Current Status and Future Possibilities of High Harmonic (HHG) Sources for Characterization/Metrology in the Semiconductor Industry

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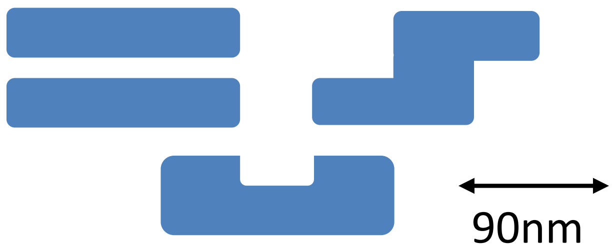
Thanks to KM Group @ JILA , STROBE
Margaret Murnane, Henry Kapteyn (all the material!)
Dan Hickstein, Scott Domingue, Matt Kirchner, Sterling Backus, Daisy Raymondson @ KMLabs

Obligatory Moore's law slide

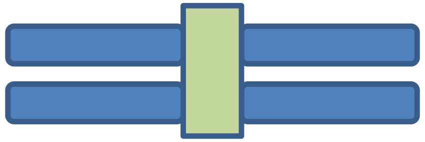
Moore's (extended) law:
Information per wafer doubles

<2005



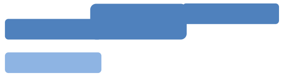
'Single Pattern'

2005-2015



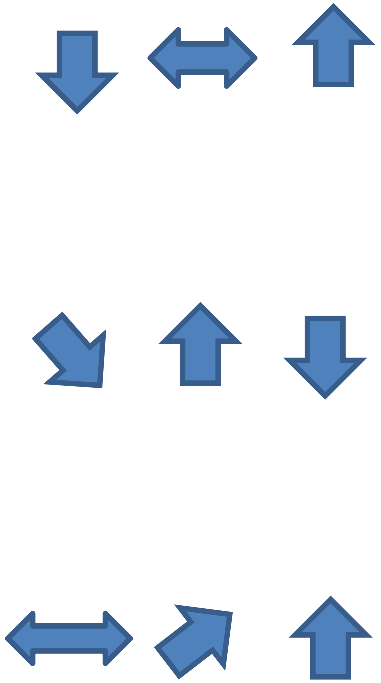
'line&cut patterning'

>2020



'analog & Selective patterning'

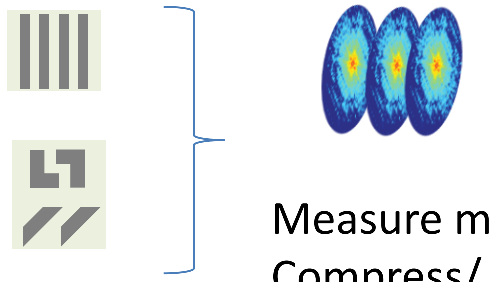
Pitch Materials Pattern Entropy



$$C \approx BWlog(\frac{S}{N})$$

Metrology challenges

Mapping Challenge



1E16 wfr

1E5 metro

Measure more
Compress/ extrapolate

Information

$$I\_met \approx S * C_i * P_i * log(F)/Pa$$

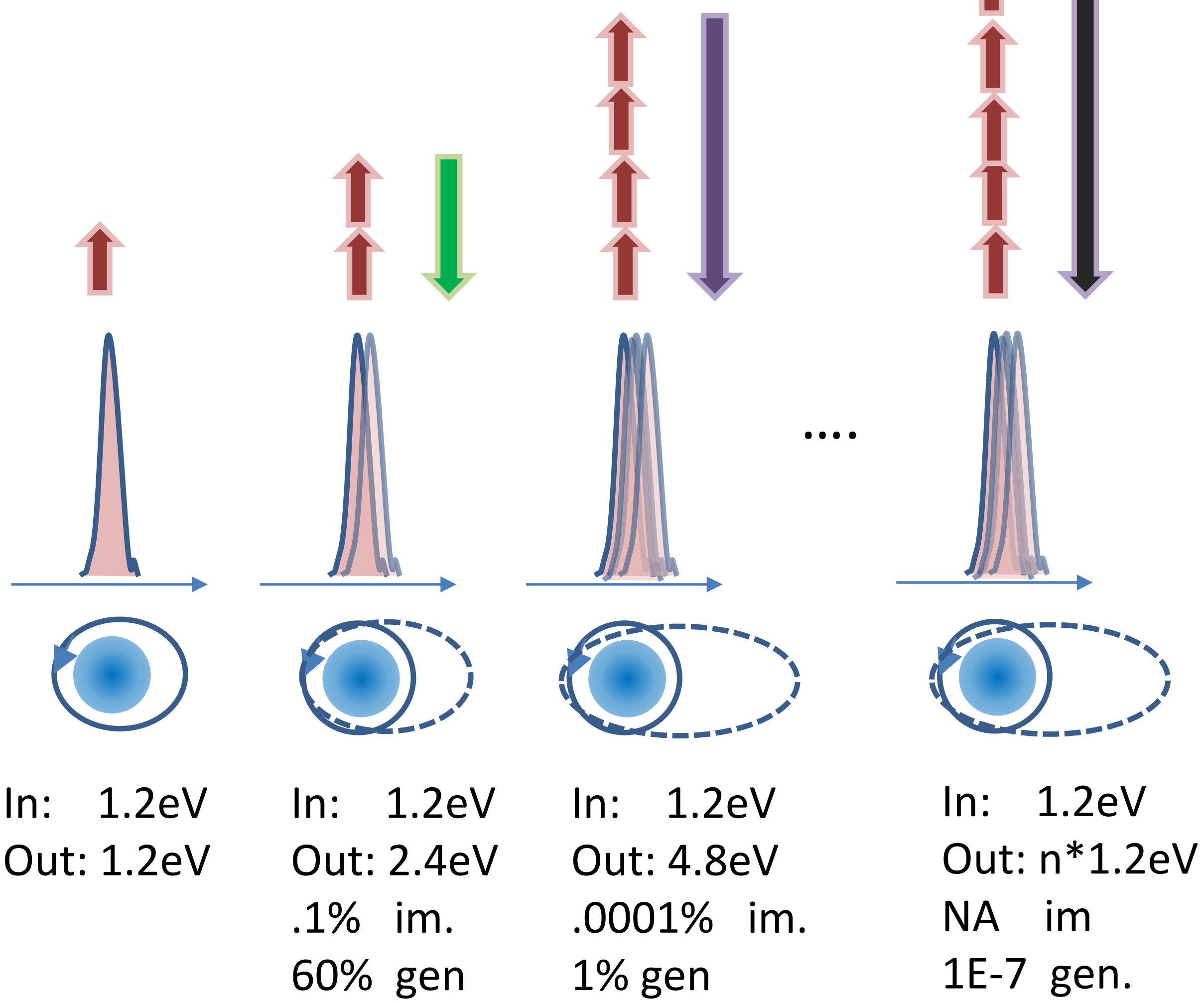
S: sampling
C: channels
P: probed states (like polarization)
F: features
Pa: parameters (corr.)

