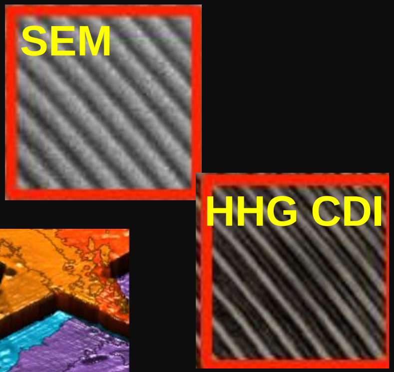
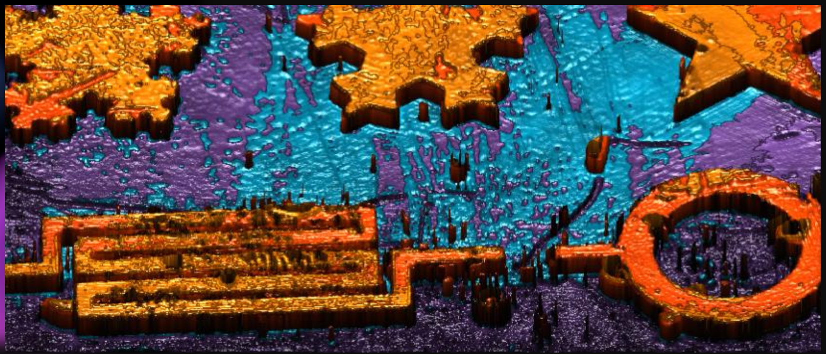
Tabletop-scale EUV coherent imaging using High Harmonic Light

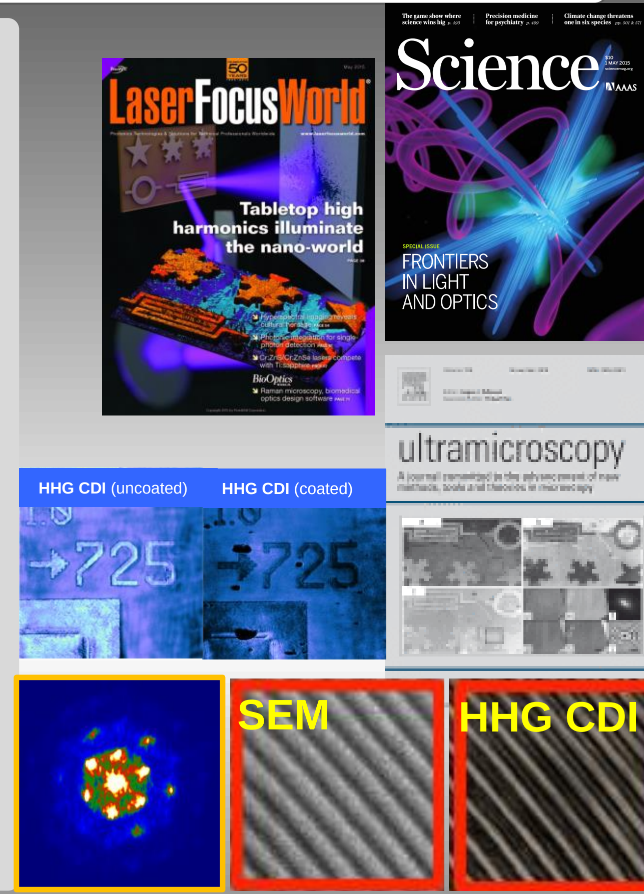
Henry C. Kapteyn
KMLabs Inc. and JILA





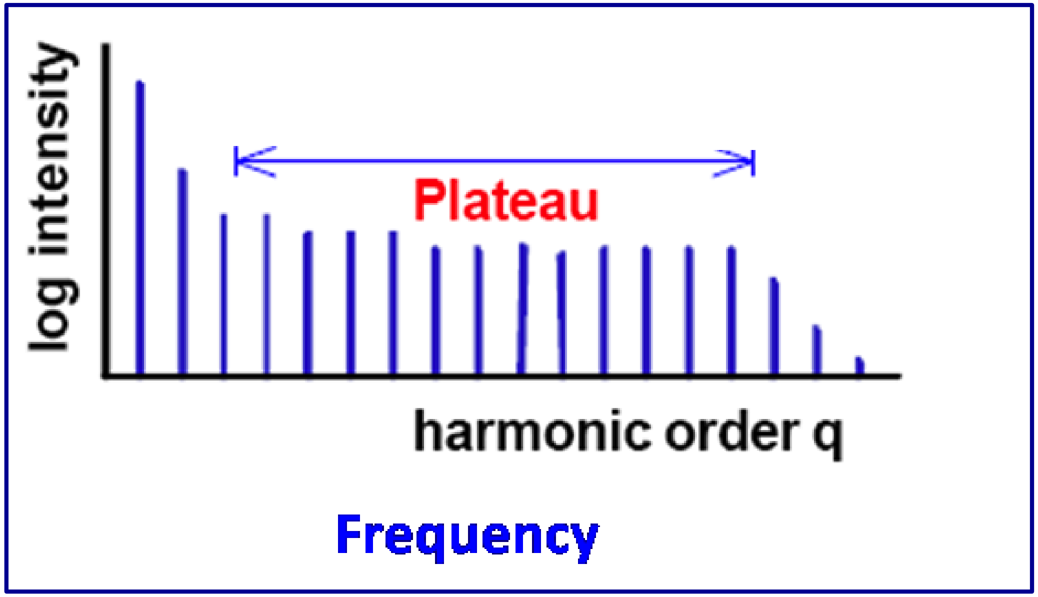
Talk overview

- Tabletop coherent EUV light sources – high-order harmonic generation.
- Revolution in coherent imaging: 14 nm spatial resolution @13.5nm.
- Progress in commercial “tabletop x-ray laser” light sources– **the KMLabs XUUS$_4$™.**



High Harmonic Generation: atomic response to extremely bright light

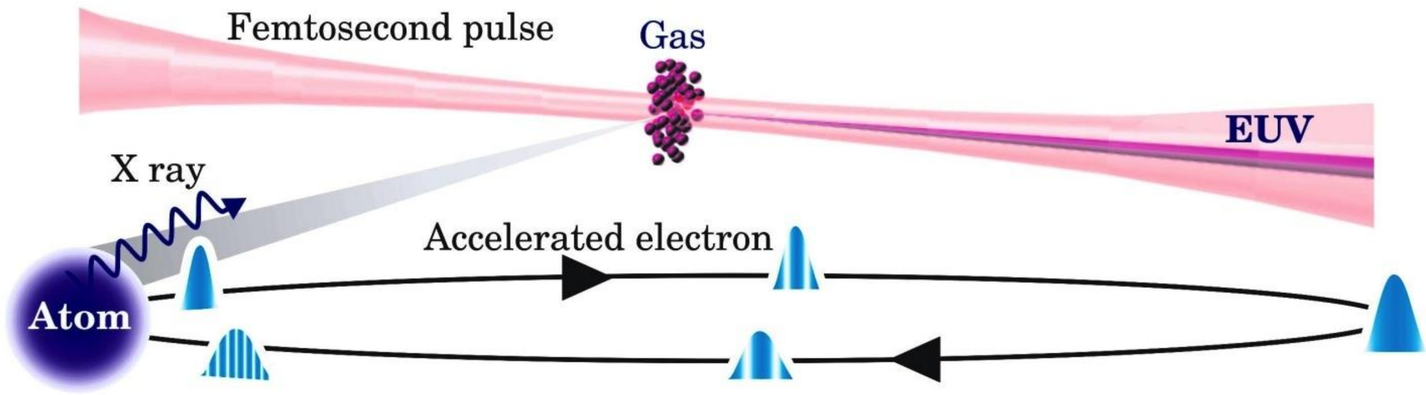
- **Take a few-cycle (~10^{-14} sec) laser pulse, focus to ~10^{14} W cm^{-2}:**



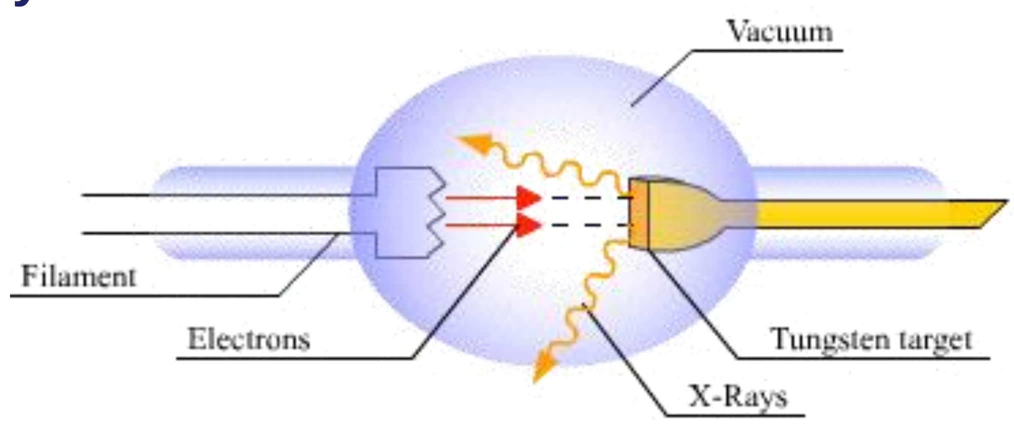
McPherson, 1987
Ferray, 1988

High harmonics - coherent version of X-Ray tube

- **High Harmonic Generation**

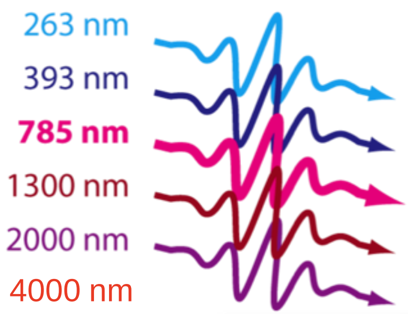


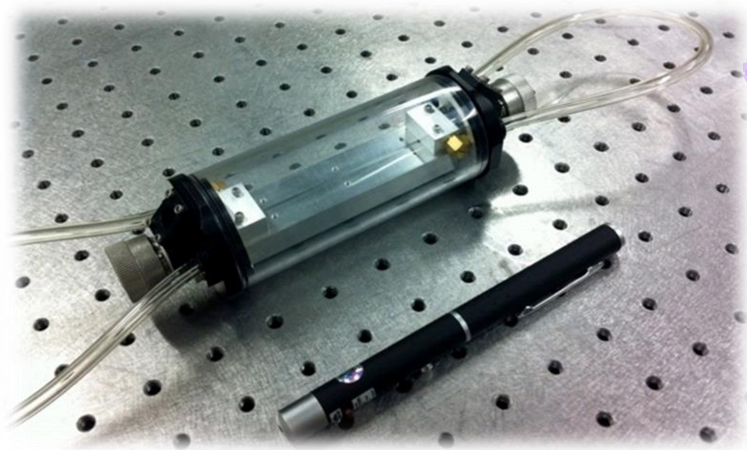
- **Röntgen X-ray Tube**



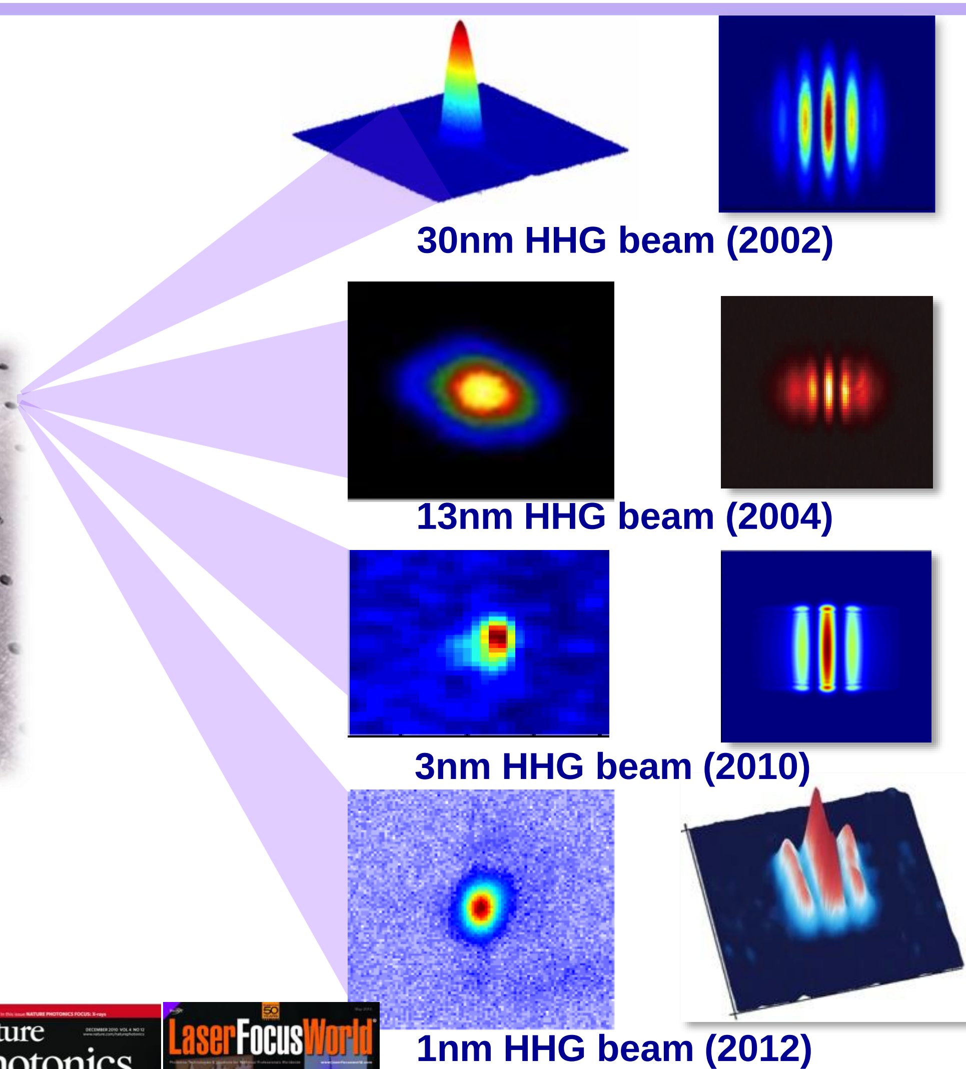
1895

Coherent light from UV to keV: High Harmonic Generation

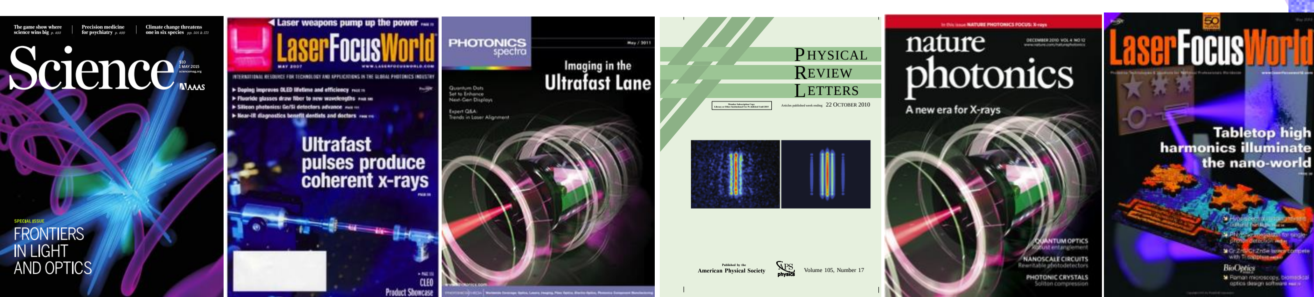




High pressure waveguide



Science ***280****, 1412 (1998)*
Science ***297****, 376 (2002)*
Science ***336****, 1287 (2012)*
Science ***348****, 530 (2015)*
Science ***350****,1225 (2015)*



