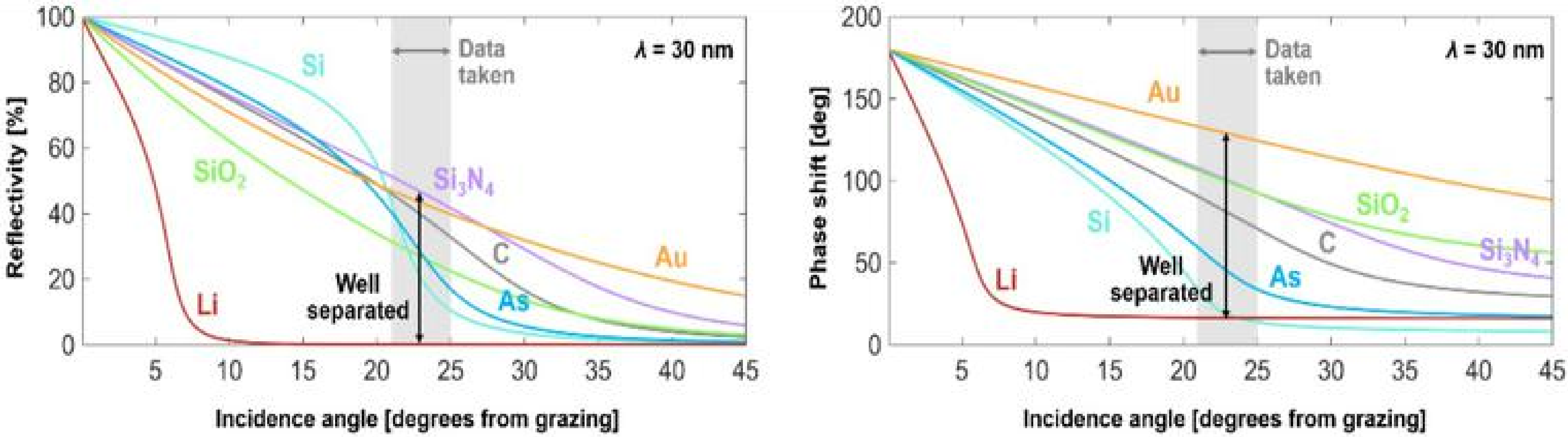
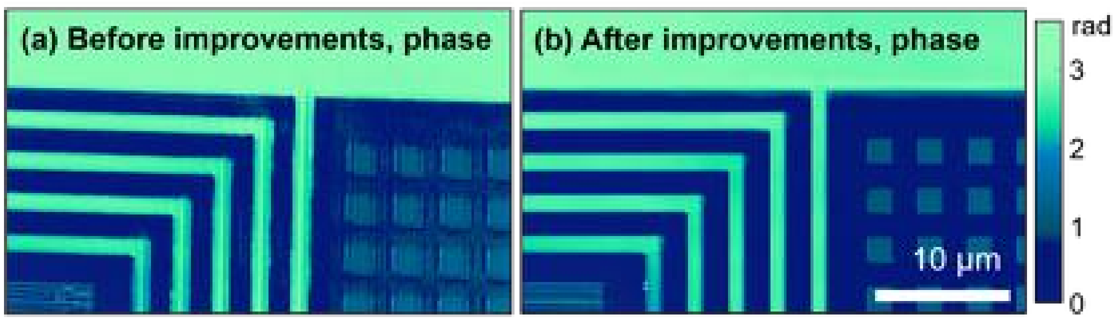
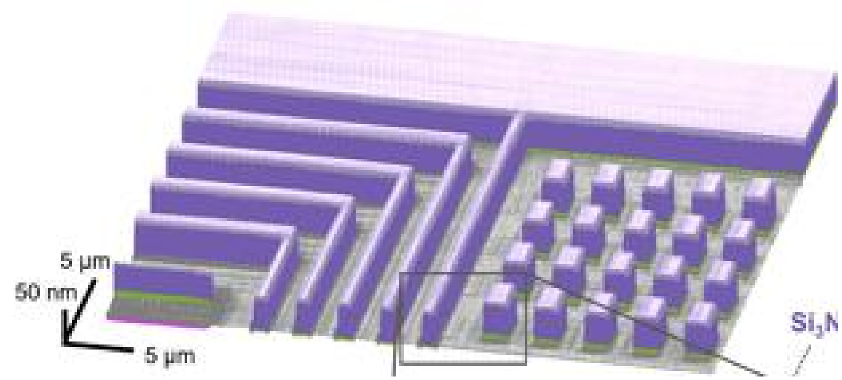


Complex EUV Imaging Reflectometer: Nondestructive spatial and depth-resolved maps

- New non-destructive spatial/depth compositional mapping
  - ***extract interfaces, layers, dopant profiles, composition.***



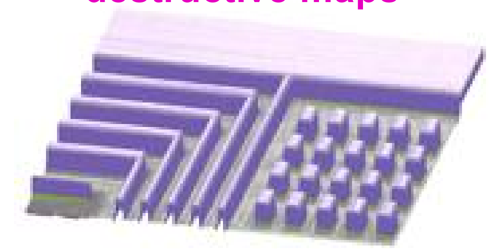
Science Advances 10.1126/sciadv.abd9667 (2021)



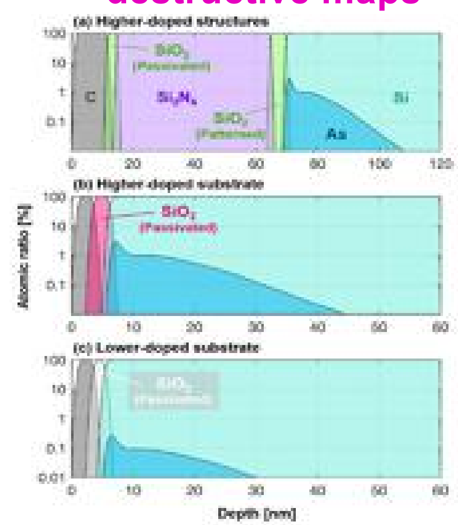
Comparison table of different imaging methods:
Each modality optimized for different sample parameters!

Feature	Complex-Imaging Reflectometry	SIMS	AFM	EDS/HAADF-STEM
Layer thickness	✓✓	✓✓	✗	✓
Step height	✓✓	✗	✓✓	✓
Surface roughness	✓	✗	✓✓	✗
Interface roughness	✓	✓	✗	✓
Dopant	✓	✓✓	✗	✓
Transverse resolution	✓	✗	✓	✓✓
Depth resolution	✓	✓✓	✗	✓✓
Field of view	✓✓	✗	✓	✗
Non-destructive	✓✓	✗	✓	✗
	$$$	$$$	$	$$$

EUV spatially-resolved non-destructive maps



EUV depth-resolved non-destructive maps

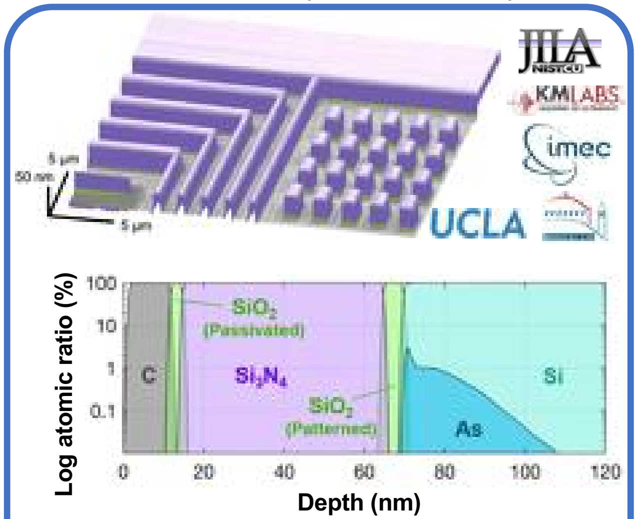


- **EUV imaging:**
  - Non-destructive
  - Needs no sample preparation
  - 3-D, Composition info

- **Electron microscopy:**
  - Higher resolution
  - Destroys sample

Rapid growth of materials characterization capabilities with HHG

- 3D Compositional Maps via Phase-Sensitive EUV Imaging Reflectometry
- Full Characterization of Ultrathin 5nm Films
  - Influence of Dopants & Surfaces on Mechanical Properties
- 1st comprehensive predictive understanding of nanoscale heat transport



Non-destructive, depth-resolved, compositional and dopant maps

Tanksalvala et al., Science Advances 10.1126/sciadv.abd9667 (2021)

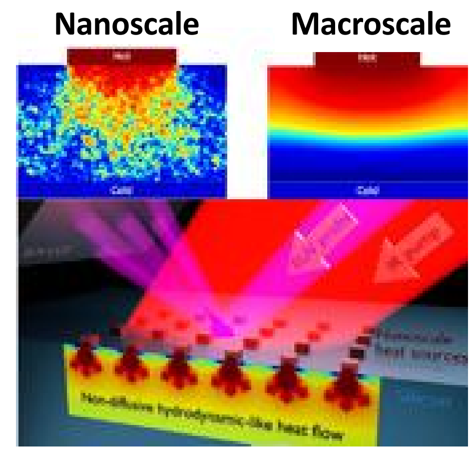

EurekAlert! AAAS

HOME COVID-19 NEWS RELEASES MULTIMEDIA MEETINGS PORTALS

Scientists open new window into the nanoworld

Full characterization of mechanical properties of ~5 nm films → influence of dopants