BP's caveat: it never gets easier

Summary and approximate understanding of (High) harmonic generation

- Optical microscopy with ultrafast pulses
- What is High Harmonic Generation (HHG)
  - Generate laser like light at 10nm-200nm
- Why:
  - Take advantage of wavelength (λ/NA)

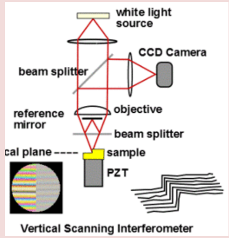
  Take advantage of light microscopy/control
  - Take advantage of energy (eV)
- Applications of VUV/EUV light
- Novel/useful semiconductor applications



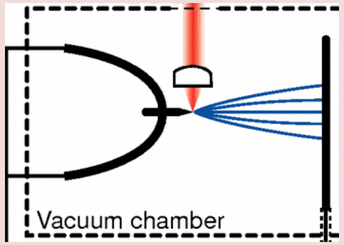
‘Low Harmonic’ sse-cases in microscopy are dramatically better due to source improvements

Source/Microscopy

Interferometry



TEM-tip source enhancement*

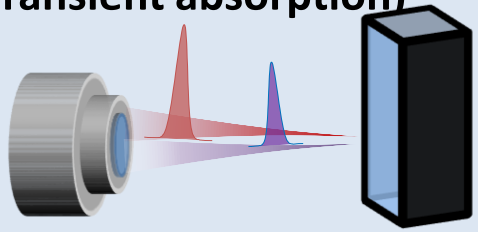


Kerr/phase microscopy

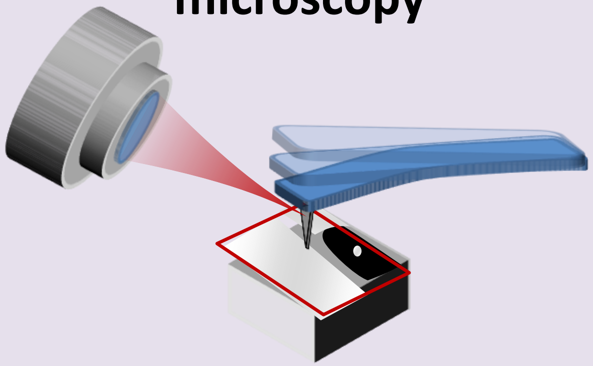
Ultrafast spectroscopy*

Needs femtosecond pulses

Pump-probe spectroscopy (Transient absorption)



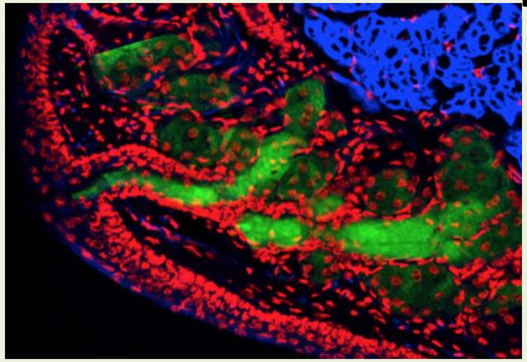
AFM-tip Nanospectroscopy and microscopy



Ultrafast microscopy

Needs femtosecond pulses at ~1 MHz rep rate

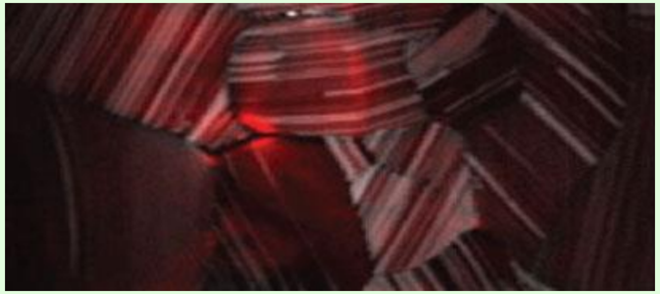
Coherent Raman microscopy



Alfonso-Garcia et al., *J. Biomedical Optics.* **19**, 071407 (2014). https://doi.org/10.1117/1.JBO.19.7.071407

*HG nonlinear microscopies

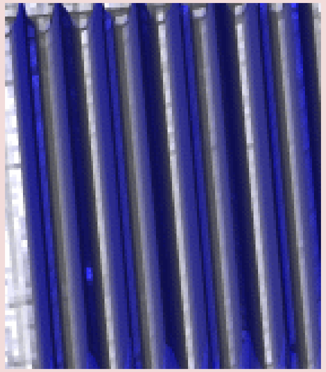
SFG, TA, FL, 2D-IR



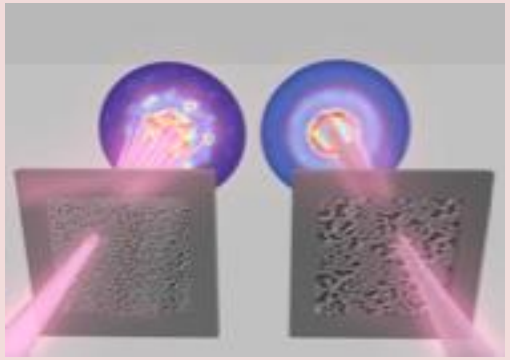
Squier/Bartels CLEO 2018

Extending optical microscopy to >20nm wavelengths using HHG

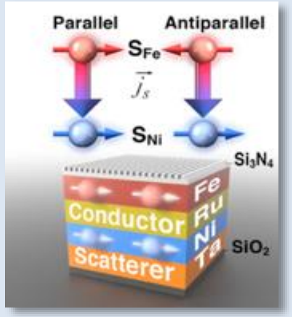
Diffractive imaging/ interferometry



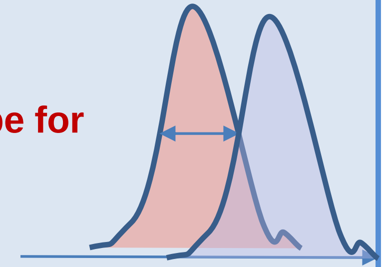
μ-scatterometry

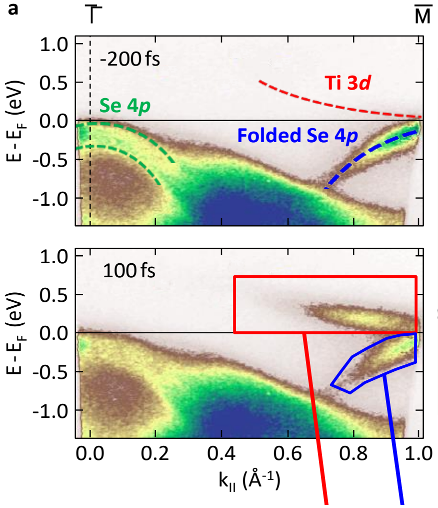


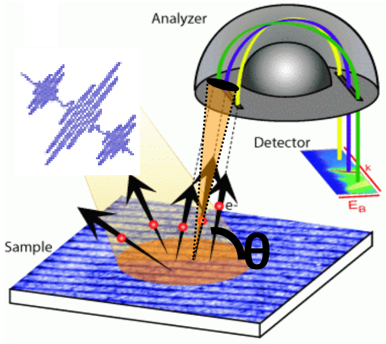
IR pump/EUV probe (Band edge)
Magneto-optical Kerr effect

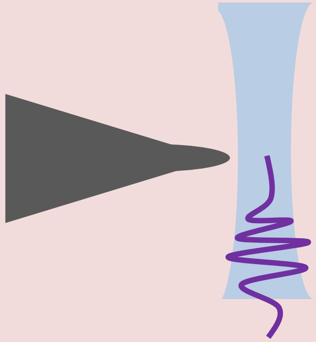


EUV pump/IR probe for photoresist

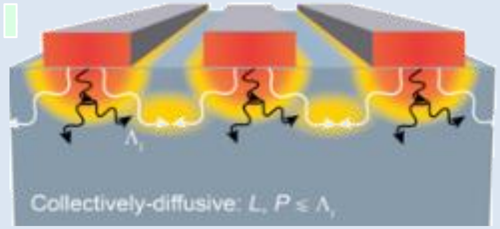








Novel SEM/TEM/APT probe



EUV pump/*probe for nanomechanics

Band structure and electron dynamics

200→6nm wavelengths, <100fs pulses of laser-like light, at uW power levels

Maximum wavelength ~ λ_p^2

400nm→60nm (20eV)
800nm→13nm (100eV)
3000nm→1.4nm (800eV)