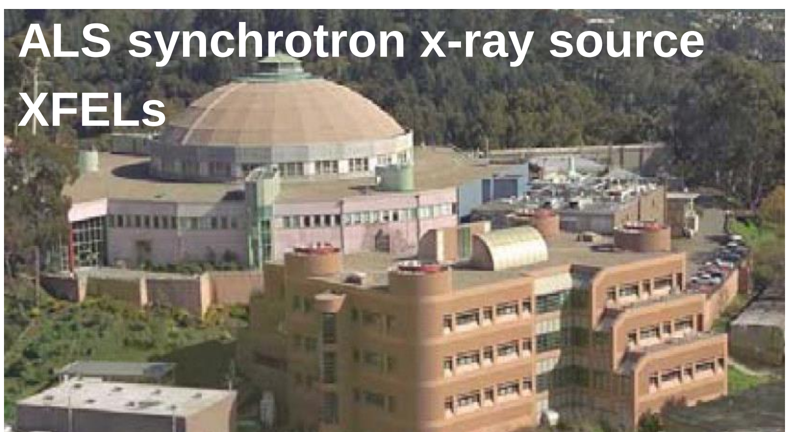
Revolution in coherent X-ray sources and imaging

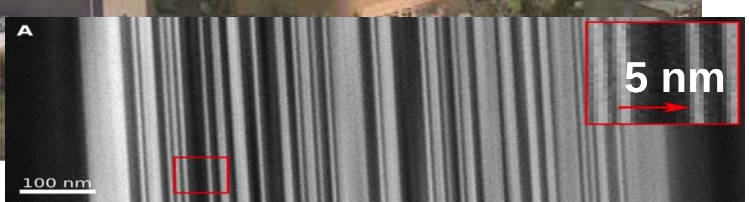
Facility scale

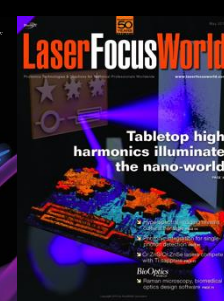
- Synchrotron and free electron lasers
- **EUV to 12 keV (EUV to hard X-rays)**
- Nano to femto time resolution
- **High flux**
- Tunable
- **Facility scale** beamline w/support

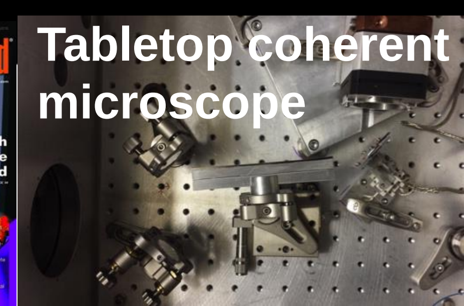
Tabletop

- High harmonic sources
- **mid-IR to 1 keV (EUV to soft X-rays)**
- Sub-femtosecond time resolution
- **Lower flux at higher hν**
- Hyperspectral
- **Tabletop** for easy student/industry access





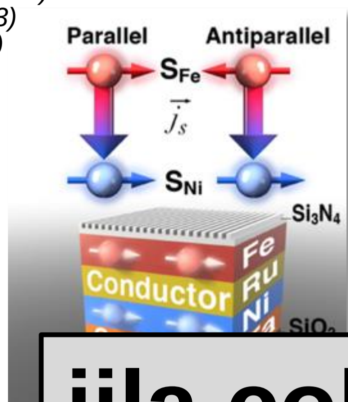




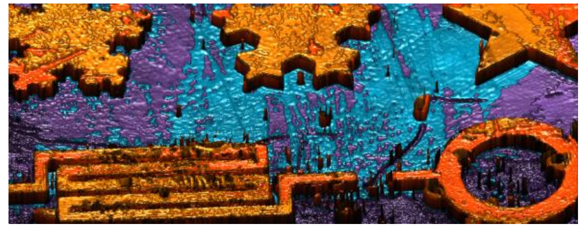
Tabletop X-rays "see" new materials/nano science

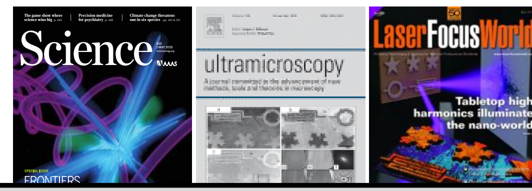
Spin scattering and transport

PNAS **109**, *4792 (2012)*
Nat. Comm. **3,** *1037 (2012)*
PRL **110**, *197201 (2013)*
arXiv:1401.4101 (2014)

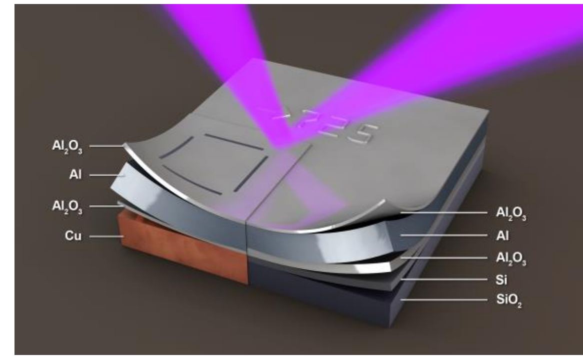


Quantitative imaging at λ limit





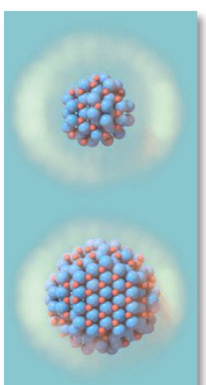
Elastic properties, dopants, elipsometry, interfaces

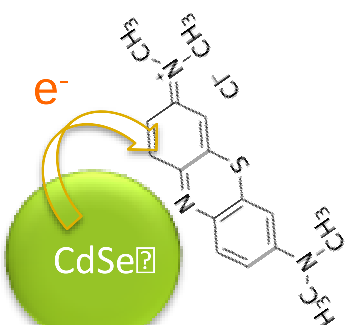


Nanoletters, in press (2016)
Submitted (2016)
PRB **85**, *195431 (2012)*
Nano Letters **11**, *4126 (2011)*

jila.colorado.edu/kmgroup

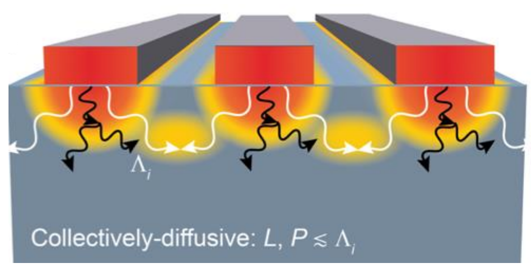
Charge transport in nano, energy science





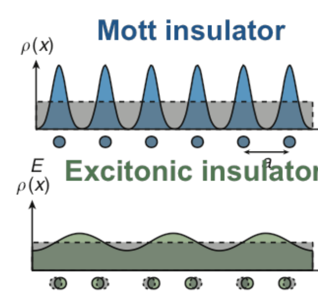
Nano Lett. **13**, *2924 (2013)*
JACS **137**, *3759 (2015)*

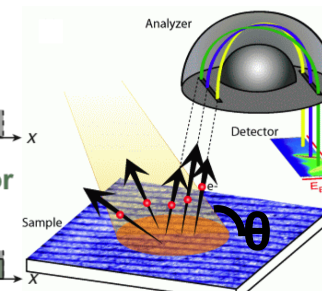
Nanoscale energy transport



Nature Mat. **9**, *26 (2010)*
PNAS **112**, *4846 (2015)*

Electronic properties: full band structure (ARPES)





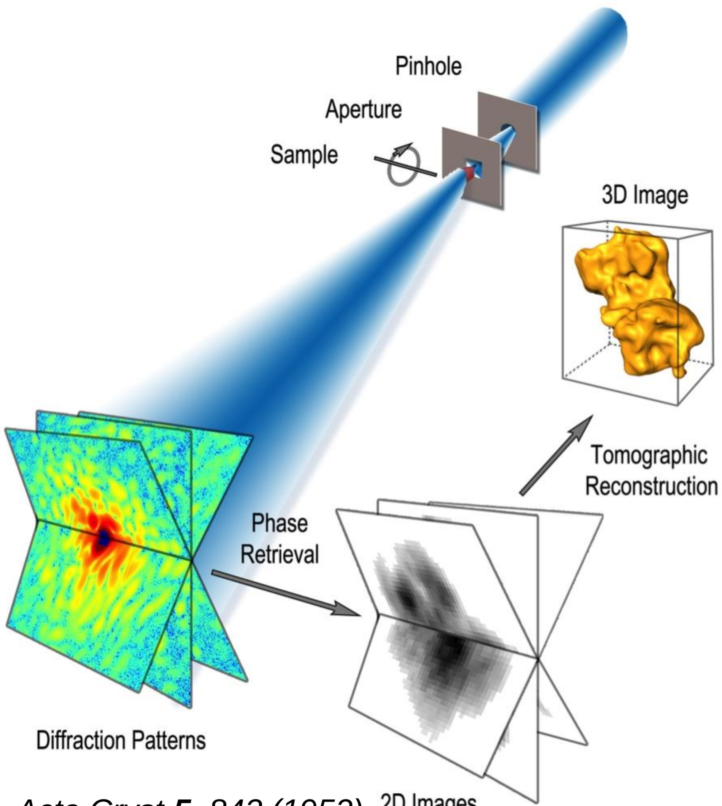
Nature **471**, *490 (2011)*
Nat. Comm **3**, *1069 (2012)*
PRL **112** *, 207001 (2014)*
PRB **92**, *041407(R) (2015)*
Science, in press (2016)

Revolution in X-ray Imaging: 3D coherent imaging of opaque materials with elemental, chemical, magnetic mapping

REVIEW

Beyond crystallography: Diffractive imaging using coherent x-ray light sources

Jianwei Miao,[1*] Tetsuya Ishikawa,[2] Ian K. Robinson,[3,4] Margaret M. Murnane[5]



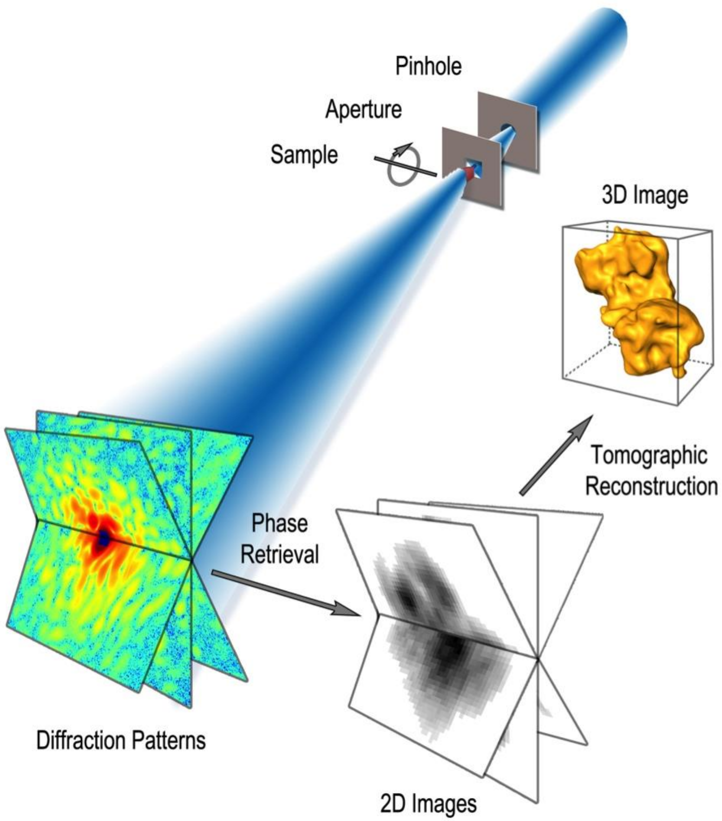
- **Diffraction-limited imaging ≈ $\lambda/2NA$**
- Image thick samples in 3D
- Inherent contrast for X-rays
- **Phase and amplitude image contrast**
  - Transmission or reflection
- Robust to vibrations
- ***Most* photon-efficient form of imaging!**

*Sayre, Acta Cryst **5**, 843 (1952)*
Fienup, Opt. Lett.. **3**, 27 (1978)
*Miao et al., Nature **400**, 342 (1999)*
*Miao et al., Science **348**, 530 (2015)*

Advanced in coherent diffractive imaging (CDI)

Initial approaches to CDI (until 2011)