Frazer et al., Phys. Rev. Materials ***4****, 073603 (2020)*



New regimes of nanoscale heat transport → engineer for better functionality

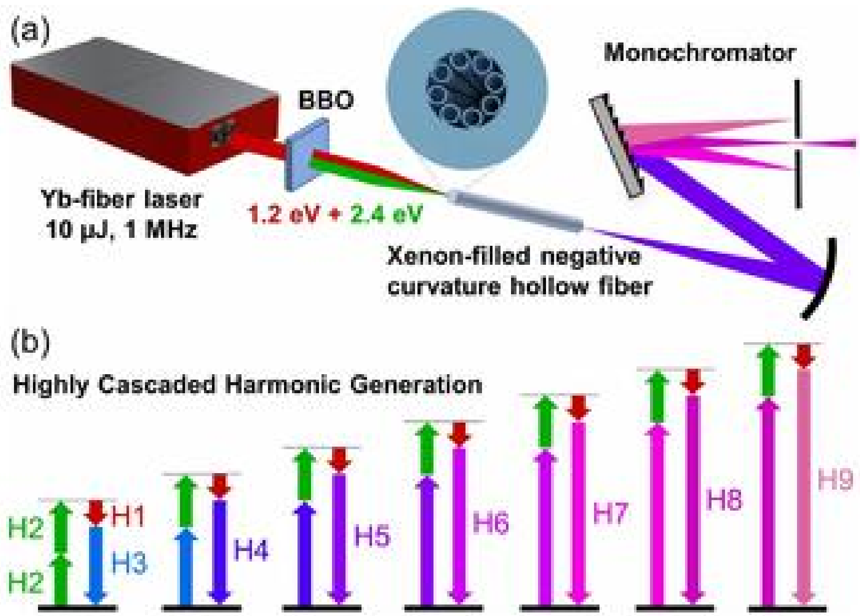
Frazer et al., Phys. Rev. Applied ***11****, 024042 (2019)*
Beardo et al, submitted (2021)

In development: TEAMS^{TM} EUVL mask microscopy

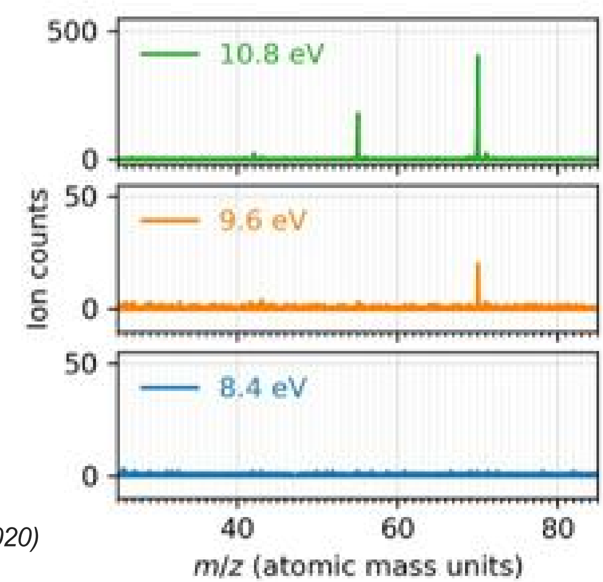
- TEAMS^{TM} – Tabletop EUV Actinic Microscope System
  - “Conventional” EUV mask review tool $500M
- Development path for
  - Mask review
  - Actinic patterned mask inspection (APMI)
  - High NA EUVL

Aside…….
VUV: Fiber laser-based MHz rep rate sources

- New high-flux MHz tabletop VUV sources ideal for photoionization spectroscopies: 1-18eV, high flux, fs
- Demonstration experiments with PIMS show how tunable VUV light can selectively ionize molecules and minimize fragmentation for advanced fuels development (Labbe and Ellison groups)
- Also ideal for angle-resolved photoelectron spectroscopy of materials (ARPES)



*Optica **7**, 832 (2020)*
Proc. Combustion Institute, in press (2020)



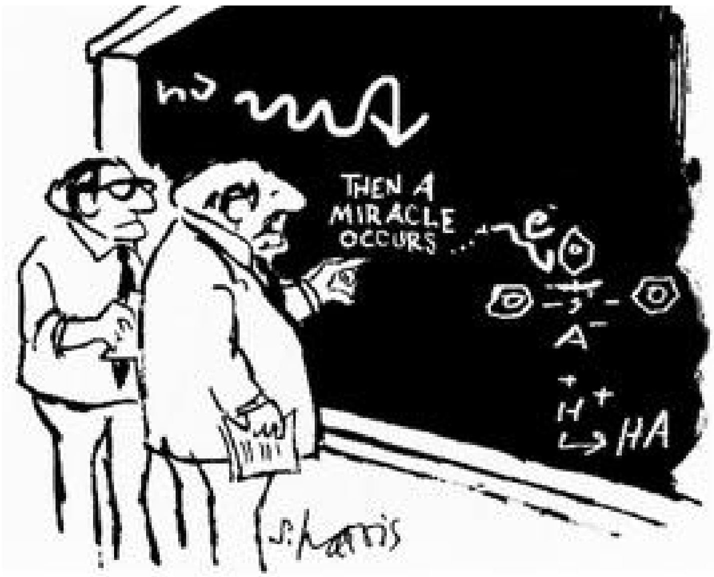
High-Harmonic Sources for Material Development and Metrology in the Semiconductor Industry

Presented by: John Petersen

AttoLab Team: K. M. Dorney, F. Holzmeier, E. W. Larsen, T. Nuytten, D. P. Singh, M. van Setten, P. Vanelderen, C. Bargsten, S. L. Cousin, D. Raymondson, E. Rinard, R. Ward, H. Kapteyn, S. Böttcher, O. Dyachenko, R. Kremzow, M. Wietstruk, G. Pourtois, P. van der Heide, J. Petersen

Throwback – SPIE Advanced Lithography 2019
John Petersen: then a miracle occurs

Who controls resolution and yield at the edge of lithography?



"I think you should be more explicit here in step two."

from *What's so Funny about Science?* by Sidney Harris (1977)

Adapted by JSP

SAN FRANCISCO [US], FEBRUARY 26, 2019 — *Today, imec, a world-leading research and innovation hub in nanoelectronics and digital technologies, and KMLabs, pioneers and world leaders in ultrafast laser and EUV technology, announce a joint development to create a real-time functional imaging and interference lithography laboratory. This lab will enable imaging in resist on 300mm wafers down to an unprecedented 8nm pitch. Additionally, it will enable time-resolved nanoscale characterization of complex materials and processes, such as photoresist radiation chemistry, two-dimensional materials, nanostructured systems and devices, emergent quantum materials.*

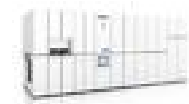
Outline

- Motivation behind imec's AttoLab
- How does the AttoLab work?
- Interference Lithography (incl. first results)
- Resist Characterization
- Imaging
- Summary

Motivation
High-NA EUV introduction via IMEC-ASML joint lab

2010

NXE3100
First prototype available



2019

NXE3400
Actual insertion into HVM

~ 10 years - ~50 tools

2023

First prototype available

2025 (tbc)

Expected insertion HVM

~ 3 years

OBJECTIVE:

- FASTER LEARNING CYCLES
- WITH LESS DEVELOPMENT TOOLS
- TO REDUCE DEVELOPMENT COSTS

NEED FASTER & MORE COST-EFFECTIVE route to **mature** HVM INTRODUCTION

Imec-asml joint high-NA lab

AttoLab:High NA EUV Litho & Attosecond Analytics Lab

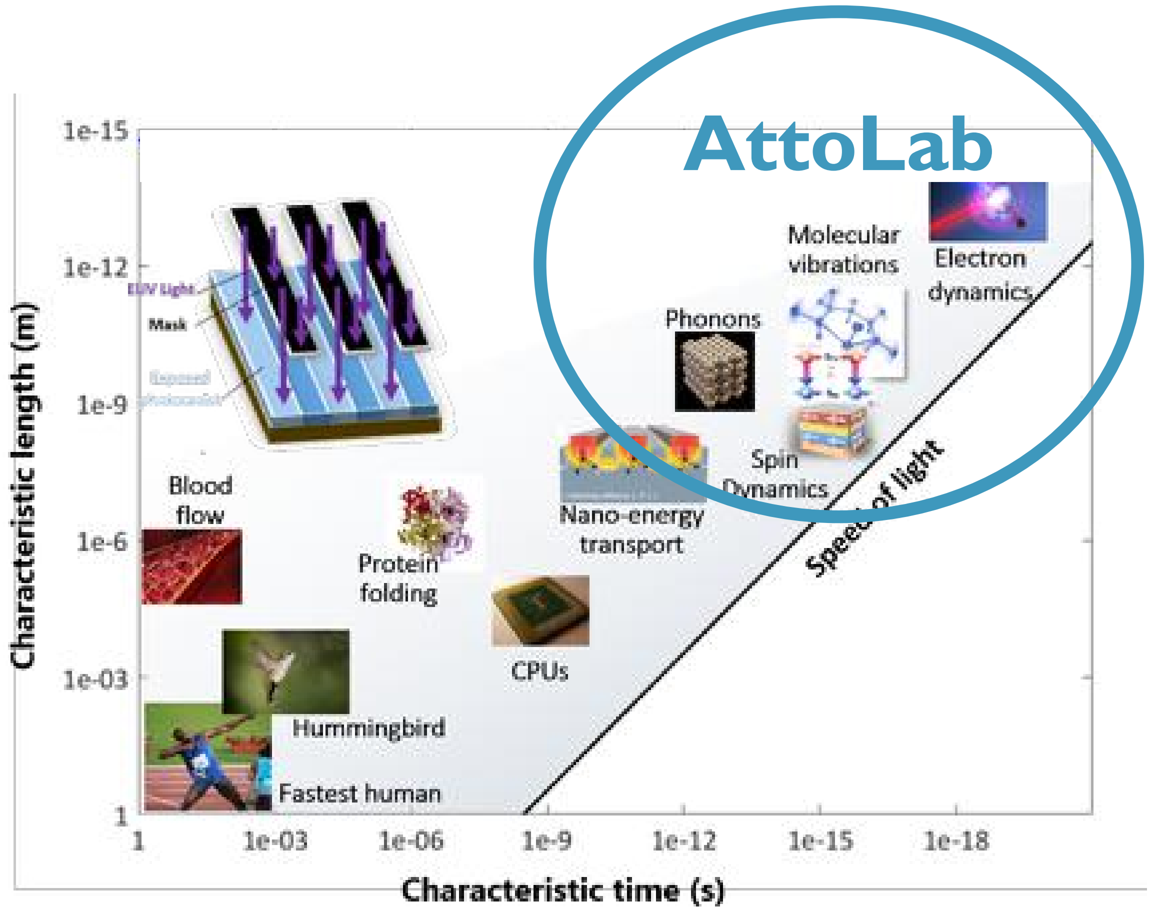
Motivation
Why ultrafast?