Output (in ph/s)

- $\sim 10^{11}$ 13nm
- $\sim 10^{13}$ 30nm
- $\sim 10^{15}$ 130nm

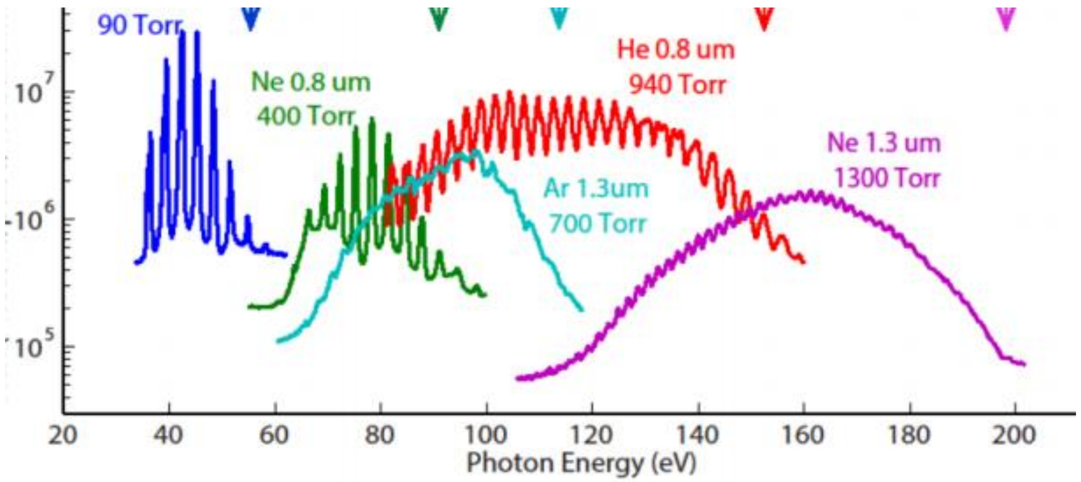
Energies

- 10eV: oxide/vacuum bonds
- 80eV: magnetic edges
- 94eV: 13.5nm

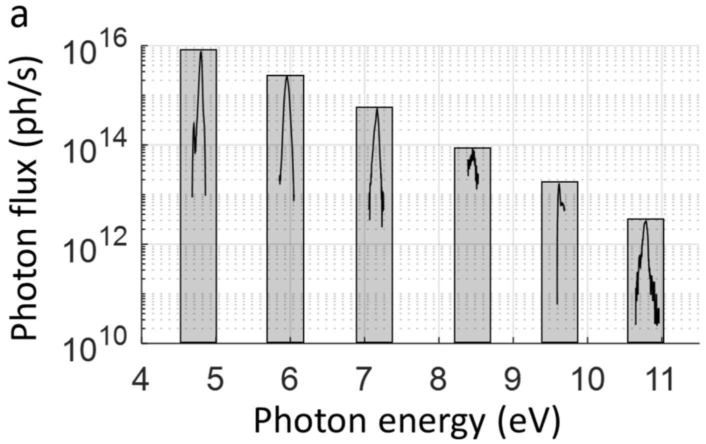
Brightness

- $\sim 4 \times 10^9$ W/m^2/Sr @ 13 eV : uW level

‘tabletop EUV’ 20-200eV (60→6nm)



‘5-15eV’ VUV



Early data 15^{+}eV

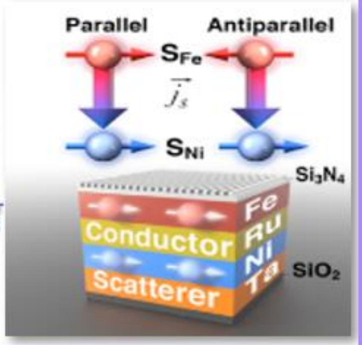
Mulitple solid state physics and materials science use cases

HHG experimental references

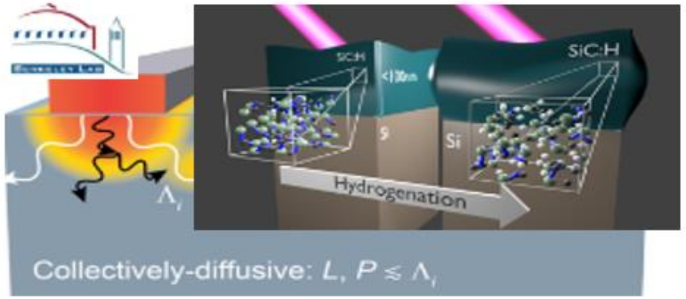
Uncovering new materials/nano science

Spin dynamics in magnetic materials

Science Advances, in press (2018)
PRB, **97**, 024433 (2018)
PRB **94**, 220408 (2016)
PRL **110**, 197201 (2013)
PNAS **109**, 4792 (2012)
Nat. Comm. **3**, 1037 (2012)

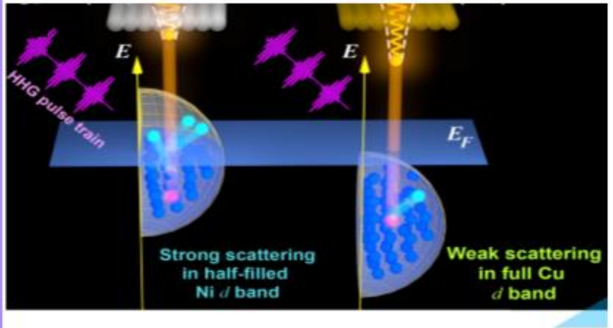


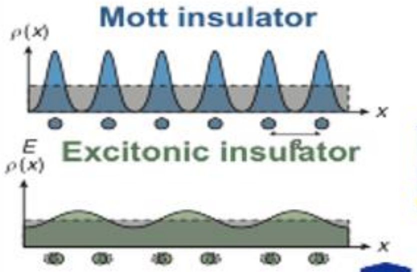
Nanoscale mechanical properties, energy transport



Nature Mat. **9**, 26 (2010); PRB **85**,195431 (2012) PNAS **112**, 4846 (2015);
Nano Lett. **16**, 4773 (2016); Nano Letters **17**, 2178 (2017)

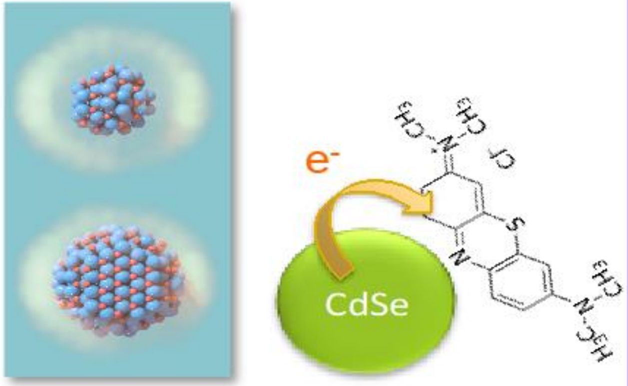
Dynamic band structure via ARPES





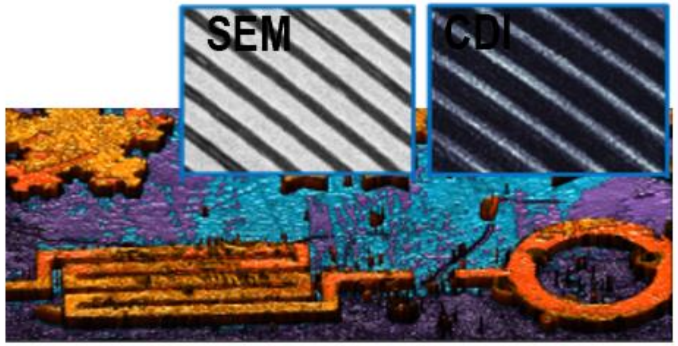
PNAS **114**, E5300 (2017)
Science Advances **3**, e1602094 (2017)
Science **353**, 62 (2016)
Science **353**, 28 (2016)
Nature **471**, 490 (2011)
Nat. Comm **3**, 1069 (2012)
PRL **112** , 207001 (2014)
PRB **92**, 041407 (2015)
Nature Comm. **7**, 12902 (2016)