- Required isolated sample or beam
- Transmission mode only



Fienup, Opt. Lett.. **3**, 27 (1978)
Miao *et al.*, Nature, **400**, 342 (1999)

Advanced CDI (2016)

- Ptychographic CDI with overlapping beams
- Robust reflection and transmission modes
- Absolute interface structure determination
- 3D structure w/o tilting or sectioning
- Hyperspectral, multibeam, direct retrieval

Rodenburg *et al.*, PRL **98**, 034801 (2007)
Thibault *et al.*, Science **321**, 379 (2008)
Maiden *et al.*, Ultramicroscopy **109**, 1256 (2009)

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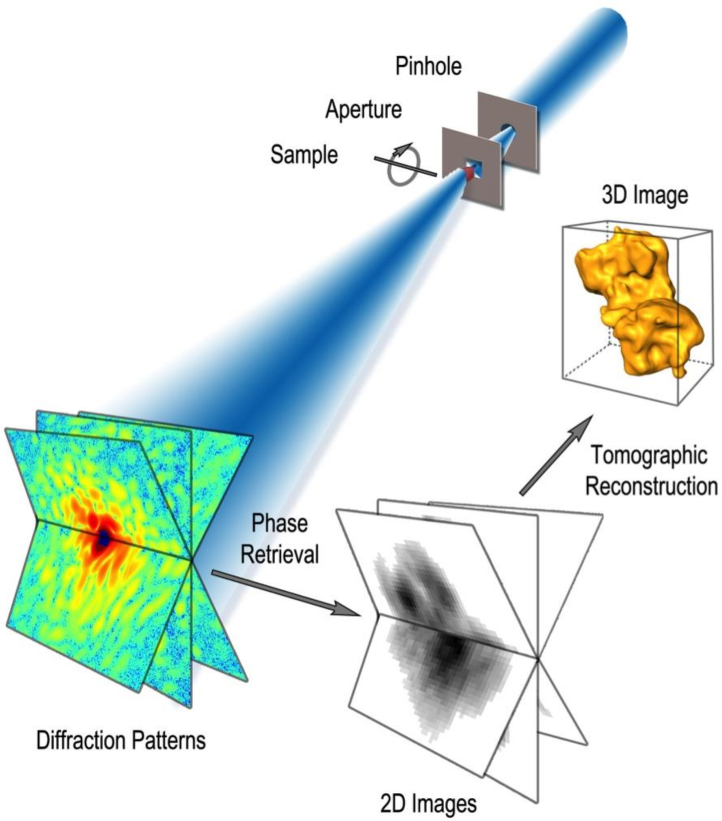

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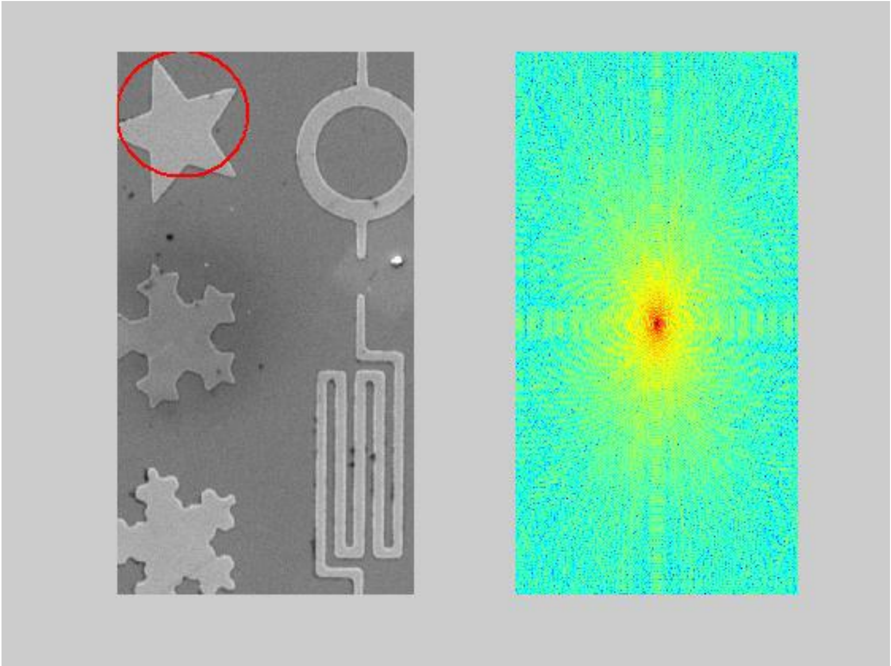
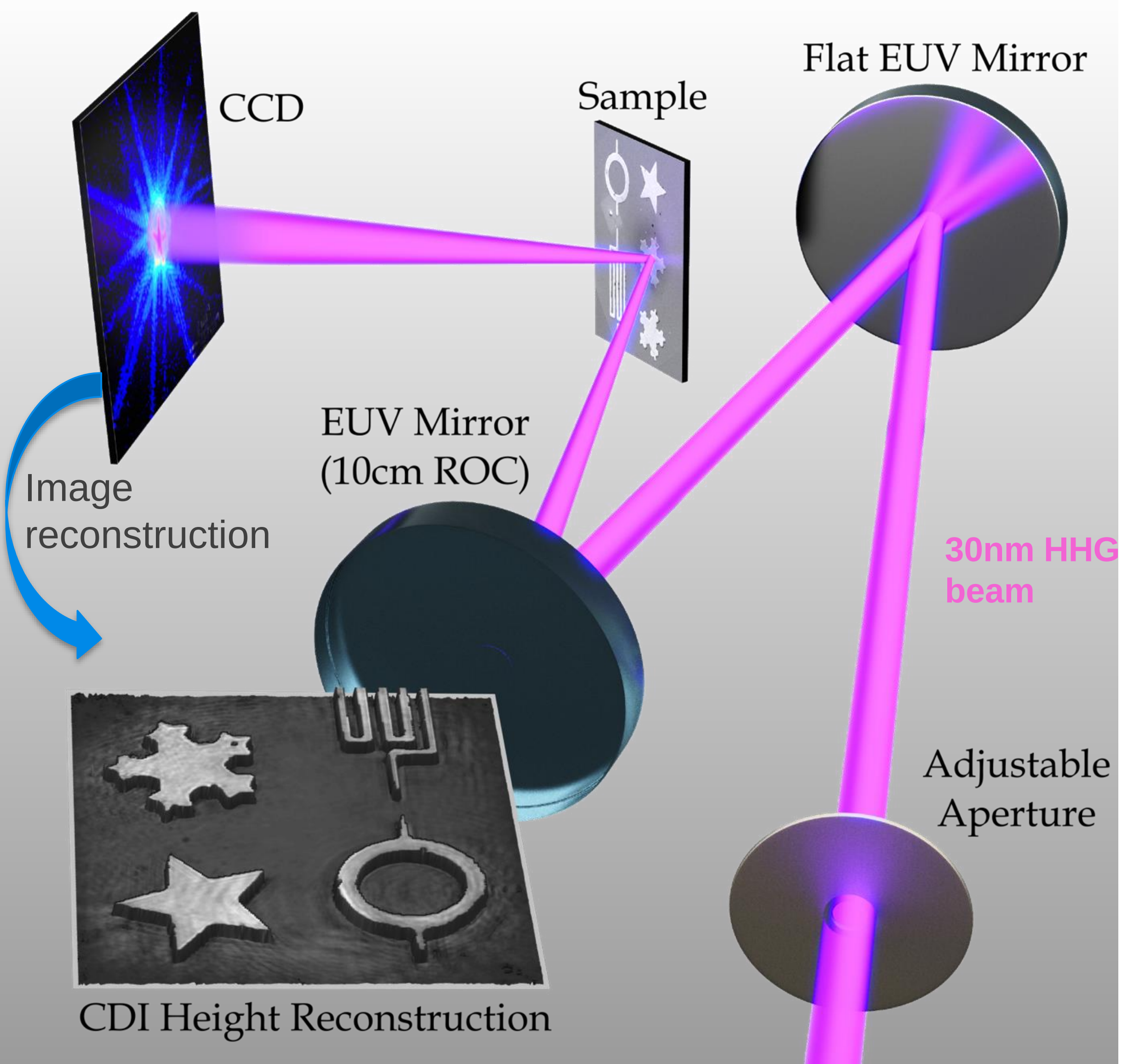


Rodenburg *et al.*, PRL **98**, 034801 (2007)
Thibault *et al.*, Science **321**, 379 (2008)
Maiden *et al.*, Ultramicroscopy **109**, 1256 (2009)

General tabletop reflection-mode full field microscope

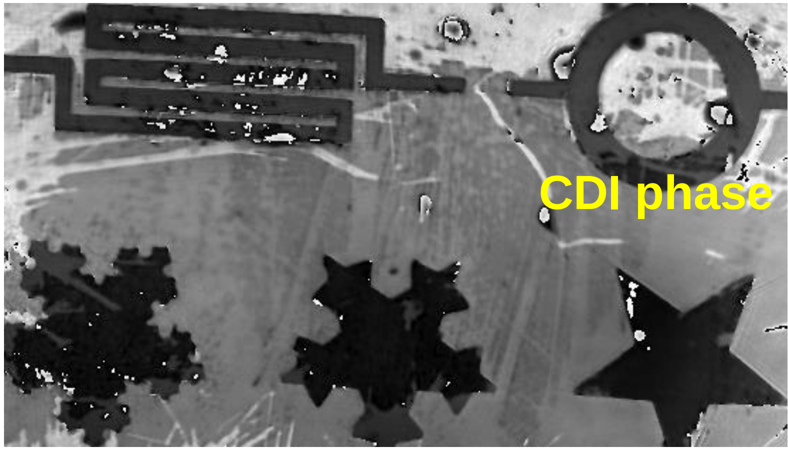


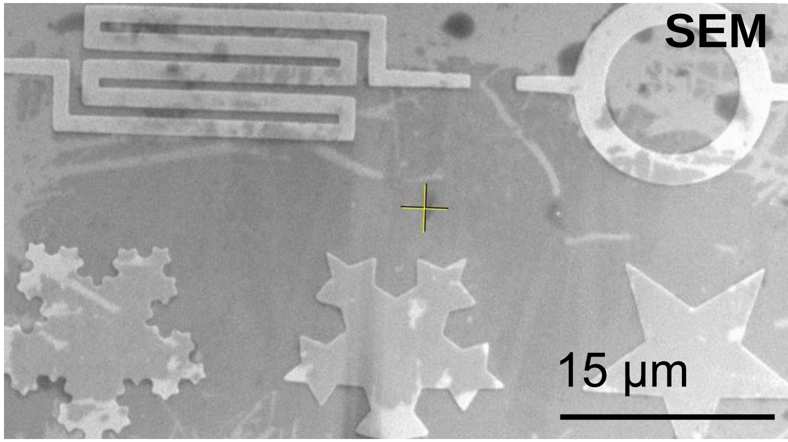
- Full field image of extended objects
- Arbitrary angle of incidence with tilted-plane correction
- Algorithm can correct for imperfect scanning stages
- Can use multiple colors and beams for elemental, chemical, spin contrast
- Reflection and transmission
- Limits in spatial/temporal resolution, speed, not known

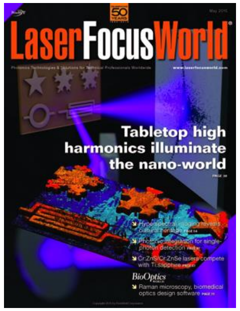
Ultramicroscopy ***109***, *1256 (2009)*
Optica ***1***, *39 (2014)*
Science ***348***, *530 (2015)*
Laser Focus World (2015)
Ultramicroscopy ***158***, *98 (2015)*

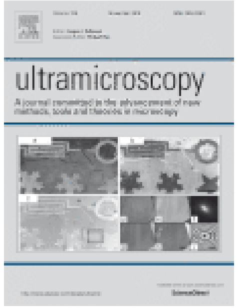
High contrast tabletop reflection-mode CDI (λ ~ 30 nm)

- Better contrast images than JILA SEM
  - phase contrast, element-specific reflectance
- 3D imaging: spatial resolution 1.3λ horizontal (<40nm), <5Å profile height
- <1 minute HHG exposure time for full image (old laser, bad optics)
- Less damage than AFM or SEM
- Unlimited working distance
- Faster detector readout needed
  - <1 min exposure; >90 min readout
- New cluster image reconstruction, detectors, and lasers being implemented as KMLabs / JILA collaboration









Science ***348***, *530 (2015)*
Laser Focus World (May 2015)
Ultramicroscopy ***158***, *98 (2015)*
Opt. Exp. ***19***, *22470 (2011)*

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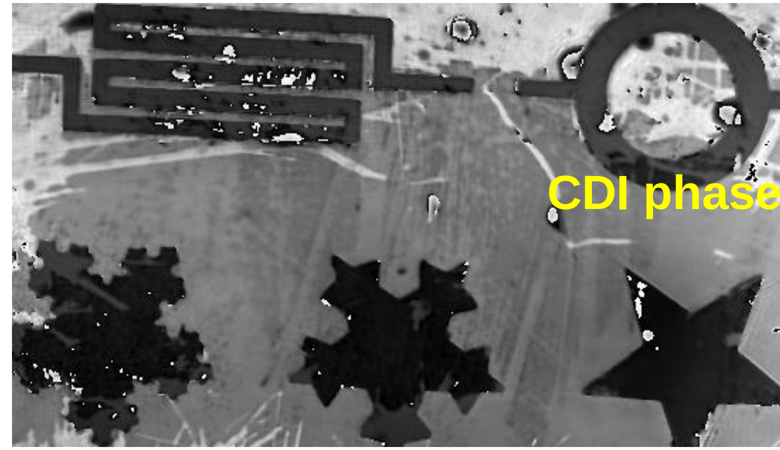
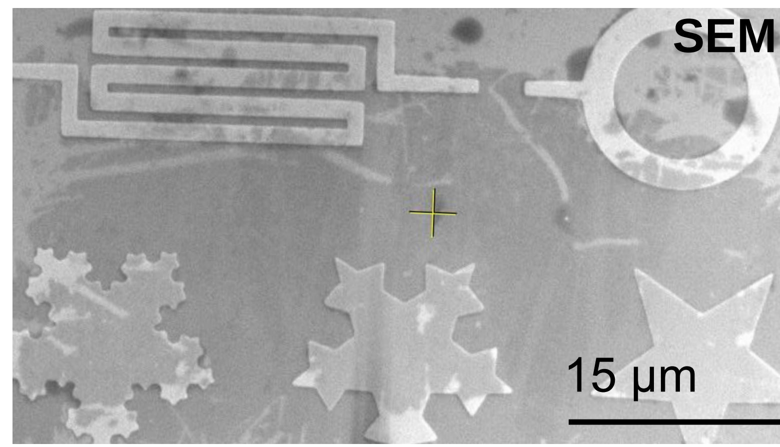
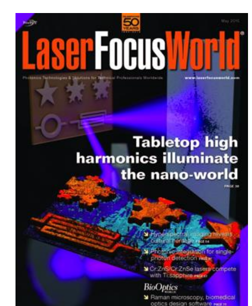
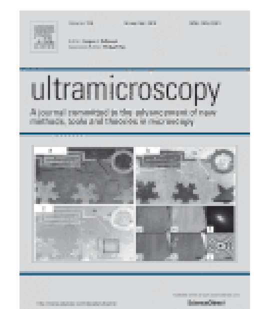