As things get smaller...
... they move faster.

Materials for the Quantum Age
Characterization and Metrology for Manufacturing
Today – spatial
Tomorrow – spatial & temporal

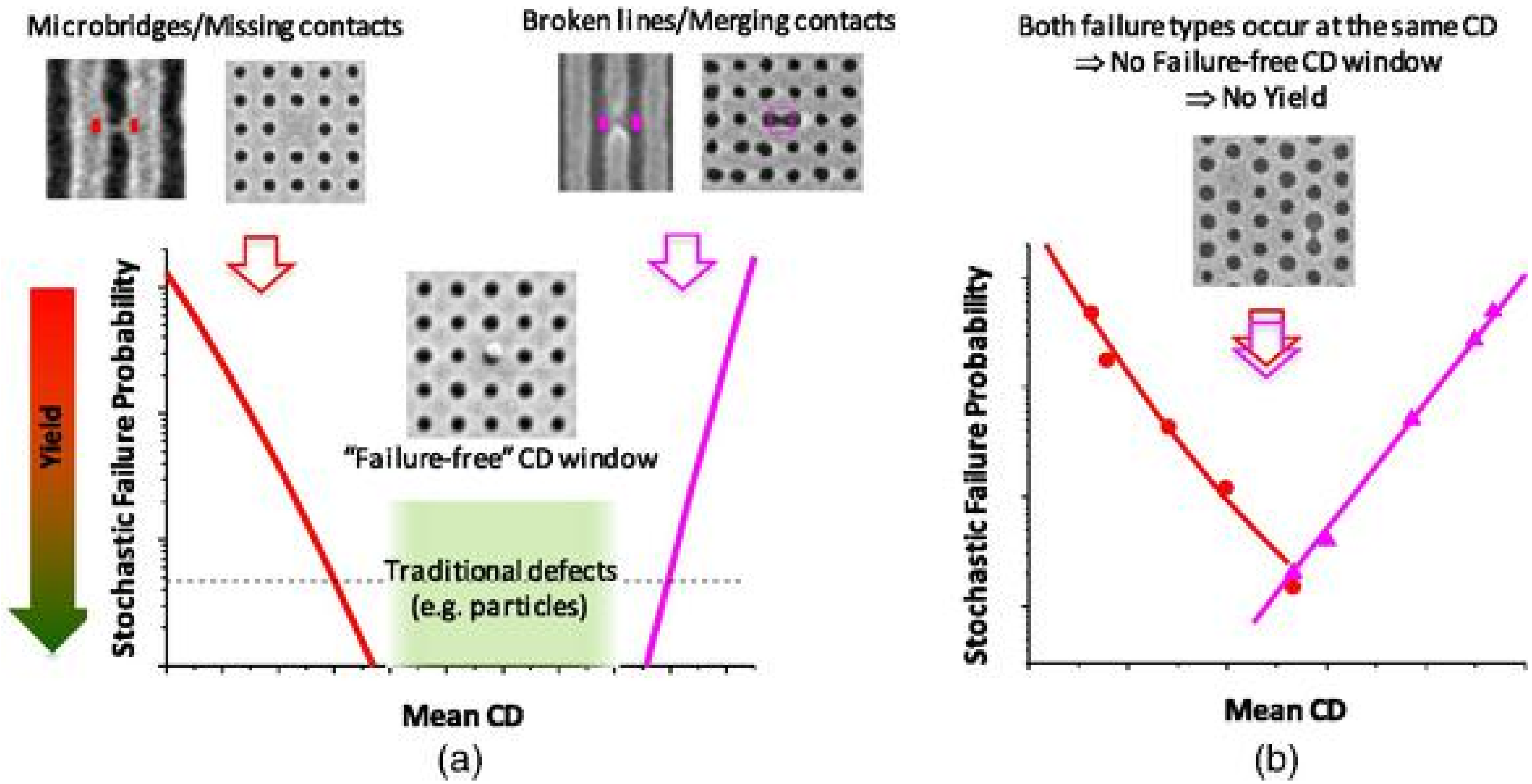
<u>EUV Lithography (13.5 nm):</u>
Chemical reaction sequence is initiated by photoionization

➢ Resist chemistry is governed by emitted electron(s)



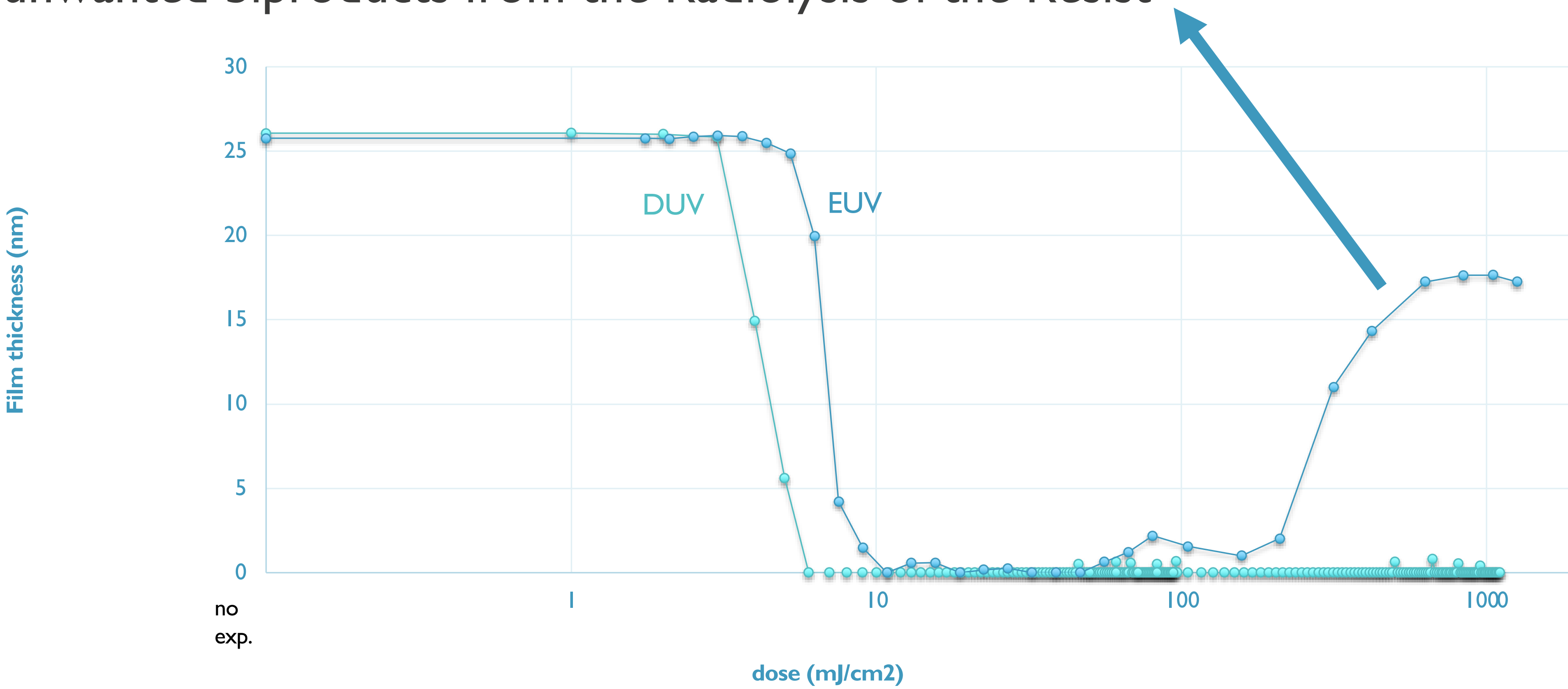
Graphic Courtesy: Nico Hernandez Charpak, Matt Seaberg, Chan La-o-vorakiat, Kevin Dorney, KM Group