Charge transport in nano-materials



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

1st sub-wavelength EUV / X-ray imaging

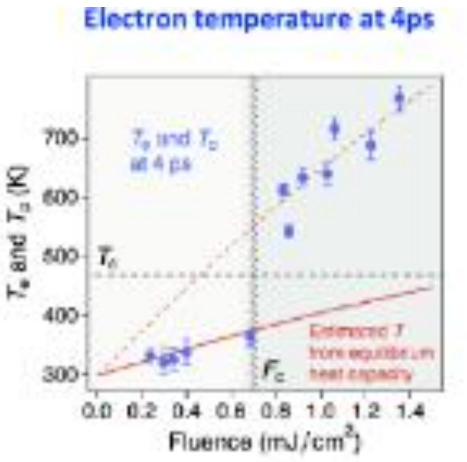


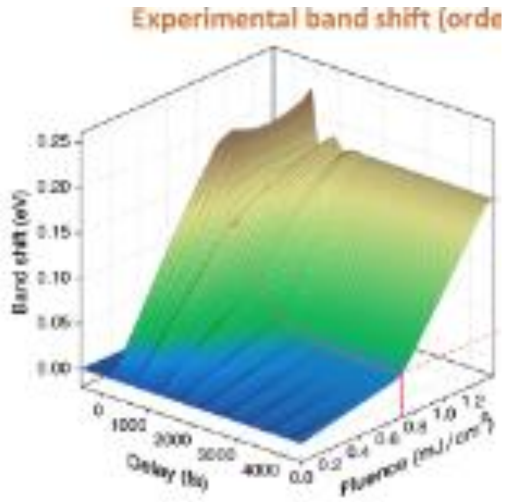
Science **348**, 530 (2015); Ultramicroscopy **158**, 98 (2015)
Nano Lett. **16**, 5444 (2016); IQT **8**, 18 (2016); Nature Photonics **11**, 259 (2017); Optica **4**, 1552 (2017)

Material band structure and evolution can be measured with laser photoemission (ARPES)

- New metastable phase seen in TaSe2

- Magnetization dynamics studied via electron temperature in Ni (Tengdin et al)





Ultrafast Phenomena Xun Shi et al.
Science Advances 01 Mar 2019:
Vol. 5, no. 3, eaav444

PNAS **114**, E5300 (2017)
Science Advances **3**, e1602094 (2017)
Science **353**, 62 (2016)
Science **353**, 28 (2016)
Nature **471**, 490 (2011)
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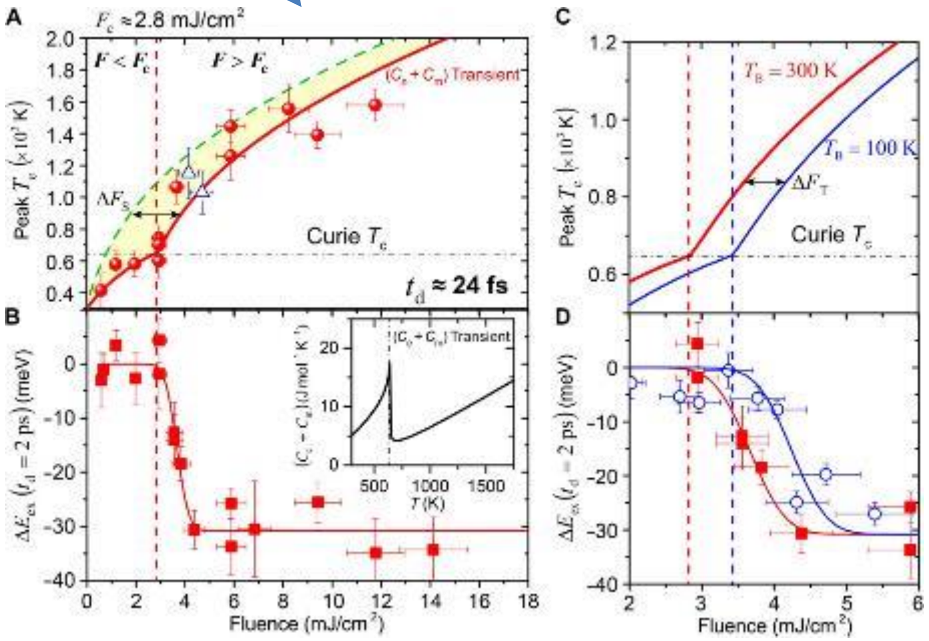
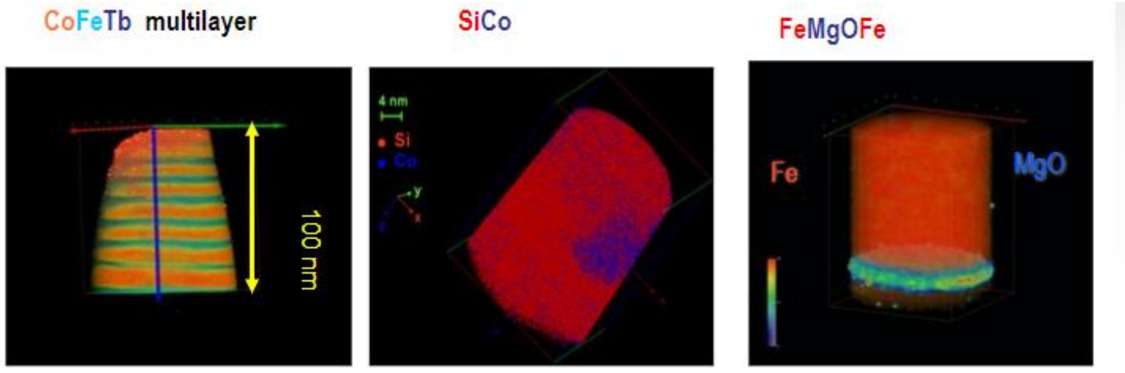
PRB **92**, 041407 (2015)
Nature Comm. **7**, 12902 (2016)



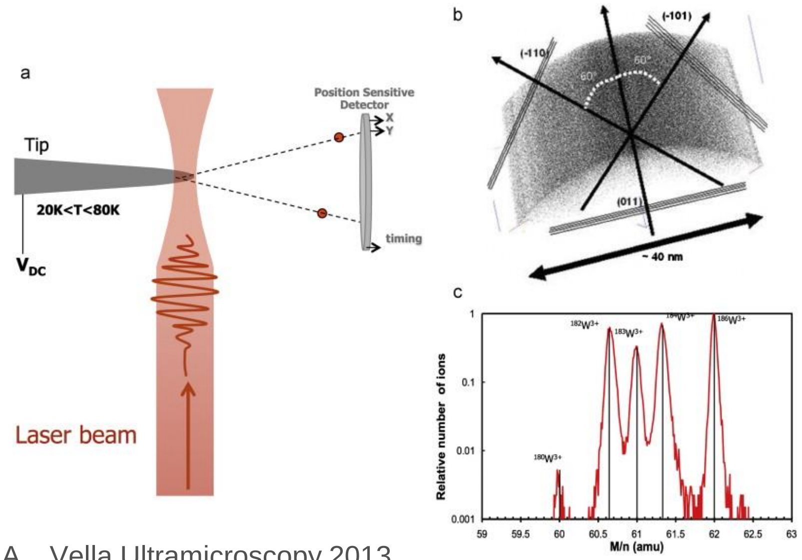
Tip based photoemission: APT: unique opportunity to do single photon ionization and surface heating