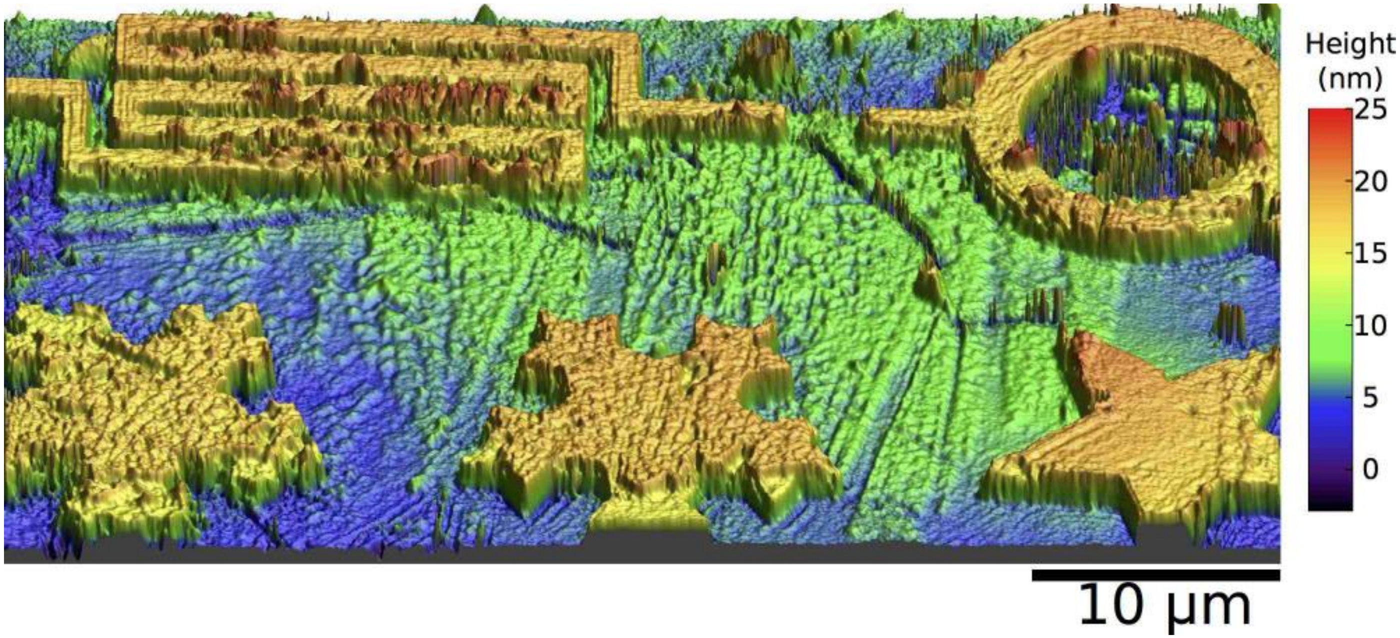


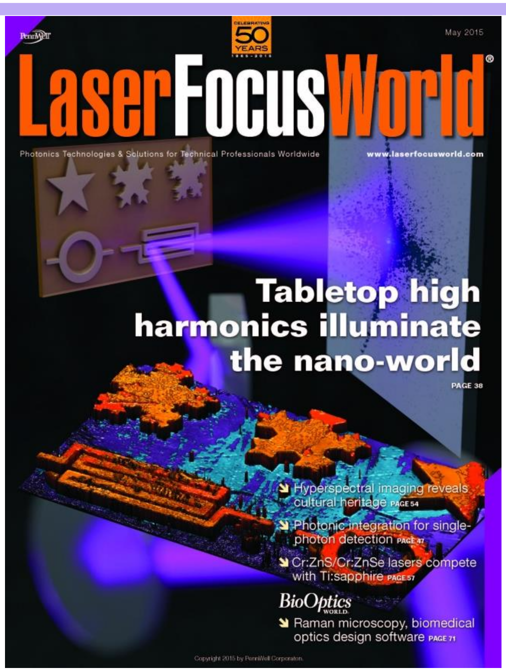


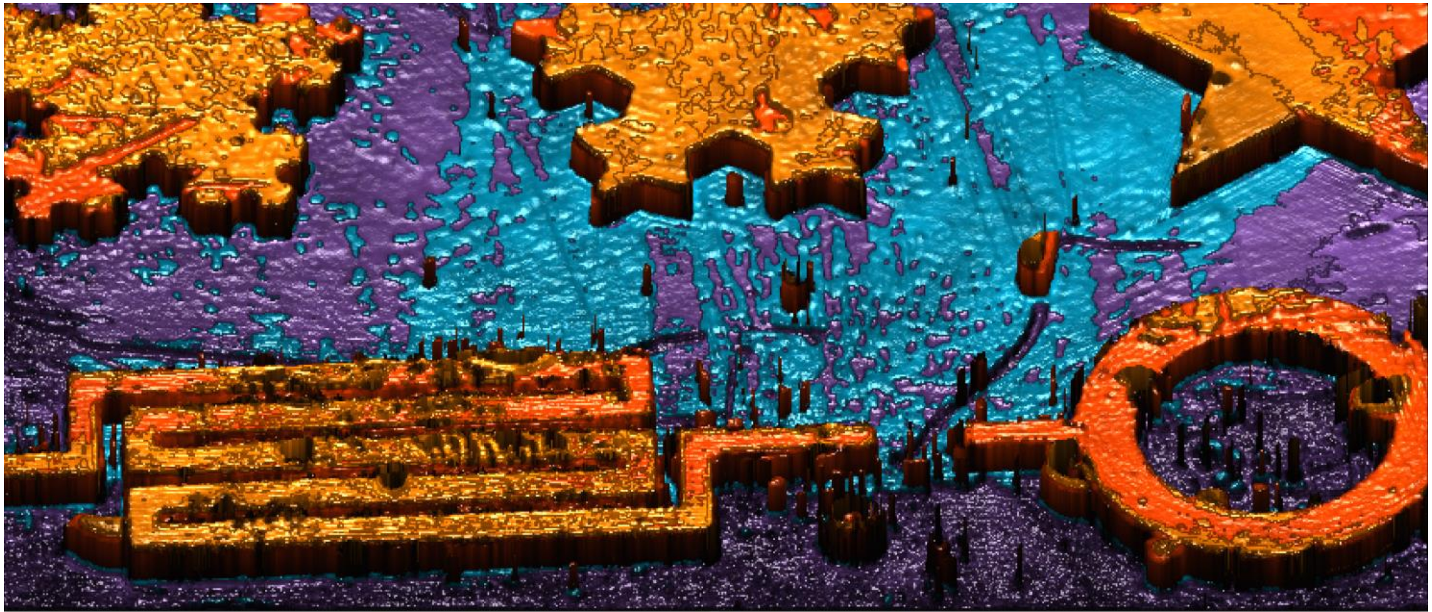


*Science **348**, 530 (2015)*
Laser Focus World (May 2015)
*Ultramicroscopy **158**, 98 (2015)*
*Opt. Exp. **19**, 22470 (2011)*

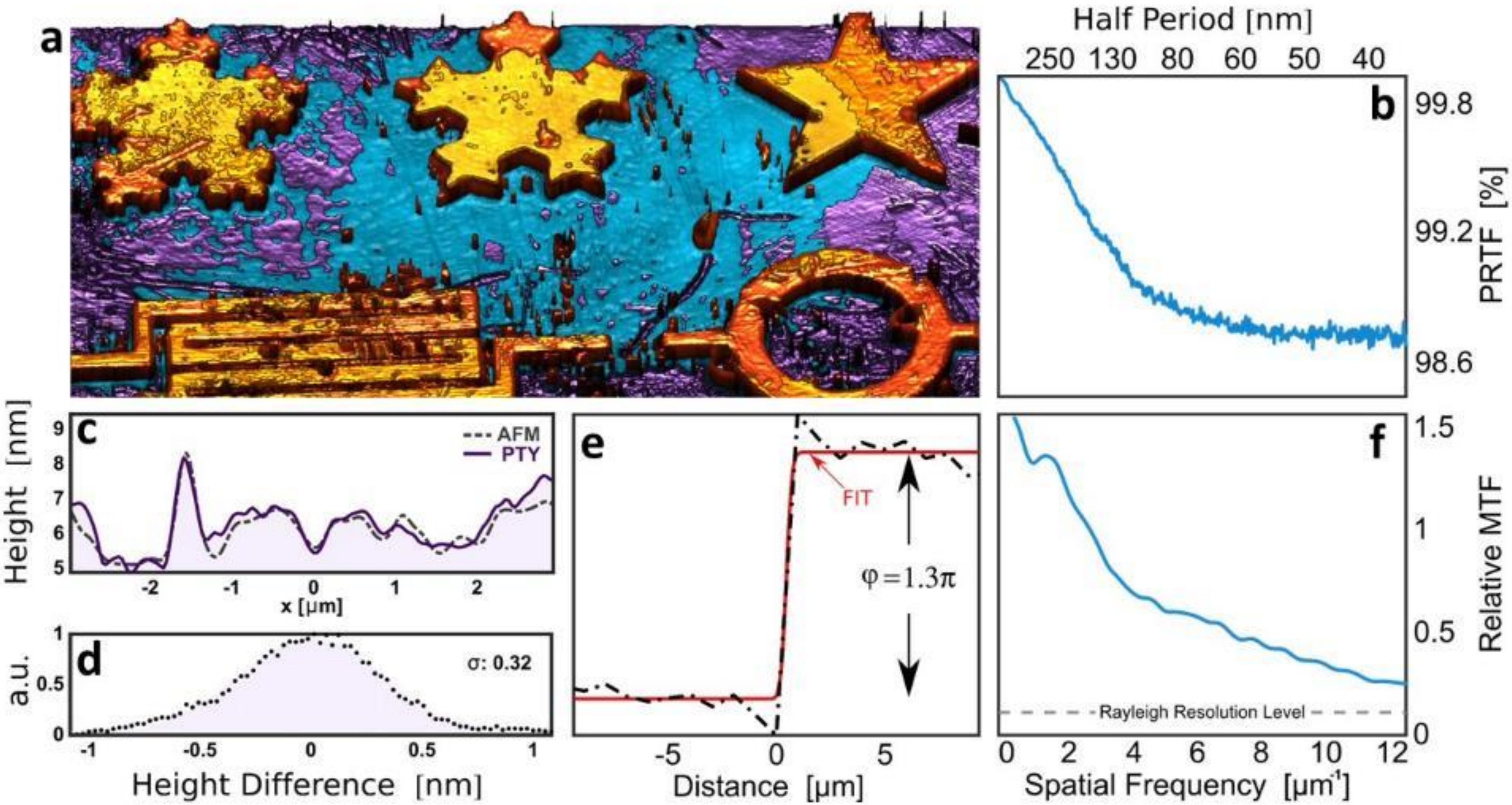
Quantitative CDI: height/composition/tomography maps







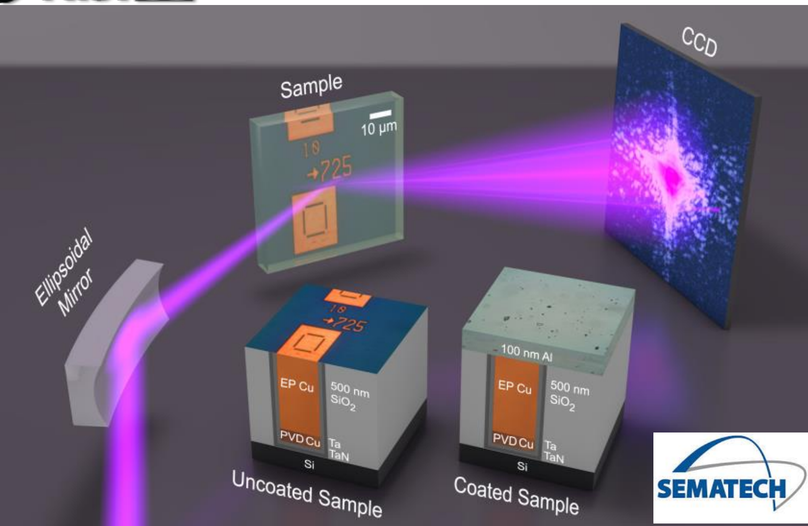
Determining the spatial resolution – 3 approaches