Motivation
Stochastic Print Defects



P. De Bisschop, "**Stochastic printing failures in extreme ultraviolet lithography**," J. Micro/Nanolith. MEMS MOEMS 17(4) 041011 (25 September 2018) https://doi.org/10.1117/1.JMM.17.4.041011

Hypothesis for formation of Stochastic Defects unwanted biproducts from the Radiolysis of the Resist



I. Pollentier, Y. Vesters, J. S. Petersen, P. Vanelderen, A. Rathore, D. De Simone, G. Vandenberghe, "**Unraveling the role of photons and electrons upon their chemical interaction with photoresist during EUV exposure**," Proc. SPIE 10586, Advances in Patterning Materials and Processes XXXV, 105860C (19 March 2018); doi: 10.1117/12.2299593

Mechanisms
Time Ranges from <20 Attoseconds to 200 Picoseconds

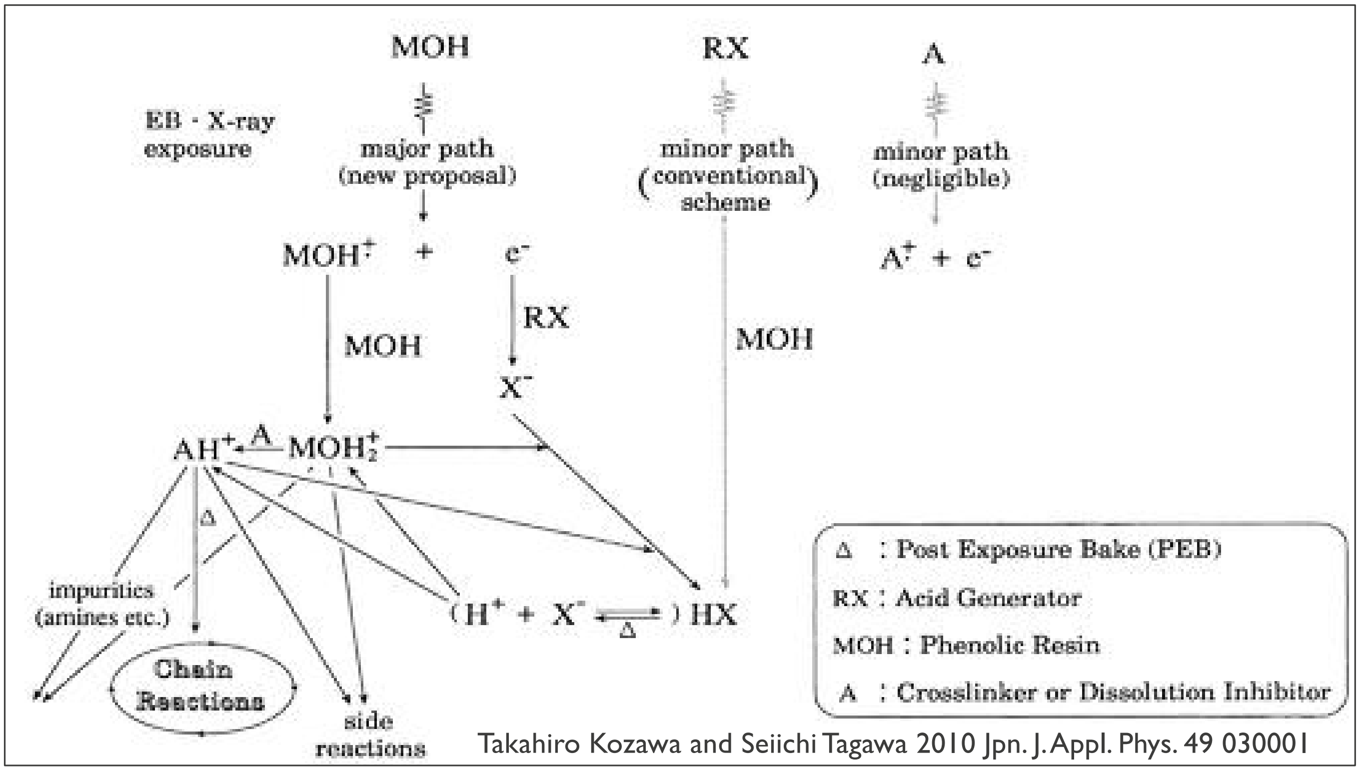
attosecond

femtosecond

picosecond

nanosecond

µsecond



Takahiro Kozawa and Seiichi Tagawa 2010 Jpn. J. Appl. Phys. 49 030001

(1) $MOH \rightsquigarrow MOH^{+\bullet} + e^-$

(2) $MOH^{+\bullet} + MOH \rightarrow MOH_2^+ + MO\bullet$

(3) $RX + e^- \rightarrow X^- + \text{other products}$

(4) $X^- + MOH_2^+ \rightarrow HX + MOH$

(5) $HX + MOH \rightarrow MOH_2^+ + X^-$

(6) $HX + A \rightarrow AH^+ + X^-.$

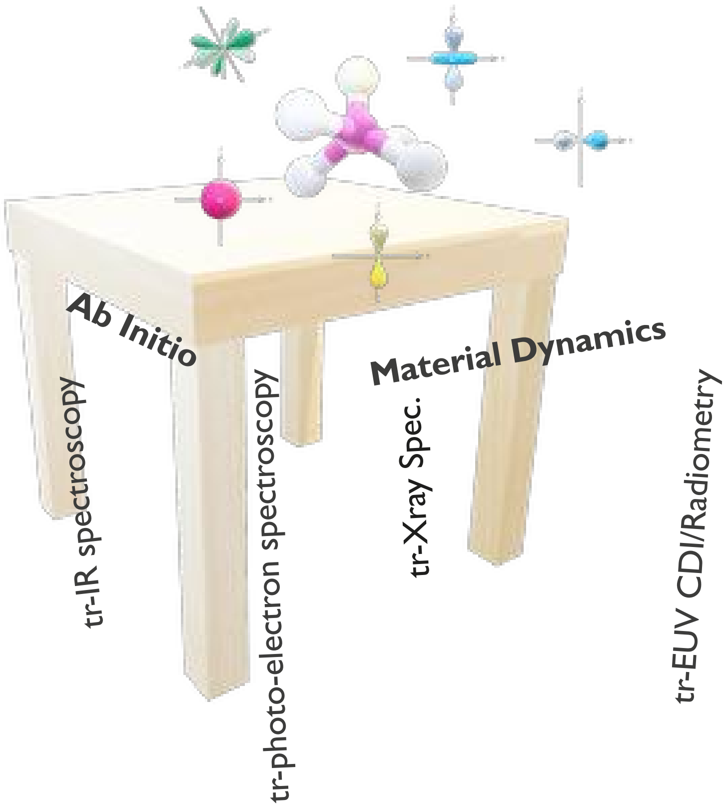
(7) $HX \rightleftharpoons H^+ + X^-,$

(8) $H^+ + MOH \rightarrow MOH_2^+,$

(9) $H^+ + A \rightarrow AH^+.$

(10) $MOH_2^+ + A \rightarrow MOH + AH^+$

AttoLab Study of Exposure Dynamics
Beyond Lithography-- the study of radiation chemistry of EUV



AttoLab 2021 with 26 - 130 eV 5 kHz lasers

- Infrared spectroscopy
- EUV radiometry & reflectometry
- Photoelectron spectroscopy
- Coherent Diffractive Imaging, & scattering

Outline

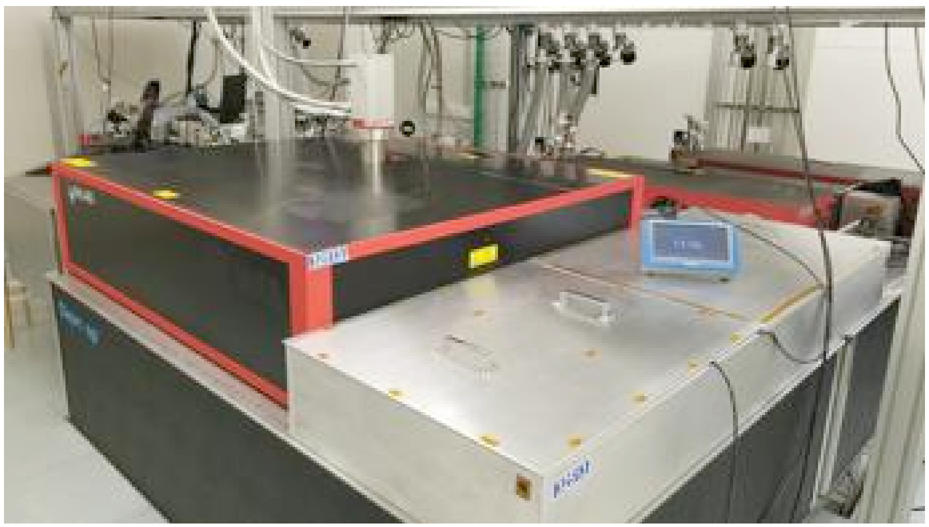
- Motivation behind imec's AttoLab
- **How does the AttoLab work?**

- Interference Lithography (incl. first results)
- Resist Characterization
- Imaging