- APT: Generation of UV light (might) benefit due to
  - High energy per pulse → uniform absorption
  - Multiphoton surface enhancement→single photon at >11eV.
  - High pulse rate (MHz)

- Diagnostics
  - Direct diagnostic tip imaging possible



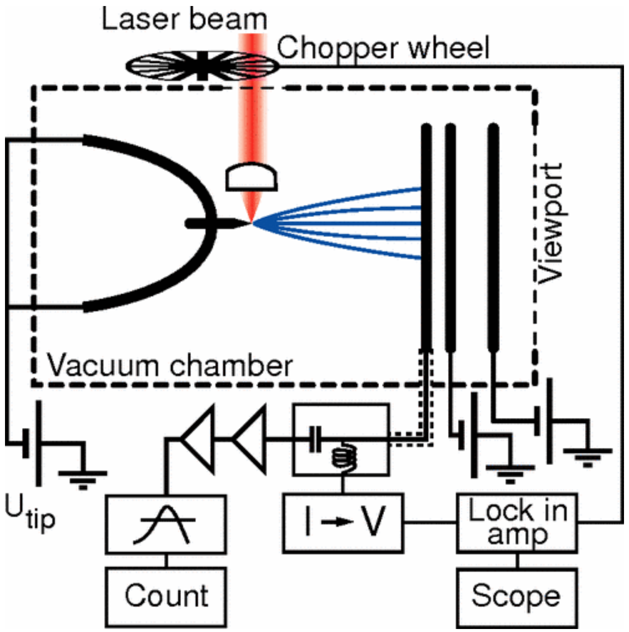
A. Grenier et al. JAP 102,033912 2007 M.Gilbert et al. Ultramicroscopy 107,767,2007 Talaat Al Kassab, IJMR 99,5,2008



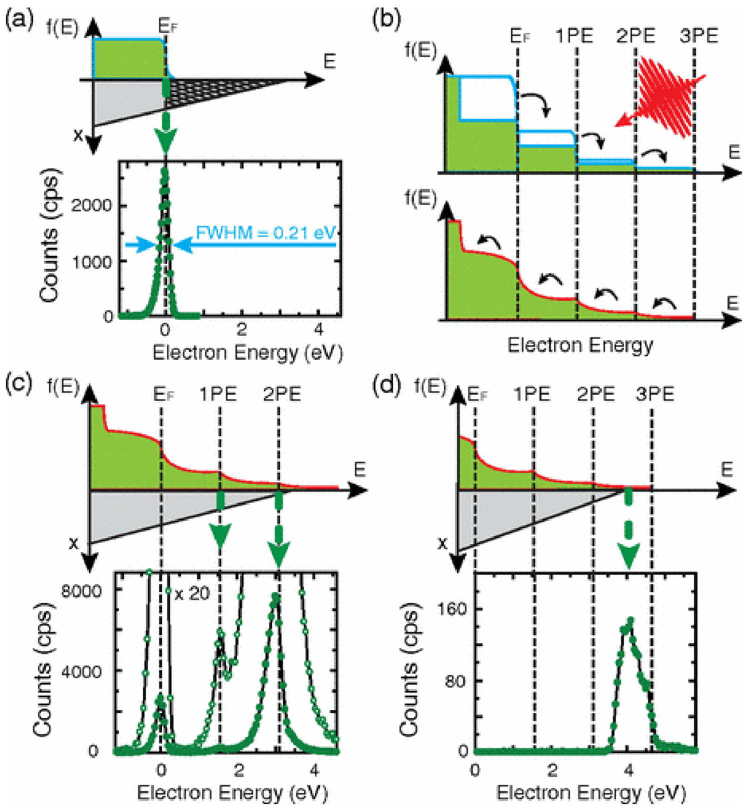
A. Vella Ultramicroscopy 2013

Lasers for ultrafast electron emission: UV avoinds multiphoton effects

- Using the energy to drive emission
  - Time resolution!
- VUV (~6eV) energies can directly ionize for high efficiency electron generation
  - This can also greatly increase effectiveness, as we can directly ionize, rather than rely on multiphoton processes
  - Or use a very good pulse, to improve MP efficiency!



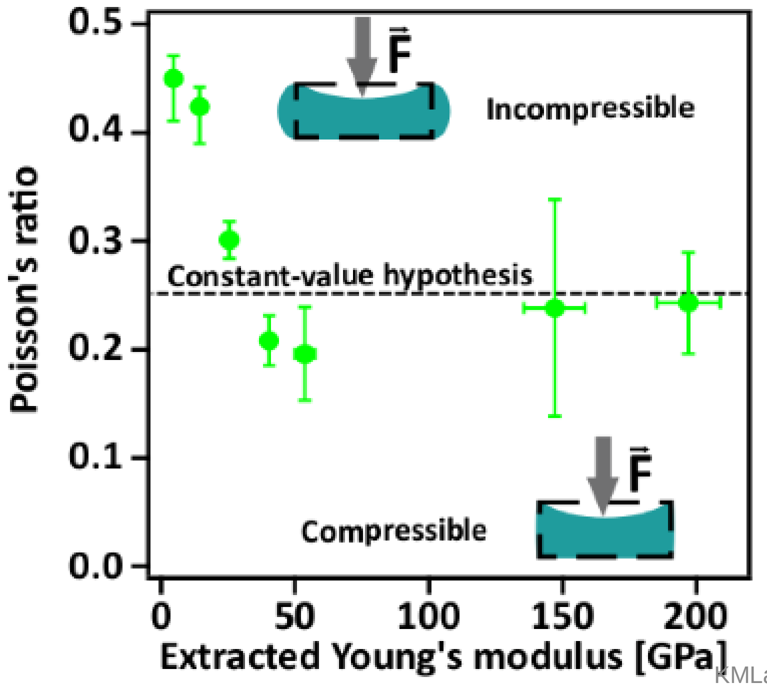
Peter Hommelhoff et al
Phys. Rev. Lett. **96**, 077401 – Published 21 February 2006

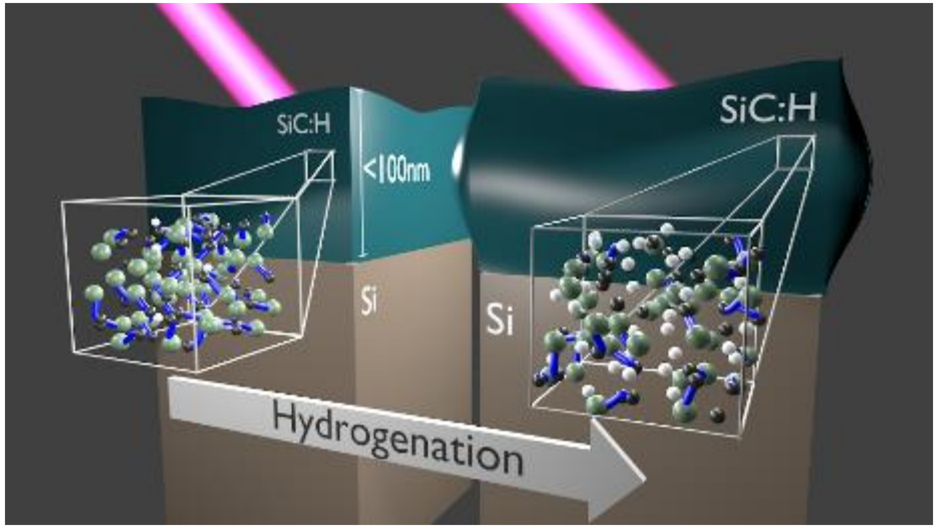


Hirofumi Yanagisawa et al.
Phys. Rev. Lett. **107**, 087601 – Published 16 August 2011