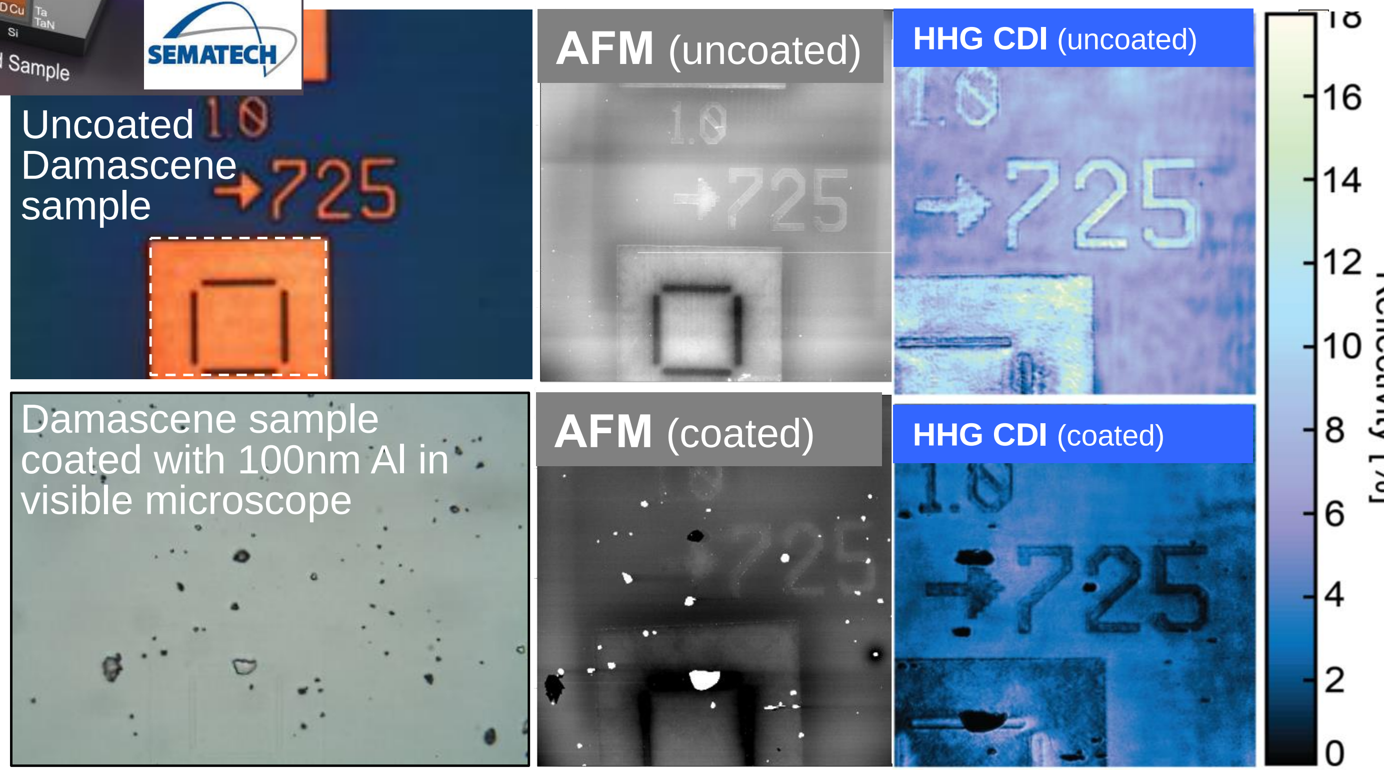
1. Comparison with AFM **2. Lineout at edge** **3. Spatial frequencies**

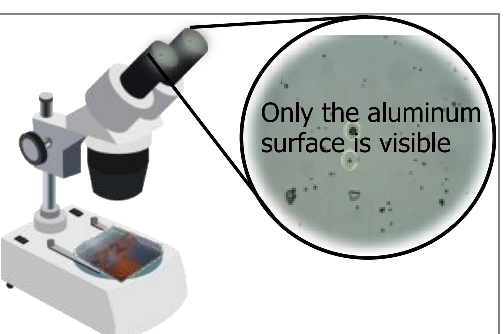
Ultramicroscopy ***158****, 98 (2015)*

Seeing through buried layers and interfaces



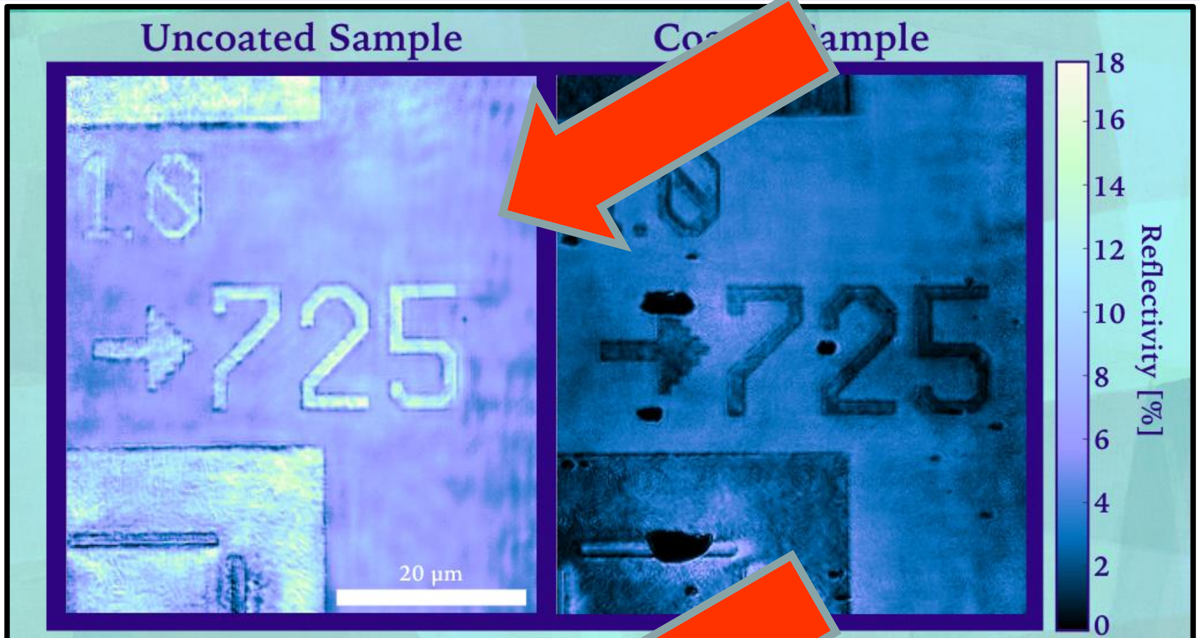
- **CDI amplitude** image enables imaging of elemental composition **through** 100nm of Al
- Quantitative non-destructive imaging of elemental and interfacial properties due to changes in EUV reflectivity
- Identified interdiffusion of Al into Cu, and formation of thin Al oxide layer on SiO_2