- Summary

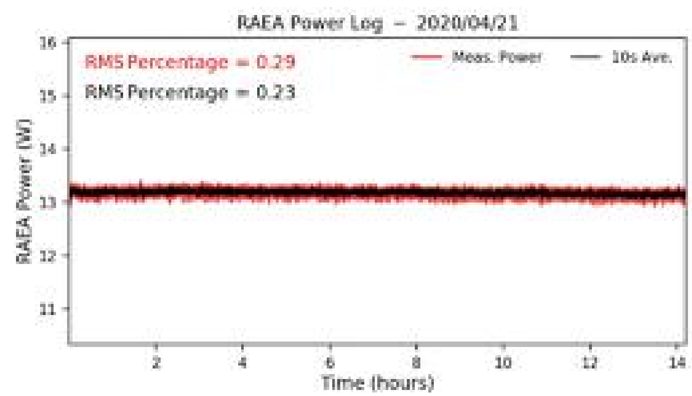
Laser system
High-power pump laser system

RAEA: Ultrafast Ti:Sapphire Amplifier



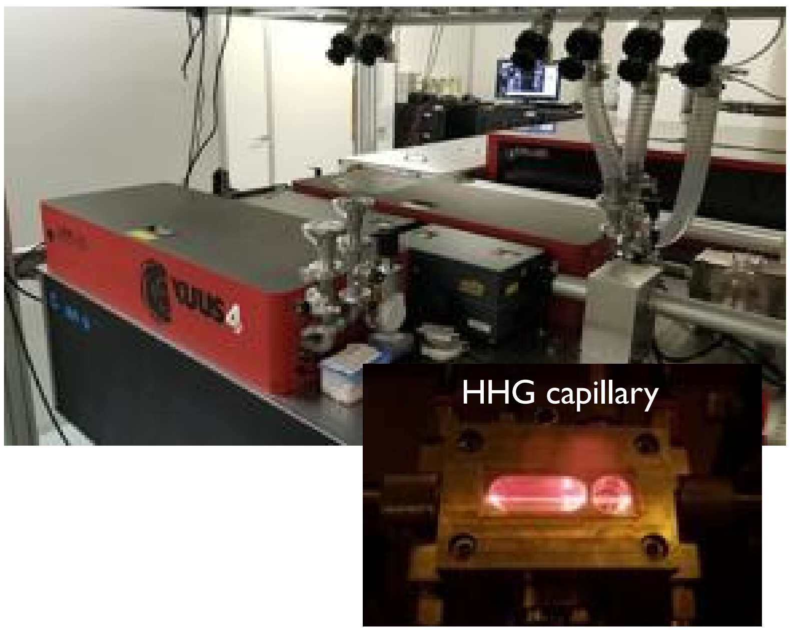
One-box configuration, "turnkey" operation

- Wavelength: 790 nm
- Pulse Energy: 2.6 mJ @5 kHz
- Pulse width: 25 fs
- Beam drift: < 1% RMS over 144 hours



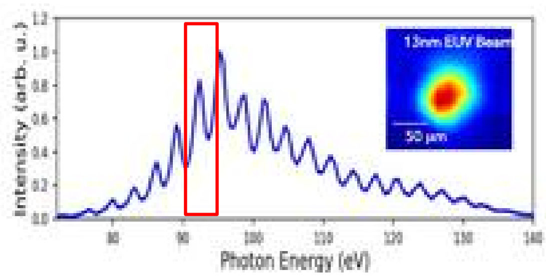
Laser system
HHG modules

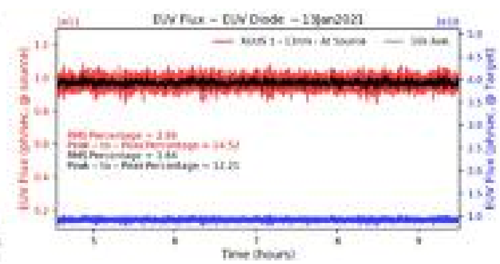
KMLABS LEADING IN ULTRAFAST XUUS: High harmonic generation source for EUV



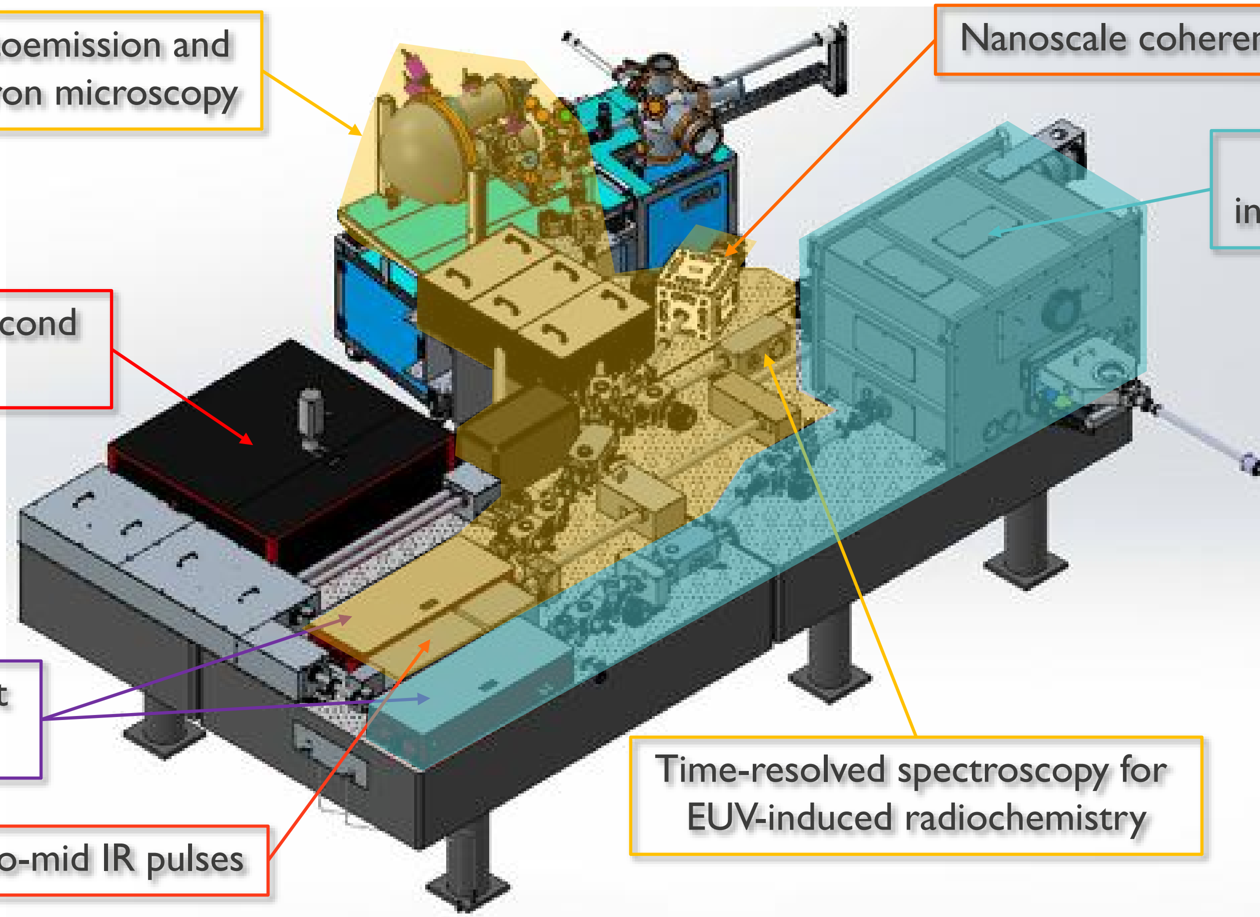
Two table-top EUV sources driven by fs amplifier

- Tunable: 26-130 eV, 61-10 nm
- coherent
- Linearly polarized (elliptical/circular possible)
- Femto- and attosecond pulses





IMEC's AttoLab: An ultrafast Nanoscale metrology lab



imec embracing a better life

KMLABS inc. LEADING IN ULTRAFAST

SPECS™

Outline

- Motivation behind imec's AttoLab
- How does the AttoLab work?
- **Interference Lithography (incl. first results)**
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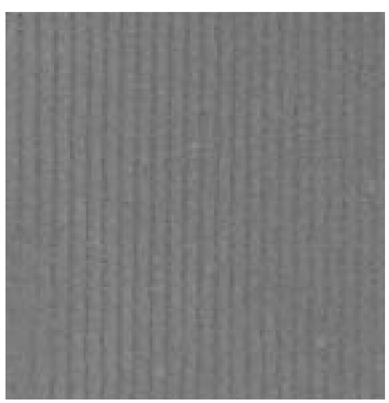
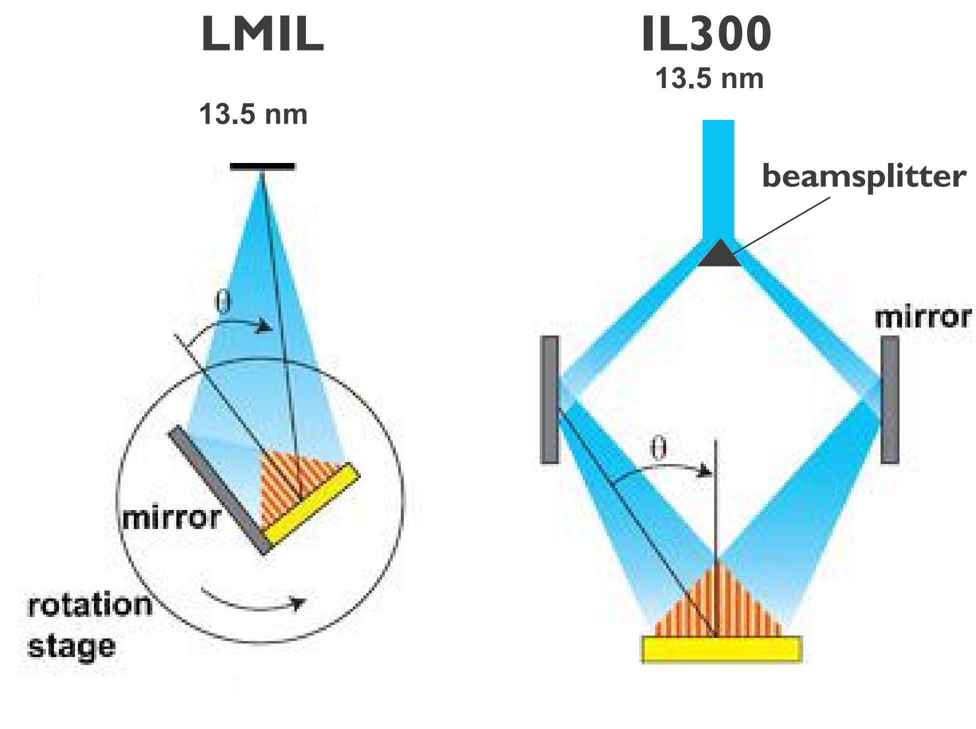
Interference Lithography
Available IL Tools