Characterization of elasticity on thin films: 11-50 nm films

- Techniques such as nano-indentation are unreliable for films <100 nm
  - Can measure the Young's modulus but not the Poisson's ratio
- For SiC:H thin films, doping breaks bond coordination and changes the mechanical properties: critical for semiconductor reliability
- Material changes from being compressible to incompressible



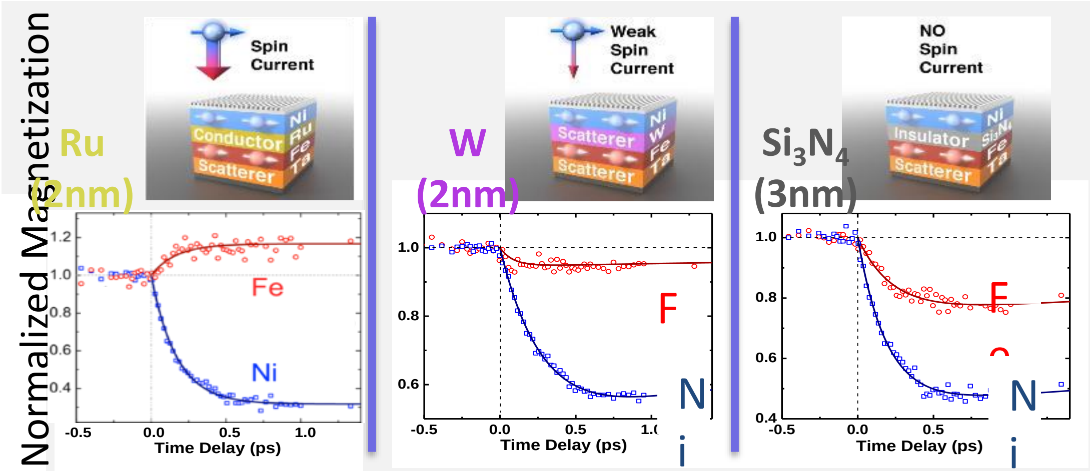


Nano Lett. **16**, 4773 (2016); *Nano Letters* **17**, 2178 (2017)

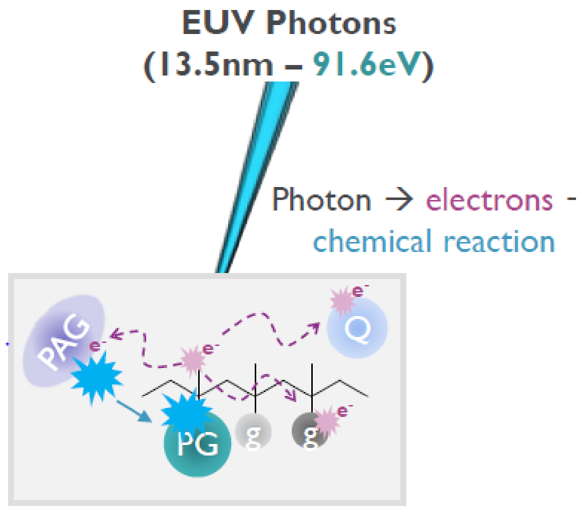
Pump/Probe for Magnetic scattering and EUV resist fundamentals

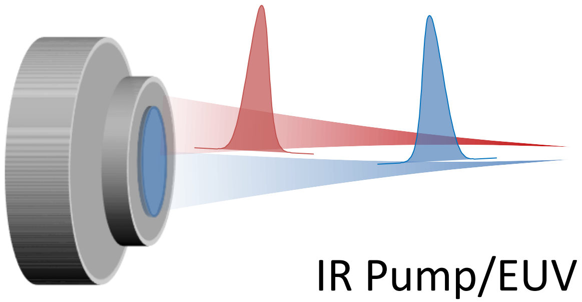
- EUV magneto-optic spectroscopies can very sensitively read out the magnetic state of each layer and element in a magnetic multilayer or alloy

- EUV pump/IR probe to measure photoresist dynamics



PRL **110**, 197201 (2013)
Nat. Comm. **3,** 1037 (2012)





IR Pump/EUV probe

EUV Pump/IR probe

Multiple chemical reactions take place…What is the balance of these reactions to acid reaction ?

John Petersen SPIE 2019

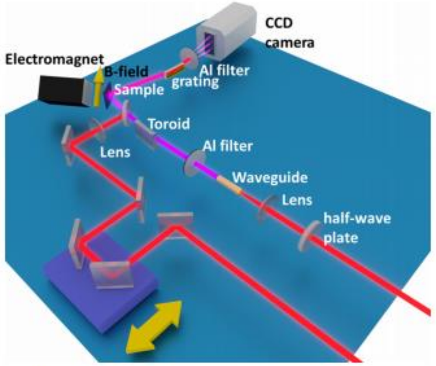


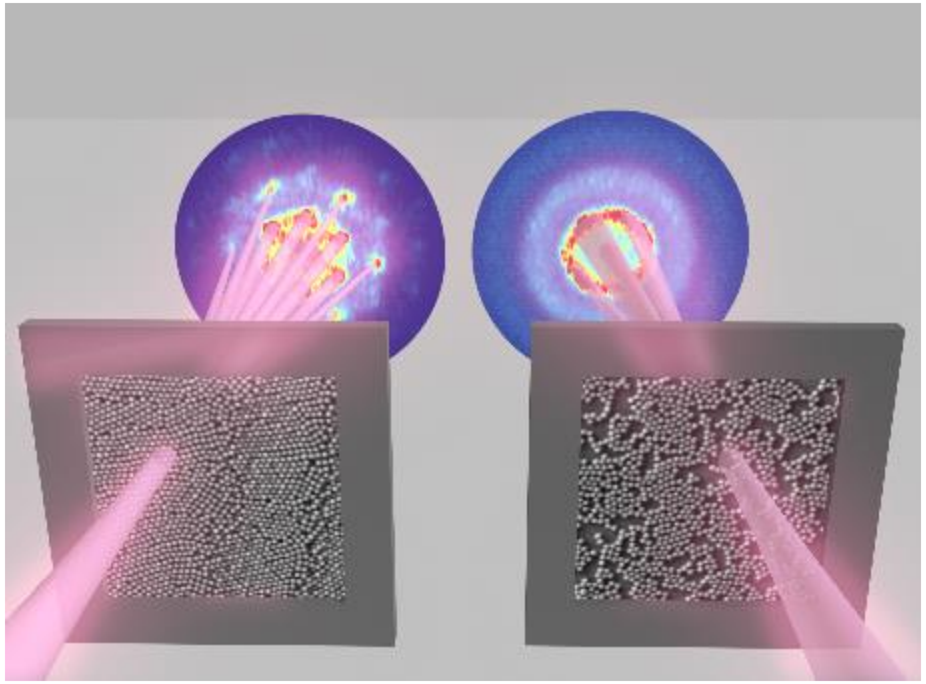
FIG. 2. Experimental setup to implement D-MOE. A half-wave plate is used to rotate the linear polarization of the driving laser, and hence the polarization of the HHG beam.