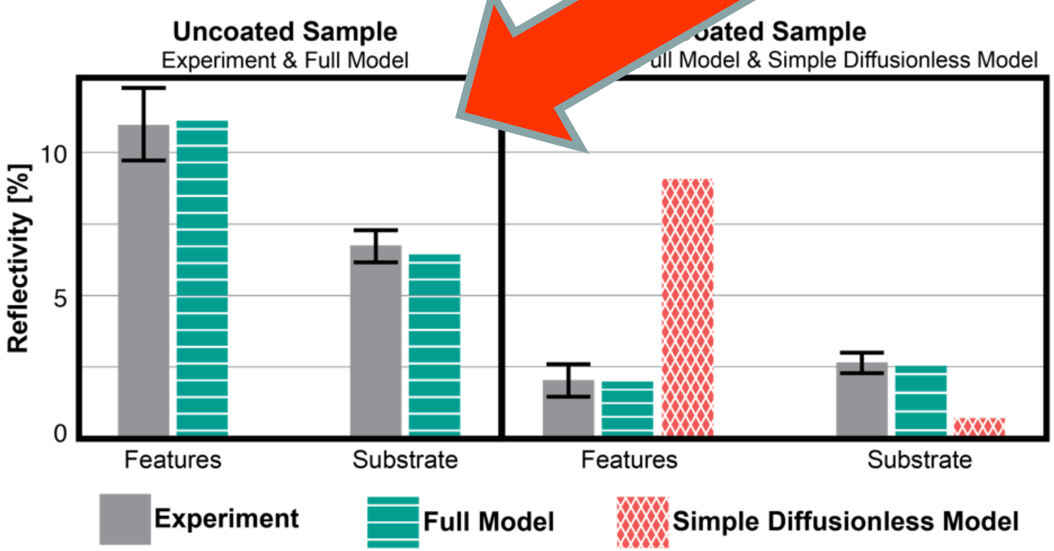


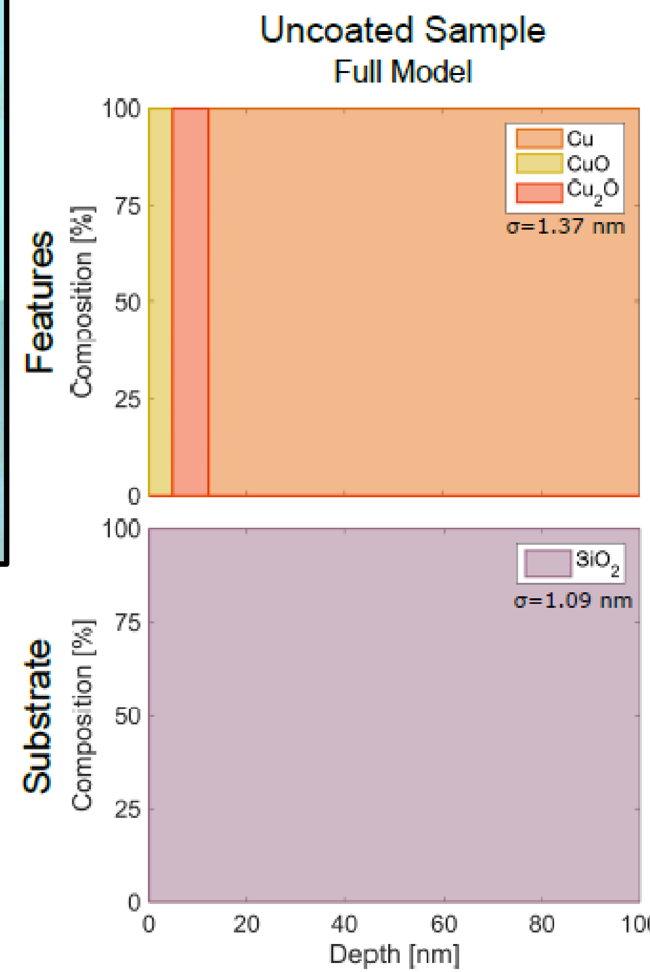


Postdeadline paper, Frontiers in Optics (2015), doi: 10.1364/FIO.2015.FW6B.2

Reflectivity of **uncoated** damascene shows oxide layer

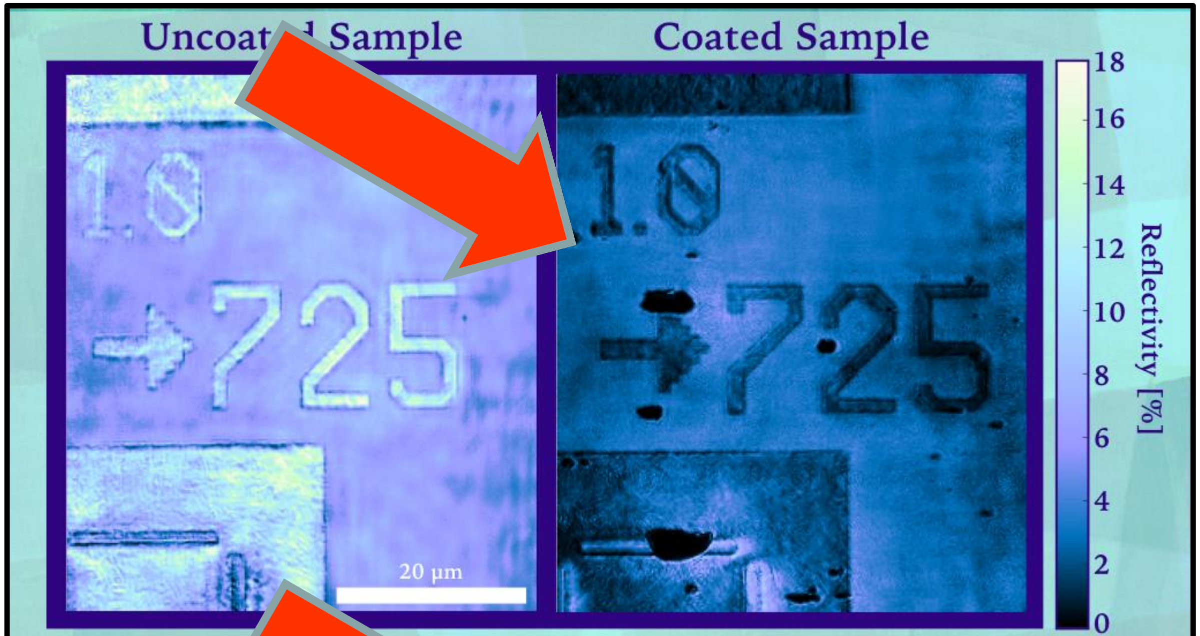


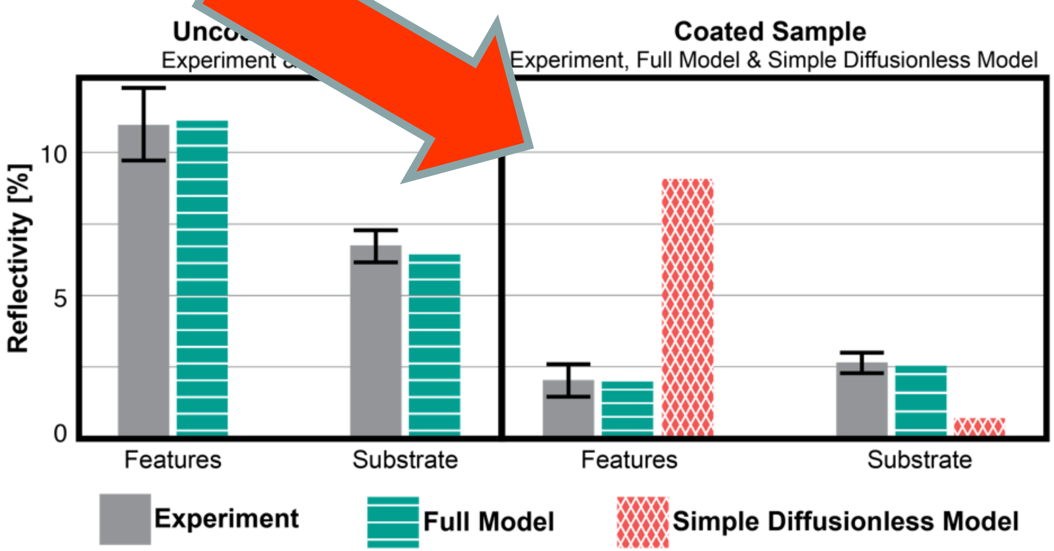


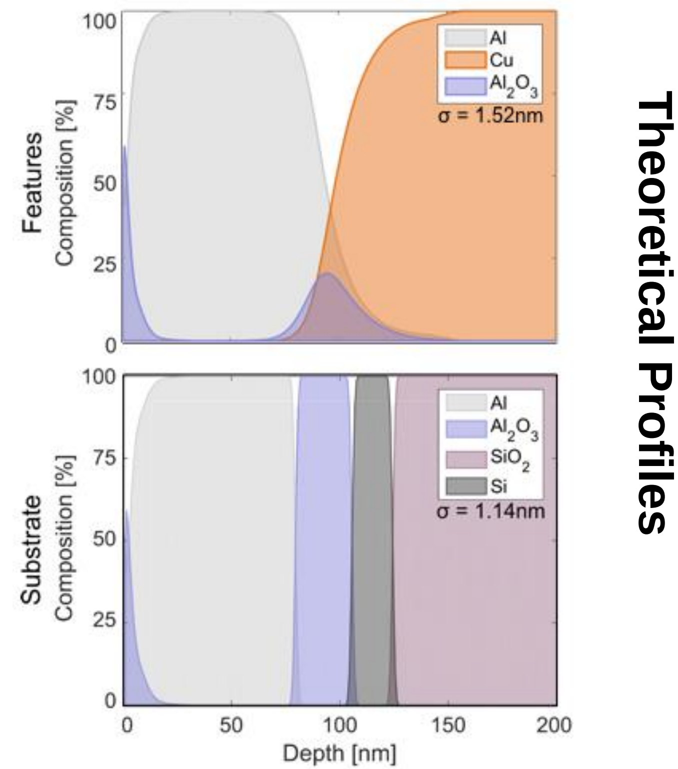


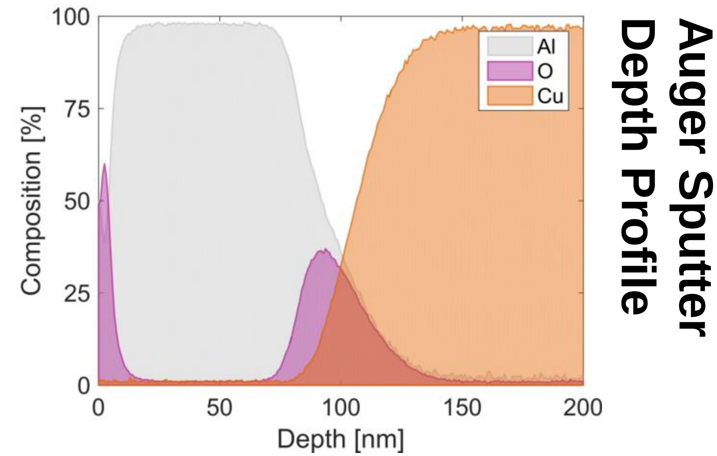
Theoretical Compound Profiles

Reflectivity of **coated** damascene shows interdiffusion – should be able to measure doping profiles



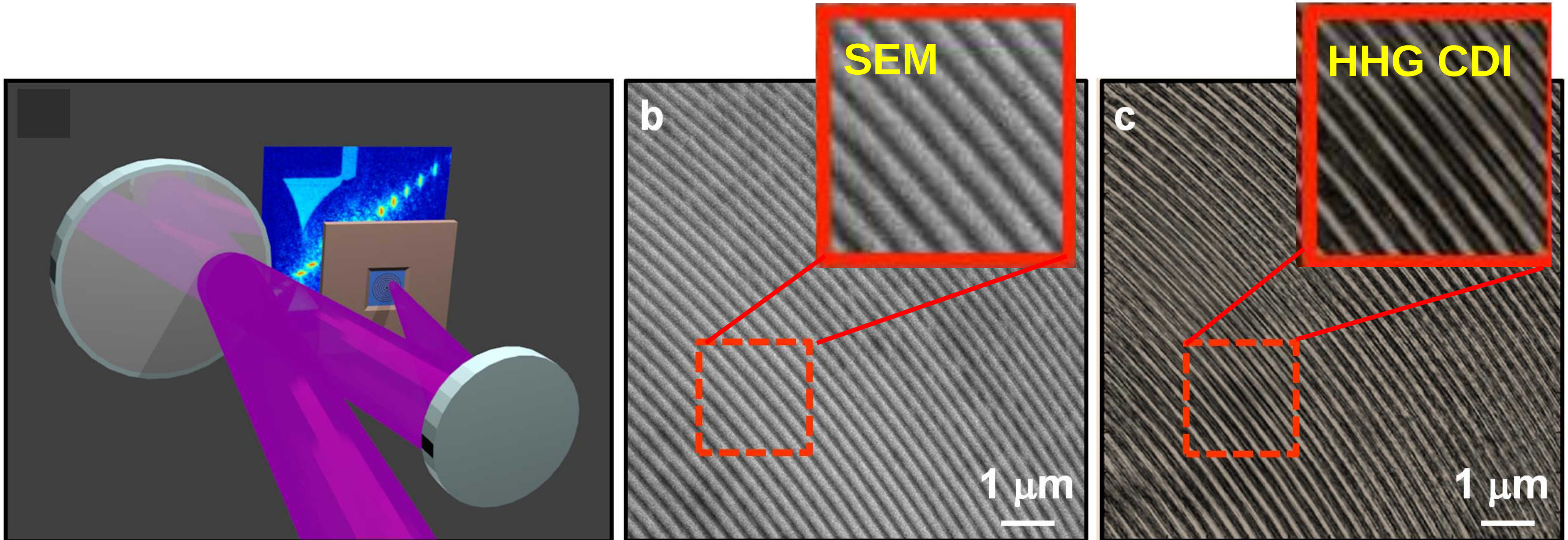






High contrast tabletop transmission-mode CDI @ 13.5 nm

- **Using λ = 13.5 nm, spatial resolution of 14 nm**
  - Spatial resolution **1.04** λ (PMMA zone plate sample)
  - Record spatial resolution for this wavelength
  - Requires ultrastable engineered HHG XUUS source
- **Not yet resolution or speed limited**
  - Exposure time ~ 10 sec/μm^2
  - Orders of magnitude increase in speed possible



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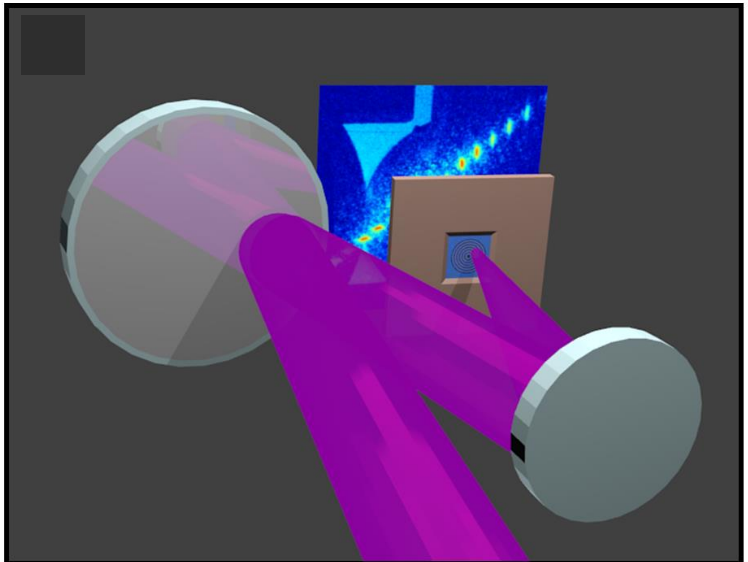
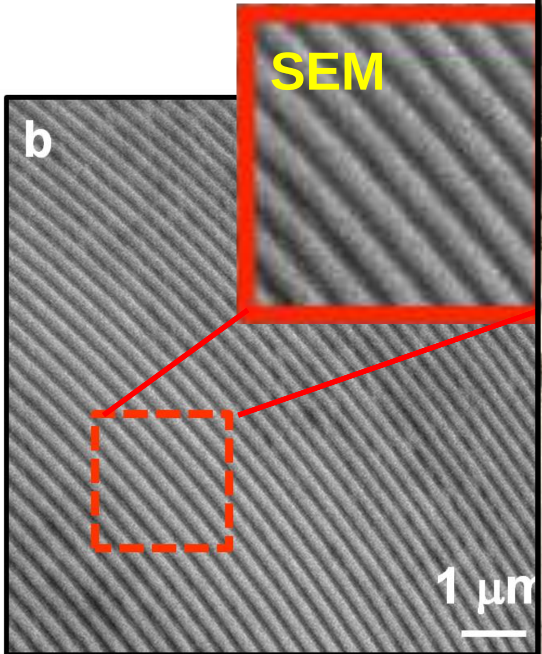
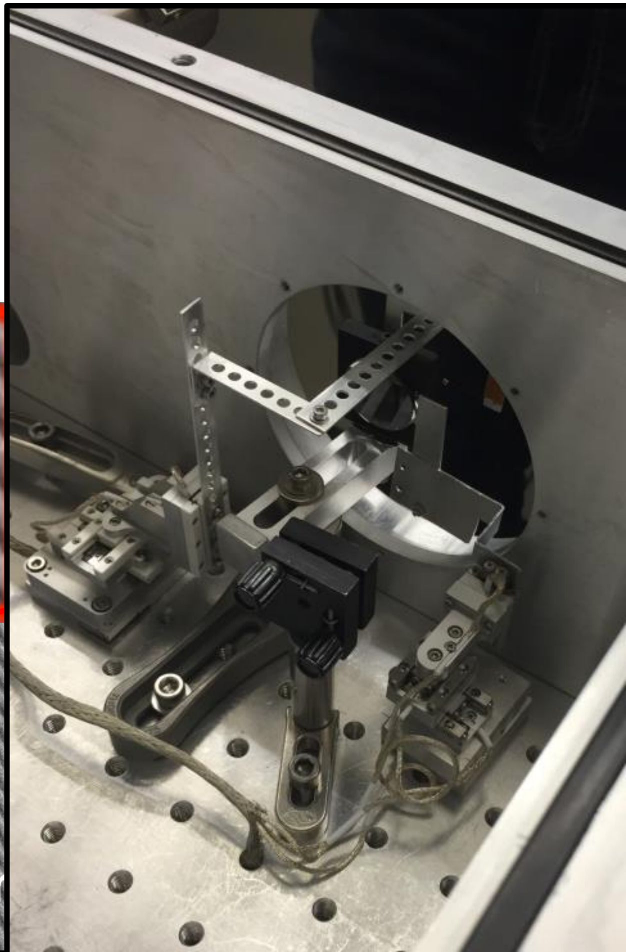
  – Spatial resolution **1.04** λ (PMMA zone plate sample)
  – Record spatial resolution for this wavelength
  – Requires ultrastable engineered HHG XUUS source
- **Next Steps**
  – Use single-stage, >20W average power cryocooled
  – Optimize HHG scheme (optimized XUUS)
  – Improve resolution to sub-10nm– simply by moving
  – Reflective geometry





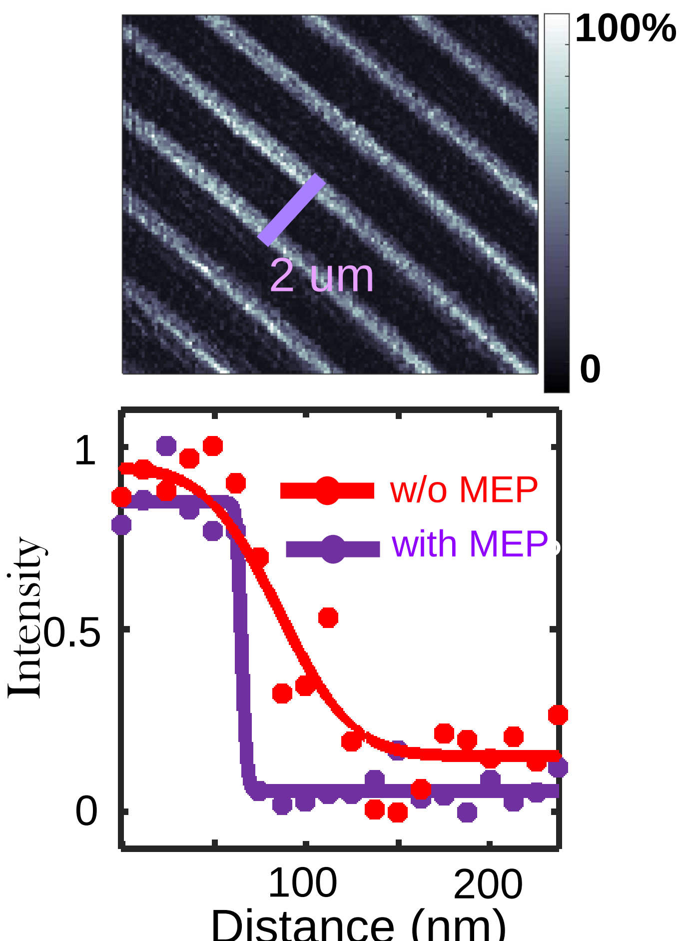


Quantifying the 13.5nm CDI resolution

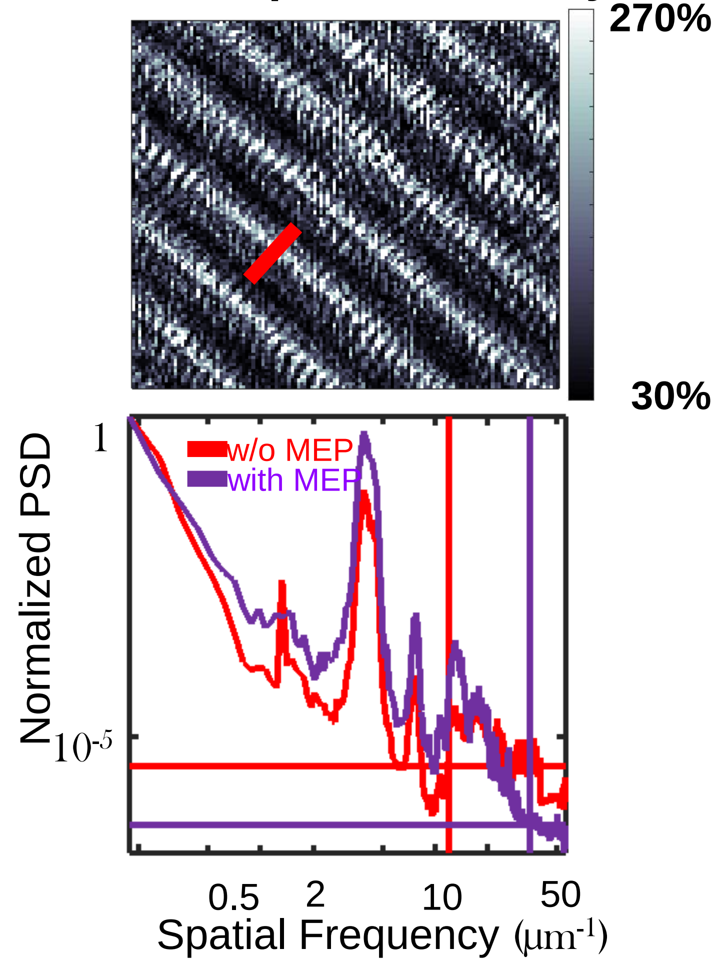
Gardner et al., in prep

- **NA:** Supports 14.4 nm Resolution
- **Lineout:** Supports 14.4 nm Resolution
- **PSD:** Supports 14.2 nm Resolution: improve resolution to sub-10nm