a) Lloyd's Mirror Interference for coupons
b) Two-Beam Interference for 300 mm wafers

$$Pitch = \frac{\lambda}{2 \cdot \sin(\theta)}$$

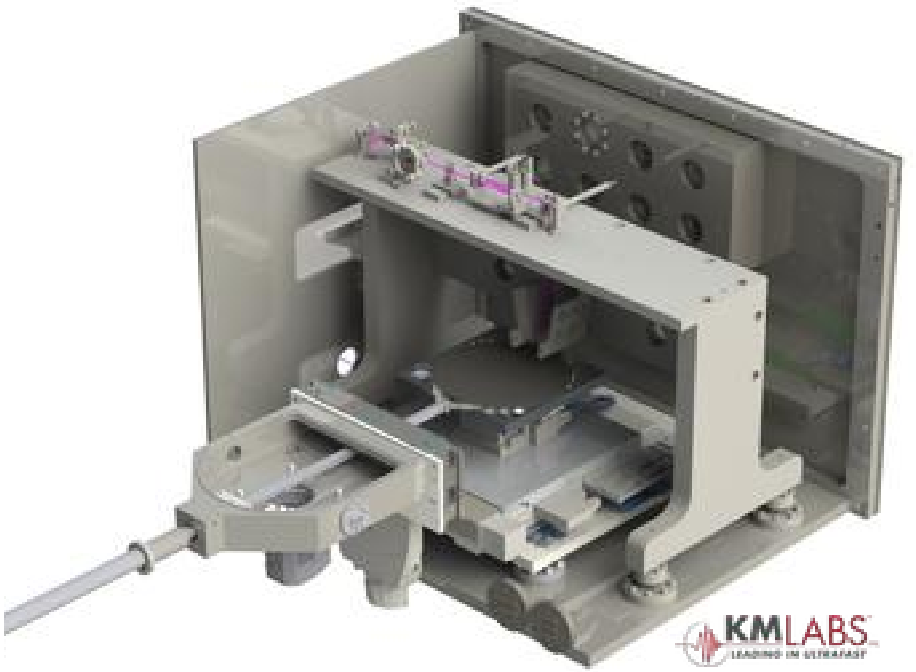




(a) (b)

Mok, et al. *Laser Interference Lithography and Shadow Lithography for Fabricating Nanowires and Nanoribbons,* Nanowires – Implementations and Applications, Intech Open (2011).

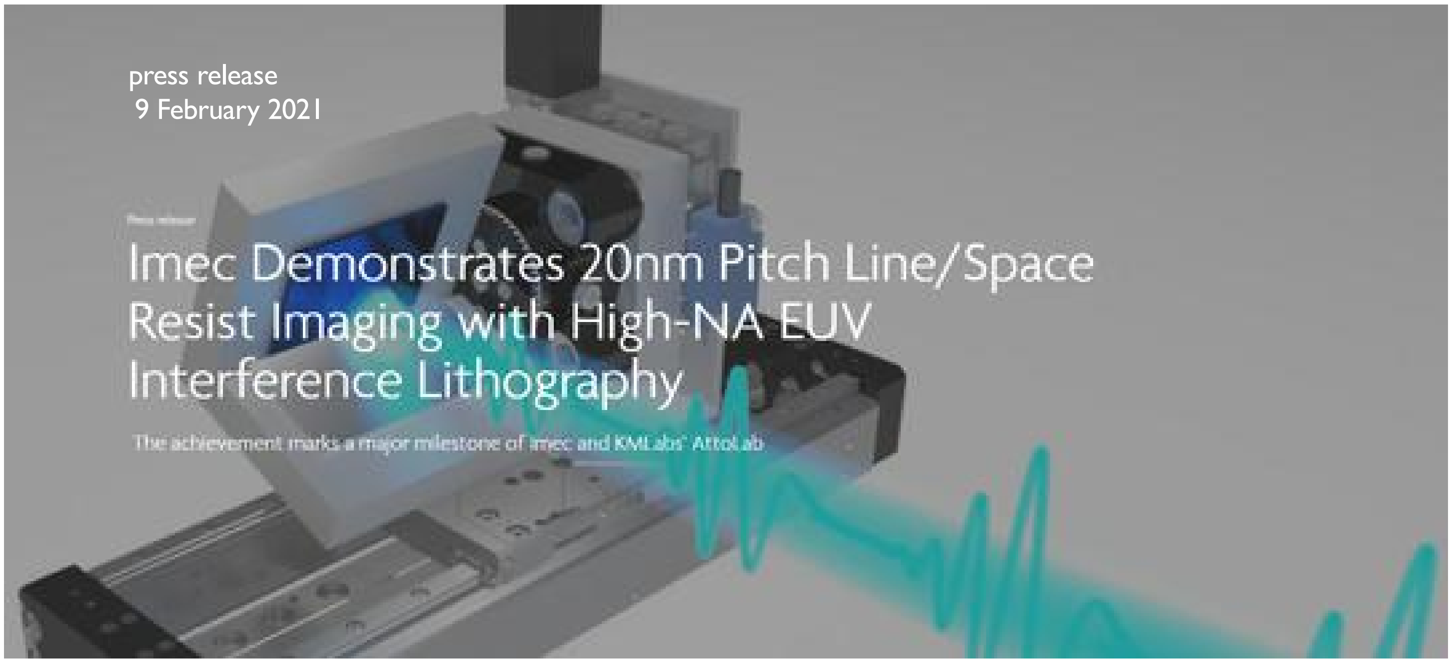
Interference Lithography
IL chamber for 300 mm wafers



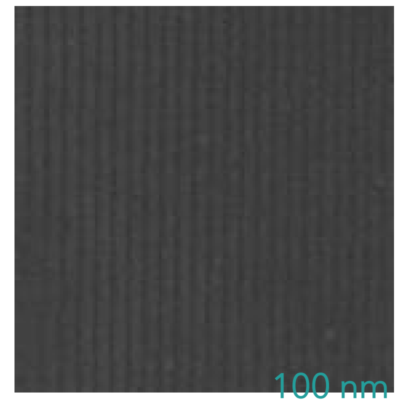
- 300 mm wafer compatible
- Vacuum load/lock for wafer loading
- 32 nm to 8 nm pitch
- Autofocus
- Rudimentary alignment
- Beam metrology

Start install at imec on 2 February 2021:

Interference Lithography
Lloyd's Mirror



20 nm pitch lines/spaces



presentation by
Kevin Dorney
SPIE Novel Patterning

Kevin Dorney, et. al., "Lloyd's mirror interference lithography below a 22-nm pitch with an accessible, tabletop, 13.5 nm high-harmonic EUV source," Proc. SPIE 11610, Novel Patterning Technologies 2021, 1161011 (22 February 2021)

Outline

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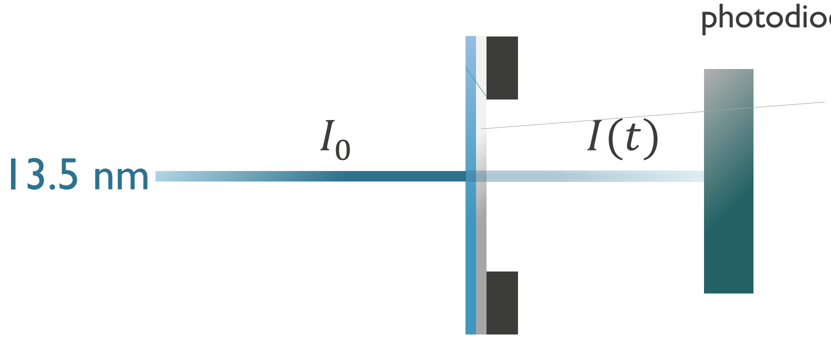
Radiometry



Linear absorption coefficient:

$$\alpha = -\frac{1}{d}\ln\frac{I(t_0)}{I_0}$$

Bleaching of photoresists (Dill parameters):

$$A = \frac{1}{d}\ln\frac{I(t_{exp})}{I(t_0)}$$ bleachable coefficient

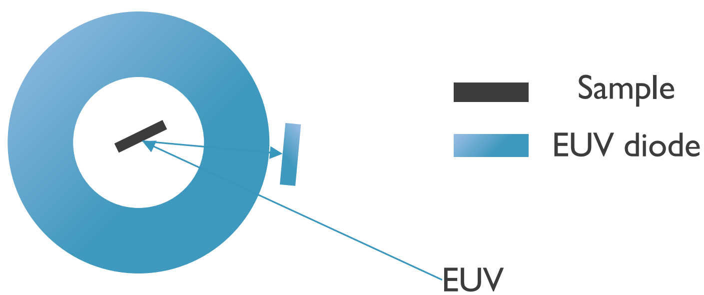
$$B = -\frac{1}{d}\ln\frac{I(t_{exp})}{I_0} = \alpha - A$$ unbleachable coefficient