PRB 2018 D Zusin

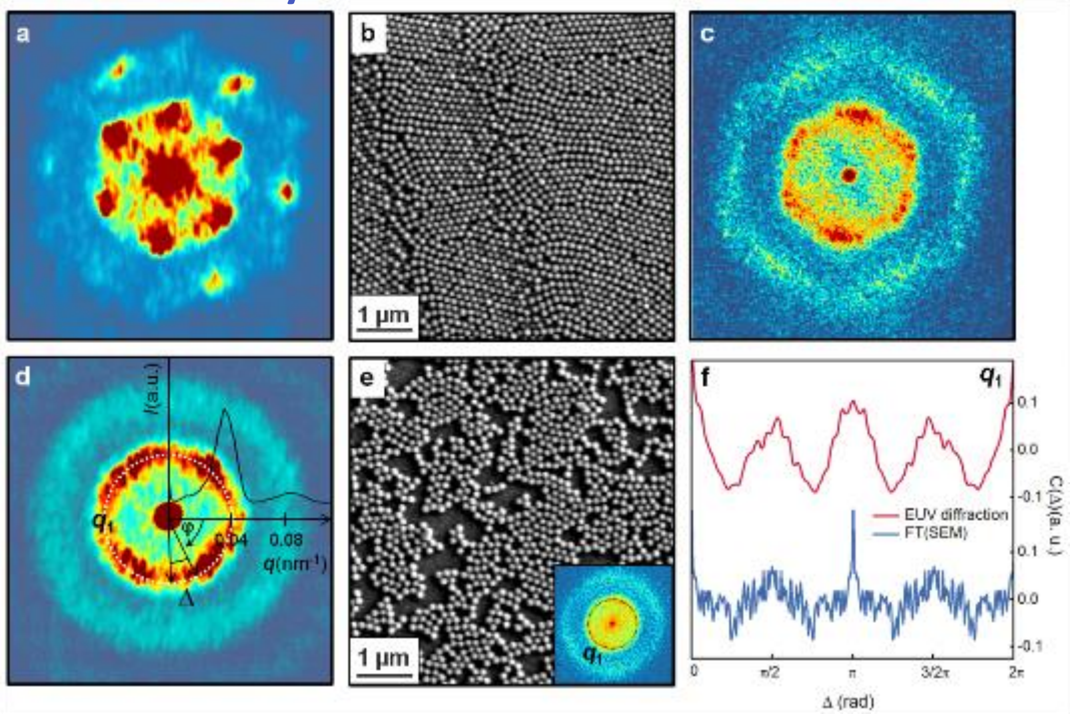
Science Advances **4**, 9744 (2018)
PRB, **97**, 024433 (2018)
PRB **94**, 220408 (2016)
PRL **110**, 197201 (2013)
PNAS **109**, 4792 (2012)
Nat. Comm. **3**, 1037 (2012)

Diffraction: nm-scale order in self-assembled materials

- Simultaneously characterize nanospheres size, symmetry, distribution within grains
- Small-angle Bragg scattering from self-assembled materials



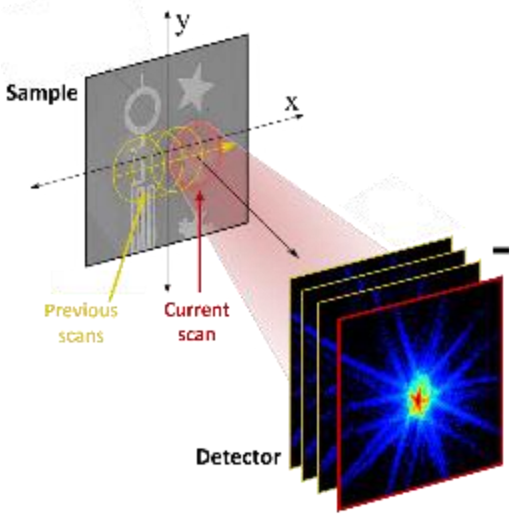
HHG Scatterometry **SEM** **from SEM**

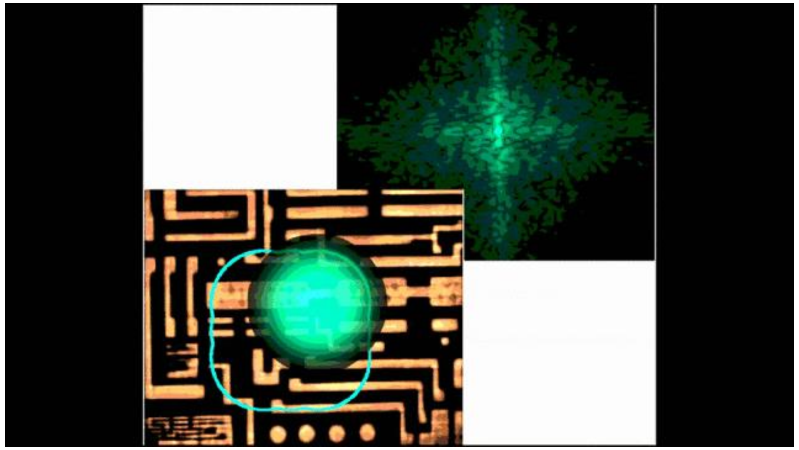


Mancini, et al. (2017)

Diffractive imaging

Diffractive imaging is critically useful at *UV wavelengths→Coherent Diffractive Imaging





- Coherent Diffractive Imaging
  - Shine a coherent beam on an object
  - Record scatter on imaging detector
  - Use computation to build image of the surface that scattered the light

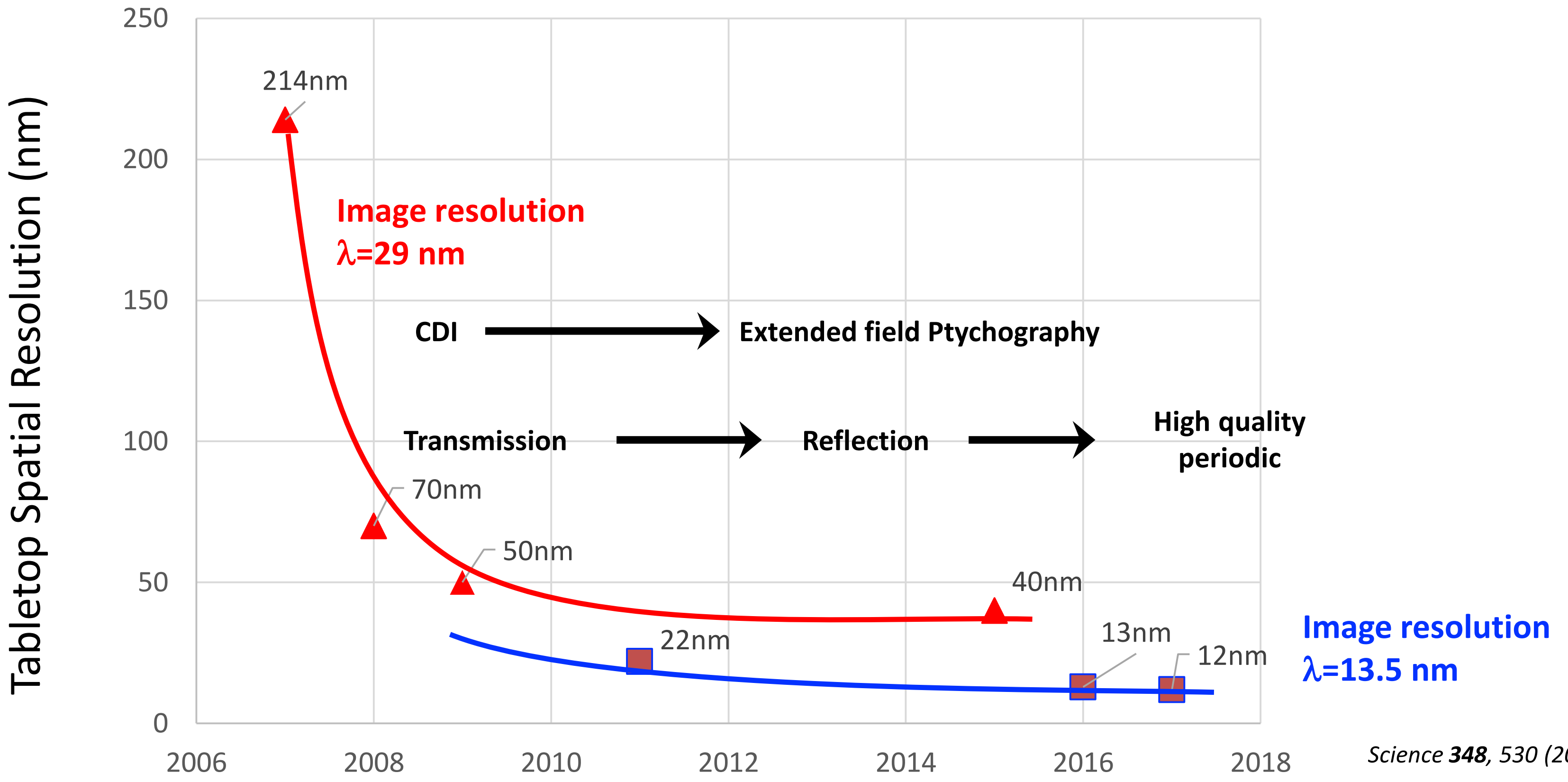
'don't use a lens to take a Fourier Transform, use a computer'