Lineouts

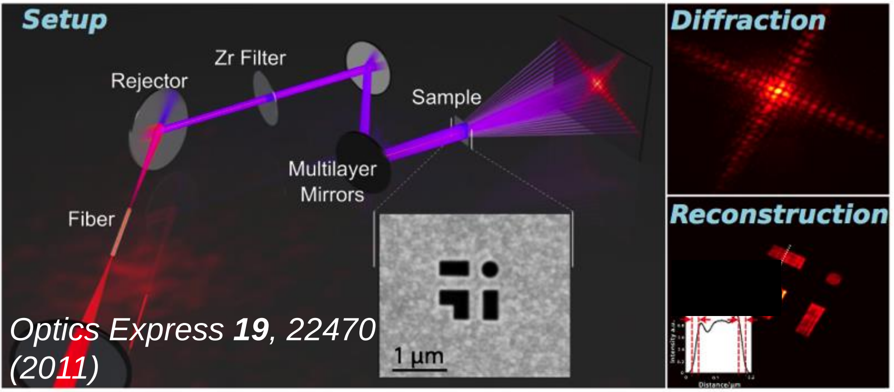


Power Spectral Density



Record 13.5nm imaging using ANY light source

TABLETOP HHG COHERENT IMAGING



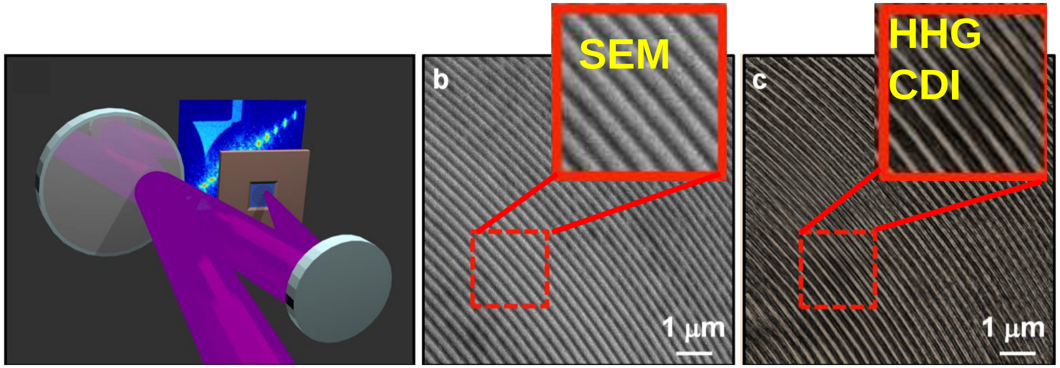
Optics Express ***19****, 22470 (2011)*

2011 HHG Results

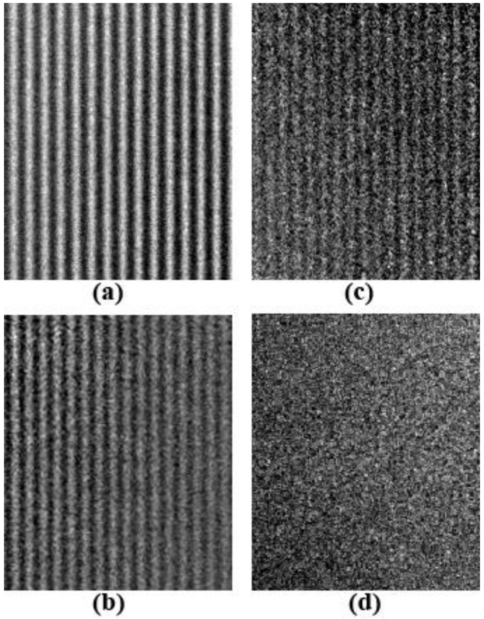
- Toy sample
- Simple CDI algorithm
- 22nm spatial resolution

New Record 13.5nm Imaging Results (2016)

- Full field, high contrast ptychography
- **New record 14 nm resolution (1.04λ)**
- Can increase spatial resolution; extend to reflection mode



FACILITY-SCALE ZONE PLATE IMAGING



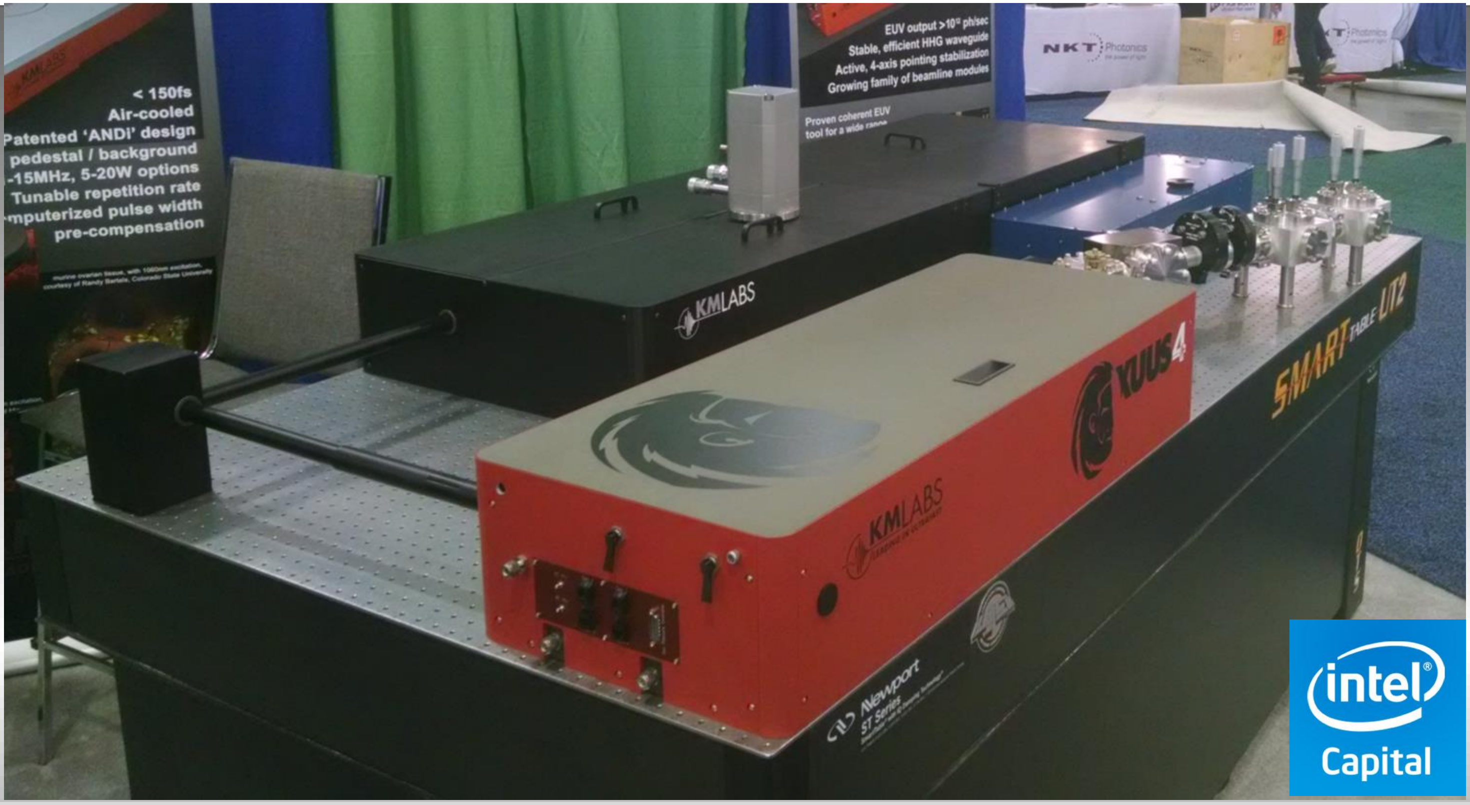
Chao et al. Optics Express **17**, 17669 (2009)

Synchrotron Source

- Zone plate image, 12nm resolution
- Used 2nm illumination

KMLABS inc. LEADING IN ULTRAFAST

XUUS$_4$™ critical for new 13nm CDI

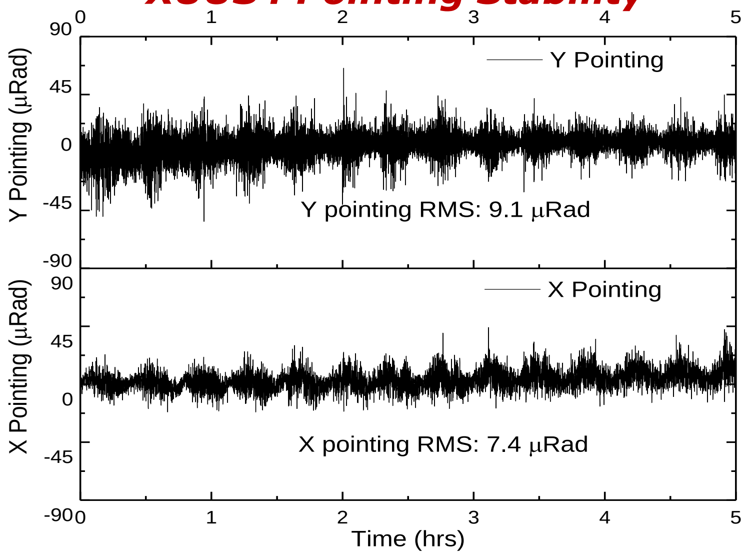


– Optimized for high average-power, high rep-rate, drive lasers: 1 to >200kHz
– Complete HHG XUUS source and beamline
– Active input laser beam stabilization – 4 axis control
– Ultrastable HHG beam intensity, wavefront, beam
– Temperature stabilized breadboard
– Stable, industrial optical mounting
– Complete software control

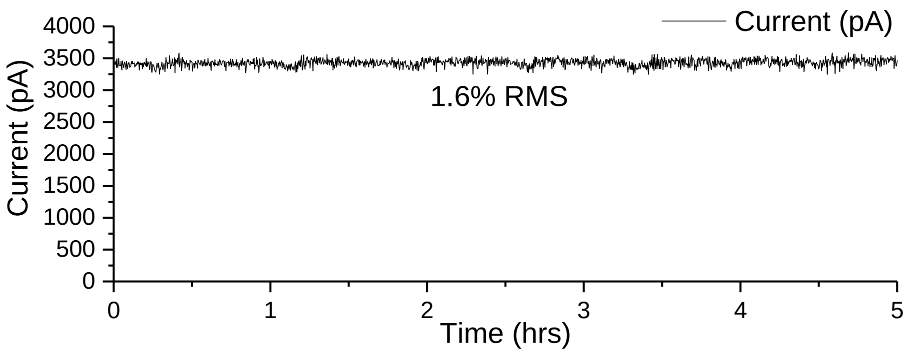
Medium-term stability data – preliminary

- Integrated HHG light source
  - Optimized for high average-power, high rep-rate, drive lasers: 1 to >100kHz
  - Cartridge waveguide: increased stability, performance, optimized at 13.5nm
  - Active input beam stabilization – 4 axis control
  - Ultrastable HHG beam intensity, wavefront, beam
  - Temperature stabilized breadboard
  - Stable, industrial optical mounting
  - Complete software control

XUUS4 Pointing Stability



XUUS4 EUV Flux Stability

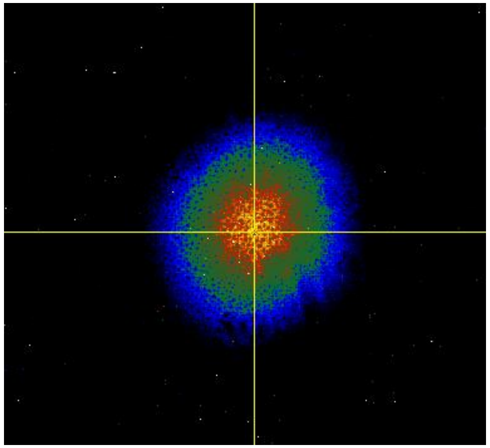


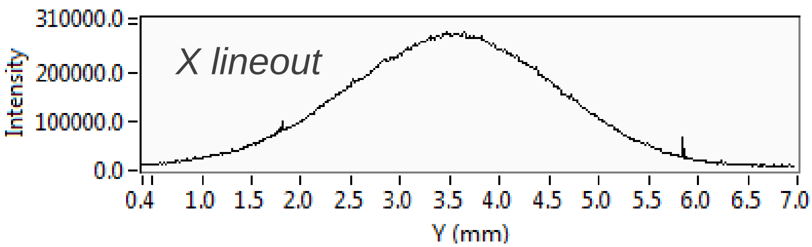
Data for 5 harmonic orders peaked at 42 eV.