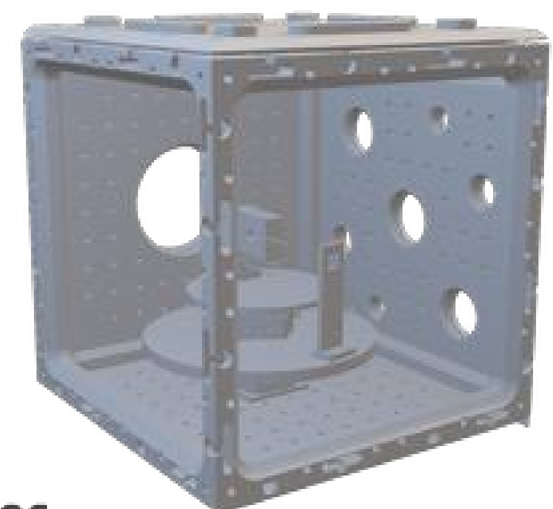
$$C = \frac{A+B}{A\Phi\left[I(0)-\frac{I(0)^2}{I_0}\right]}\frac{dI}{dt}\bigg|_{t=0}$$ exposure rate constant

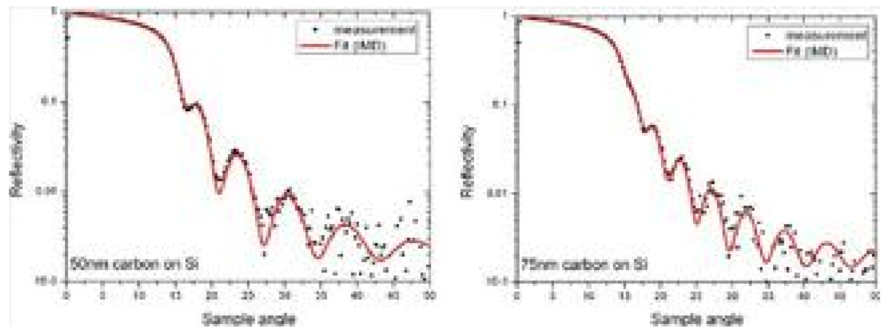
Fallica, et al. *Proc. SPIE* **9776**, 977612 (2016)
Fallica, et al. *Proc. SPIE* **10143**, 10143A (2017)

Dill, et al. *IEEE Transactions on Electron Devices* **22**, 445 (1975)

EUV reflectometry
EUV Reflectometry for n and k Determination

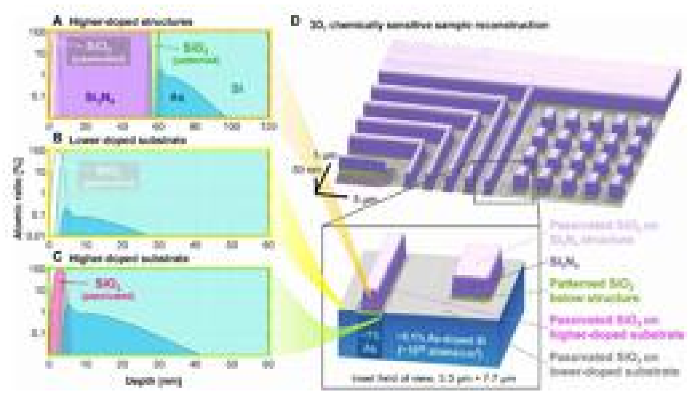






S. Döring, *et al.*, *Appl. Phys A* **107**, 795–800 (2012).

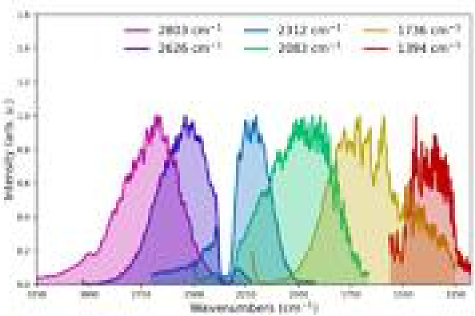
<u>Sensitive to:</u>
- material
- dopant level



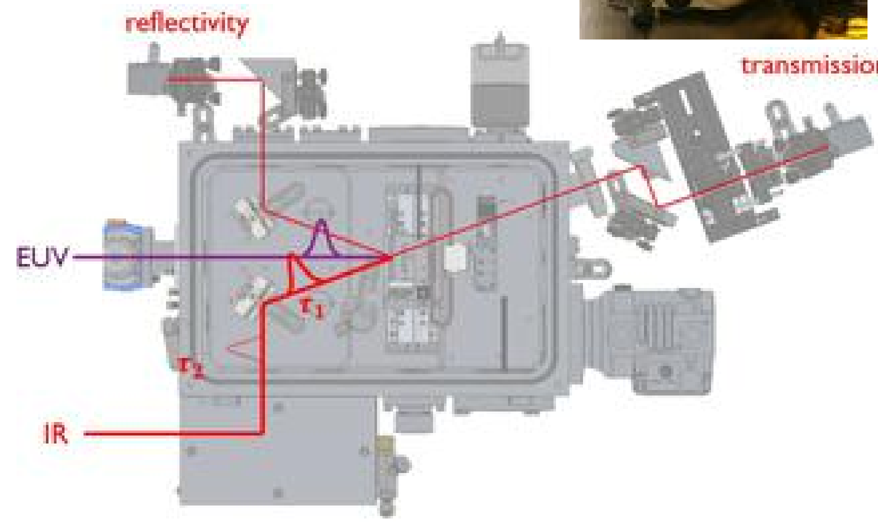
Tanksalvala *et al.*, *Sci. Adv.* **7**, eabd9667 (2021).

Spectroscopy
(time-resolved) Infrared spectroscopy

Light Conversion Mid-IR OPA
- Tunable, femtosecond mid-IR pulses
- 3.0 to 13.0 µm
- 40-200 fs pulse duration



Horiba iHR320 spectrometer



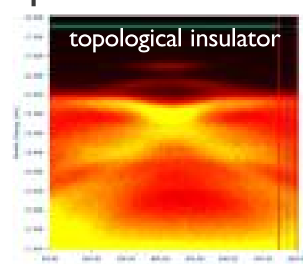
- IR spectroscopy (transmission/reflection) on photoresists coupons
- Sample holder with temperature control
- Monitor changes in IR spectrum after EUV exposure
- time-resolved EUV pump, IR probe: excited state dynamics on sub-picosecond timescale

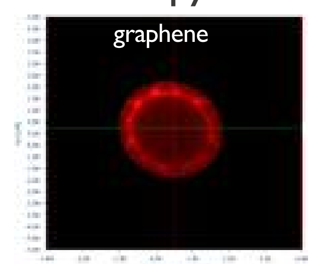
Spectroscopy
(time-resolved) Photoemission

Hemispherical Analyzer for electron spectroscopy
- 180° collection angle
- µARPES (< 2 µm field of view)
- 0-1500 eV kinetic energy range with < 5 meV resolution
- angle resolution < 0.1°

- EUV photoemission spectra
- Energy distribution of primary and secondary electrons from photoresists
- EUV/IR pump/probe spectroscopy

- Angle-resolved photoemission spectroscopy on 2D materials





Outline

- Motivation behind imec's AttoLab
- How does the AttoLab work?

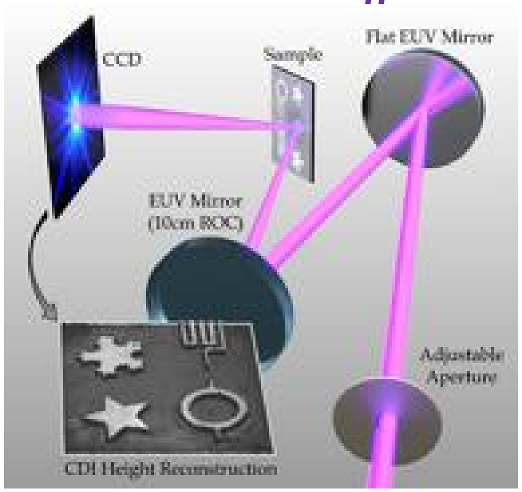
- Interference Lithography (incl. first results)
- Resist Characterization
- **Imaging**