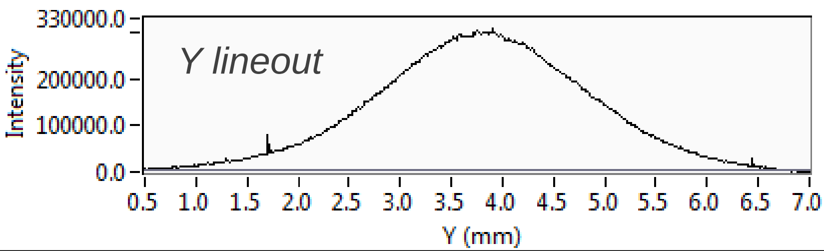
EUV Beam– preliminary

- Integrated HHG light source
  - Optimized for high average-power, high rep-rate, drive lasers: 1 to >100kHz
  - Cartridge waveguide: increased stability, performance, optimized at 13.5nm
  - Active input beam stabilization – 4 axis control
  - Ultrastable HHG beam intensity, wavefront, beam
  - Temperature stabilized breadboard
  - Stable, industrial optical mounting
  - Complete software control

XUUS4 EUV Beam







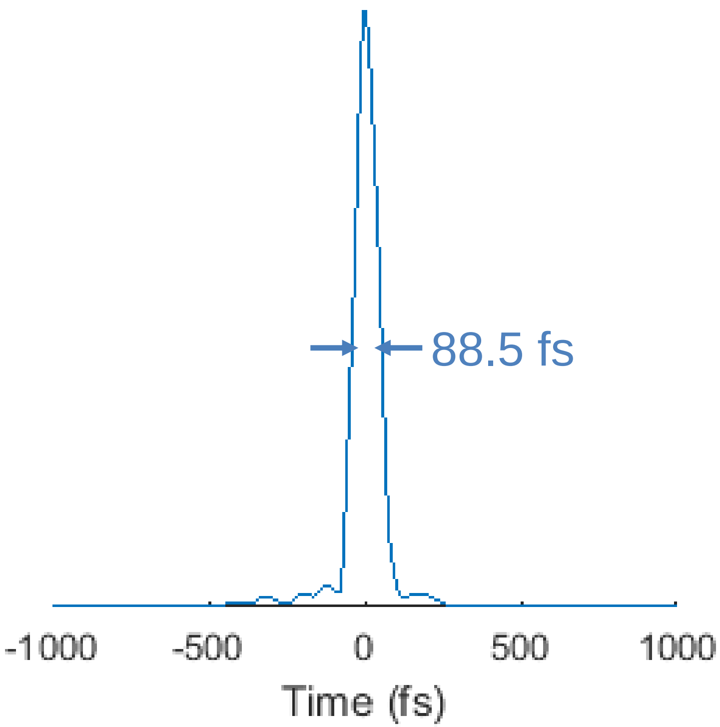
KMLABS inc. LEADING IN ULTRAFAST

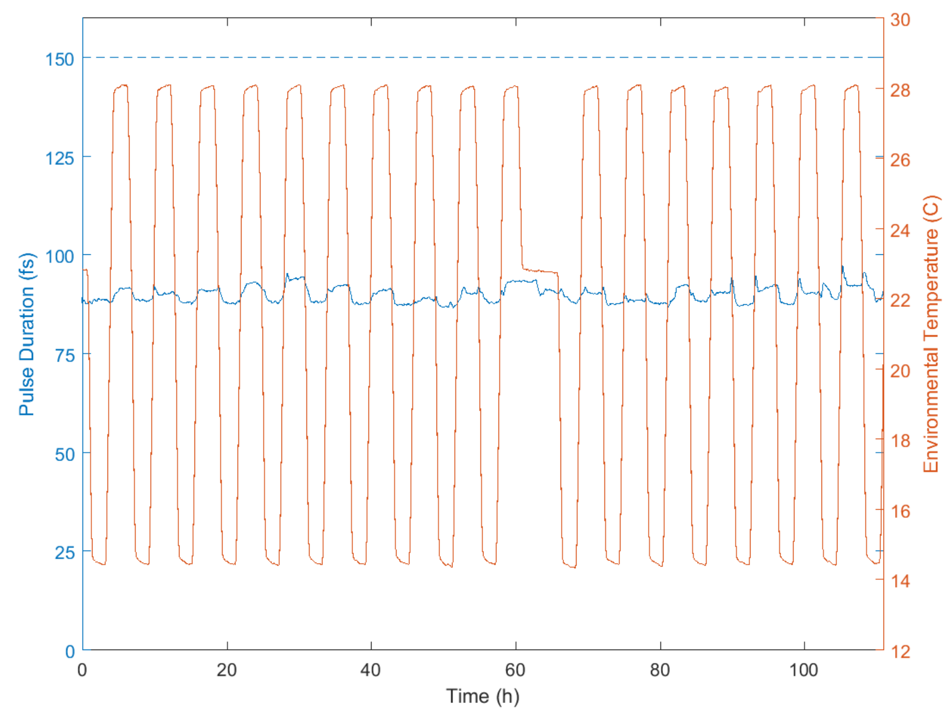
New driver lasers for HHG: record >20W Ti:sapphire and fiber lasers

- KMLabs has developed a record 25W single stage Ti:sapphire system for science market
- Repetition rates from kHz to MHz
- M^2 ~1.1– flawless Gaussian beam
- Unprecedented power and stability
- New $XUUS_{4.2}$ will enable >10x increase in HHG flux in 10 – 20 nm region
- Compact >25W hybrid fiber lasers also under development
- ≈10^{-4} – 10^{-7} into 1 harmonic order

Record Pulse Duration Performance for fiber laser

- Pulse duration over >100 hours of temperature cycling
- 90 ± 2.2 fs, <0.4% amplitude stability over 14°-28° C temp cycling
- Necessary "front end" system for future compact diode-pumped ultrafast systems





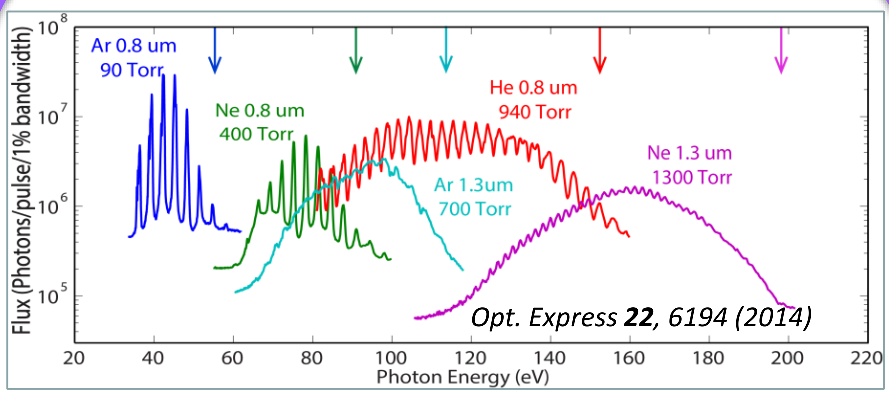
Conclusion

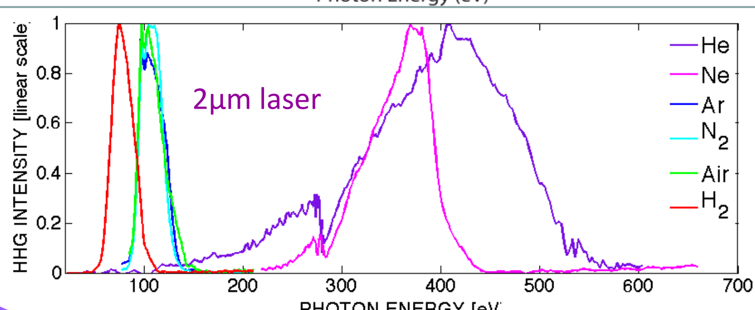
- Coherent diffractive imaging is rapidly establishing itself as the "gold standard" for EUV imaging
  - Large, redundant data set allows one to obtain a *full characterization* of how an object scatters incident light
  - i.e. everything you could *ever* know using light at that wavelength
  - With **NO** instrumental distortions/limitations
- Near future (JILA→ KMLabs) versatile general purpose 13 nm microscope
- Broader applications of HHG EUV microscopy to support nanoscience Have been demonstrated and remain to be fully-developed
  - Interfaces
  - Mechanical properties (Young's Modulus, Poisson ratio)
  - Magnetic properties
  - Dynamic behavior

HHG output powers

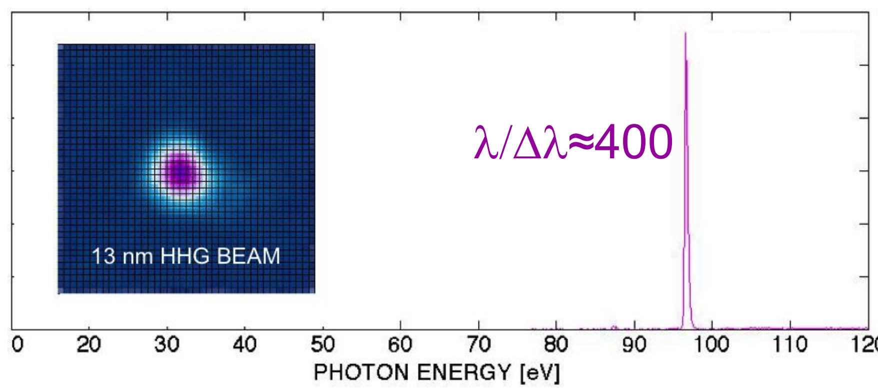
- 10^{-4} to 10^{-6} into one harmonic order at 30nm depending on HHG scheme
- Using mid-IR lasers, supercontinua ideal for spectroscopy (NEXAFS, MOKE)
- Using UV lasers, isolated HHG peaks ideal for imaging and metrology
- Using 2W, 1kHz, 0.8μm laser, achieve 10^{10} photons/s/1% band @ 13nm
- Using 2W, 1kHz, 0.8μm laser, achieve 160nW, 1% band @ 13nm
- Using 2W, 1kHz, 0.27μm laser, achieve >μW in $\lambda/\Delta\lambda \approx 400$ @ 13nm (still in research)
- Using 15W, 1kHz, laser, achieve >15μW in 1 order @ 30nm

Near and mid-IR driven HHG



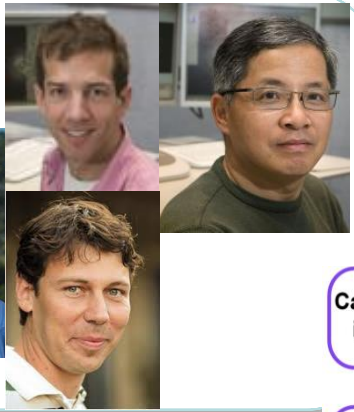
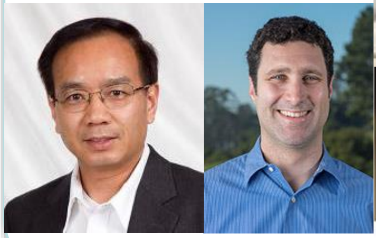


UV driven 13nm HHG



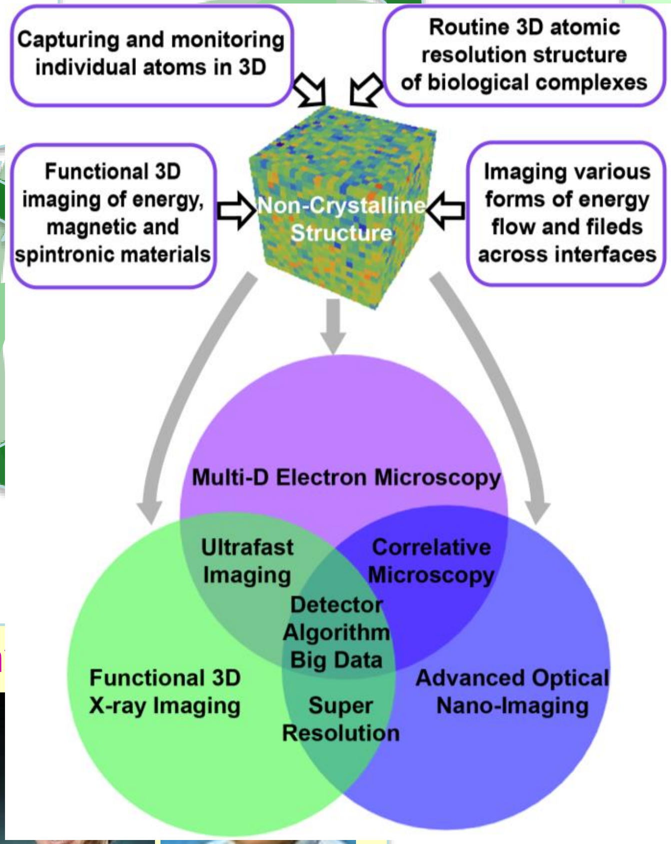
STROBE:
NSF STC on Functional Imaging w/ Electrons **and** Light

Electron imaging

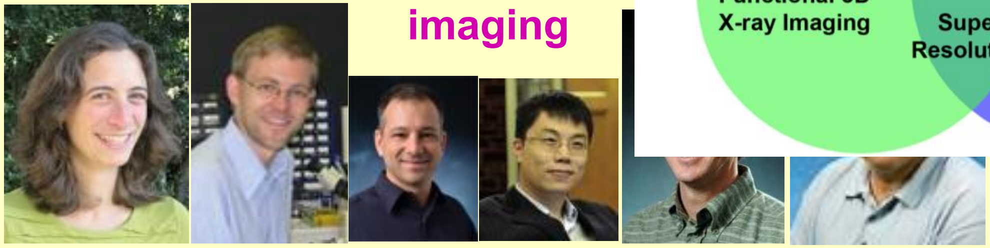
Knowledge Transfer

Education research, broadening participation



X-ray

Nano, correlative, h imaging



Underpinning technologies

Data

Detectors, algorithms