- Summary

Imaging
Coherent diffractive imaging

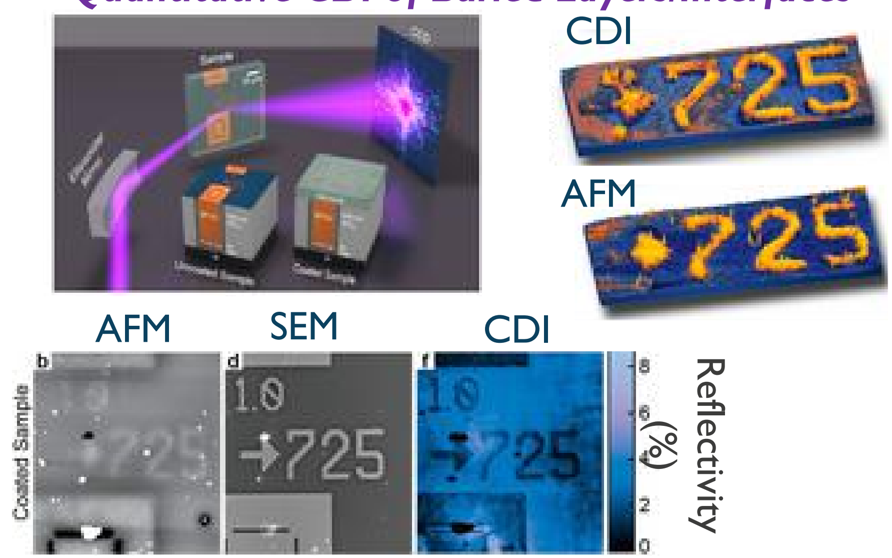
- Nanoscale coherent imaging of thin films, interfacial layers in device stacks, and topological order in spintronic materials (e.g., domain walls, skyrmions).
- With EUV light, **image resolution is ~λ (lateral) and sub-nm (axial).**

Standard Coherent Diffractive Imaging



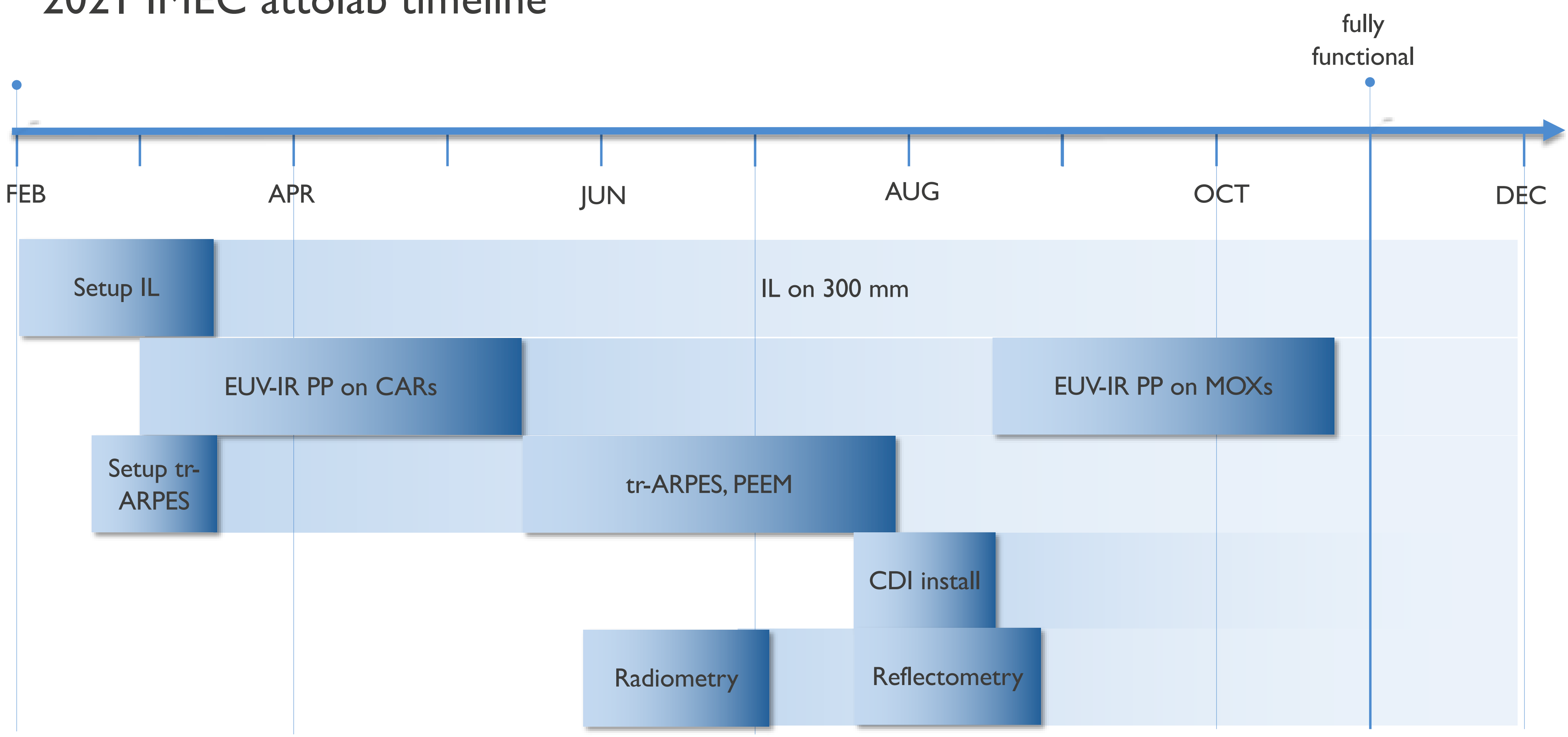
Seaberg, et al. Optica ***1***, 39 (2014)

Quantitative CDI of Buried Layers/Interfaces



Shanblatt, et al. *Nano Lett.* **16**, 5444 (2016)

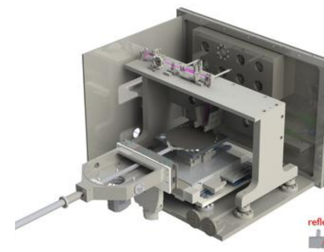
2021 IMEC attolab timeline



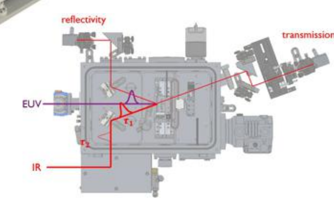
Summary
IMEC ATTOLAB

- Laser driven HHG source for **spatially and temporally coherent** EUV radiation


- **Interference Lithography**: head start on high-NA EUVL



- (Ultrafast) **Spectroscopy**:Fundamental understanding of resist chemistry



- **Imaging** techniques: nondestructive spatial and depth-resolved maps

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imec AttoLab science team

Paul van der Heide
Co AttoLab Principal

John Petersen
Co AttoLab Principal

Kevin Dorney
Postdoc

Michiel van Setten
Ab Initio

Esben Larsen
Lasers/Litho/CDI

Dhirendra Singh
Postdoc

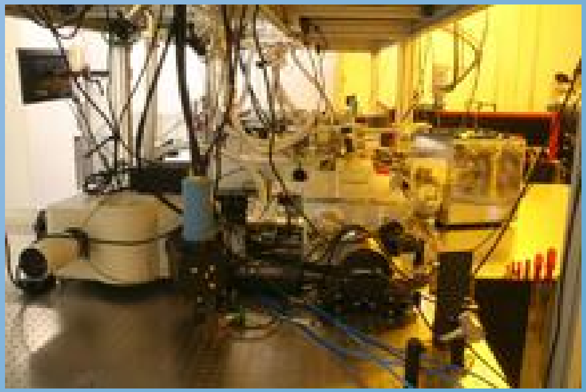
Thomas Nuytten
Project Manager

Fabian Holzmeier
Spectroscopy

Just starting: 5 PhD students and 1 master's student (they'll be in the next portrait)

Currently searching for a CDI postdoc focused on development of algorithms

Contact: john.petersen@imec.be
paul.vanderheide@imec.be
thomas.nuytten@imec.be
fabian.holzmeier@imec.be
esben.wittinglarsen@imec.be



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Resources:

Fabian Holzmeier, Kevin Dorney, Esben W. Larsen, Thomas Nuytten, Dhirendra P. Singh, Michiel van Setten, Pieter Vanelderen, Clayton Bargsten, Seth L. Cousin, Daisy Raymondson, Eric Rinard, Rod Ward, Henry Kapteyn, Stefan Böttcher, Oleksiy Dyachenko, Raimund Kremzow, Marko Wietstruk, Geoffrey Pourtois, Paul van der Heide, John Petersen, "**Introduction to imec's AttoLab for ultrafast kinetics of EUV exposure processes and ultra-small pitch lithography**," Proc. SPIE 11610, Novel Patterning Technologies 2021, 1161010 (22 February 2021)

Kevin Dorney, Sonia Castellanos, Esben Larsen, Fabian Holzmeier, Dhirendra Singh, Nadia Vandenbroeck, Danilo De Simone, Peter De Schepper, Alessandro VaglioPret, Clayton Bargsten, Seth L. Cousin, Daisy Raymondson, Eric Rinard, Rod Ward, Henry Kaptyen, Thomas Nuytten, Paul Van der Heide, John Petersen, "**Lloyd's mirror interference lithography below a 22-nm pitch with an accessible, tabletop, 13.5 nm high-harmonic EUV source**," Proc. SPIE 11610, Novel Patterning Technologies 2021, 1161011 (22 February 2021)

Summary

- High harmonic sources are a unique quantum technology allowing exquisite control over EUV and soft X-ray light

- HHG technology is already a useful tool for R&D
  - First sub-wavelength EUV imaging
  - Non-destructive maps of heterostructures for quantum technologies
  - New understanding about nanoscale thermal transport
  - New understanding of spin and charge dynamics
  - Distinguish attosecond electron screening and scattering in quantum materials
  - Bright future – everything scales with the wavelength

- Emerging industrial relevance for nanoscale metrology

VUV/EUV/SXR light science **Spin Dynamics** **Magnetics** **ARPES** **Imaging**