Benefits:

- Ptychography increases robustness/noise immunity
- Reconstruction on arbitrary objects (no regularity needed)

EUV coherent imaging has continued to improve in the lab

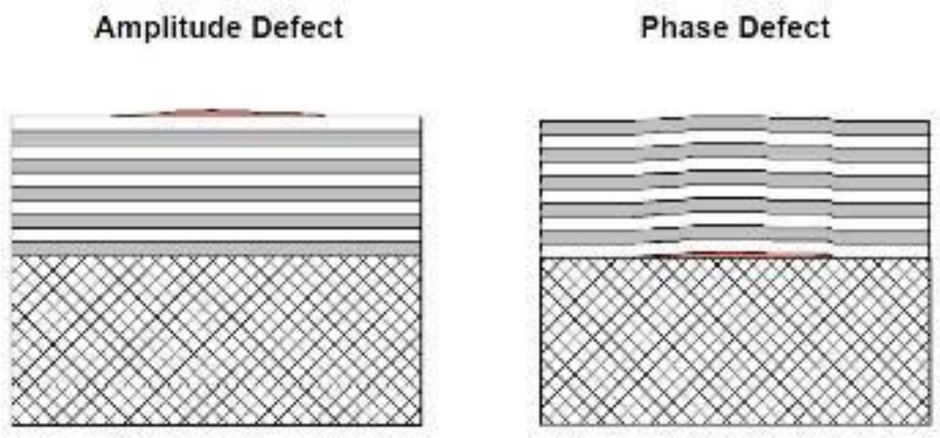
- Record spatial resolution of 0.9l: 12.6nm using 13.5nm XUUS HHG beams
- Full field imaging of near-periodic structures, with record speed, resolution
- Can scale to shorter wavelength, higher resolution, deeper penetration

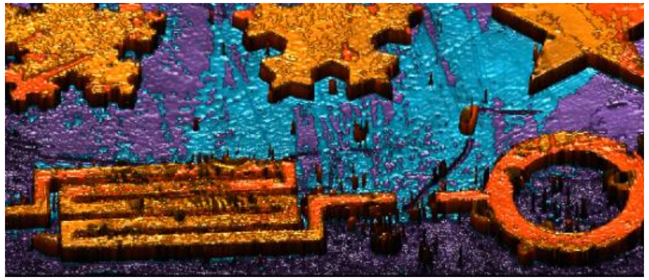


*Science **348**, 530 (2015); Nature Photonics **11**, 259 (2017)*

Semiconductor use cases for diffractive imaging and EUV/IR pump probe

Fab/Mask imager: EUV mask defect review



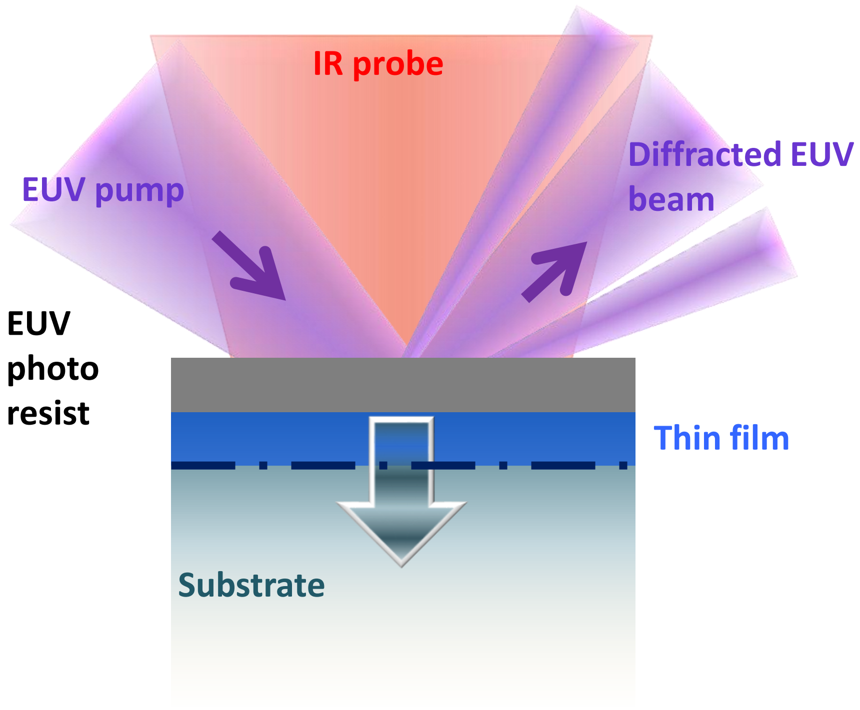


- Computational, aberration free phase reconstruction→
  - Phase image on mask is the outgoing wave: perfect for mask defect review
  - 'Direct' computational aerial image
  - 3D image
- High NA capable (~.6NA)
- Fast (reflection on masks is high!)

EUV pump/IR probe for direct resist decomposition measurement

Coupled IR probe (different detection possible) and EUV (13.5nm) pump

- Direct detection of EUV resist kinetics
  - Measure time evolution of exposure
- Measurement on substrate to determine interactions from different underlayers

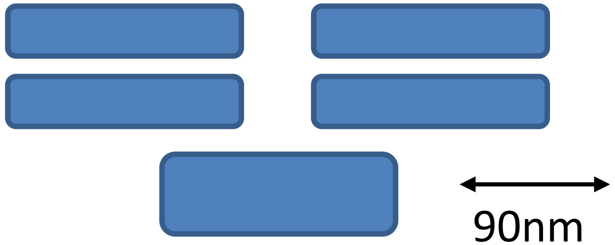


Direct calibration of photoresist models may be possible

Defectivity and metrology are different in a non-scaling era

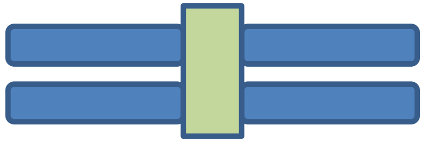
Moore’s Law era

<2005



‘Single Pattern’

2005-2015



‘line&cut patterning’

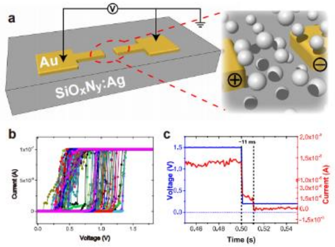
>2020

‘analog & Selective patterning’

Post-Moore’s Law era

- Physical shrink
  - Material led shrink

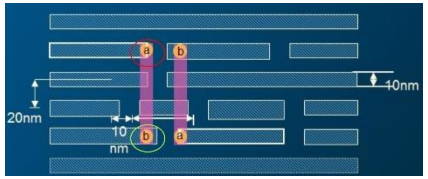
  New materials



Zhongrui Wang et al Nature Materials v16, p101–108 (2017)

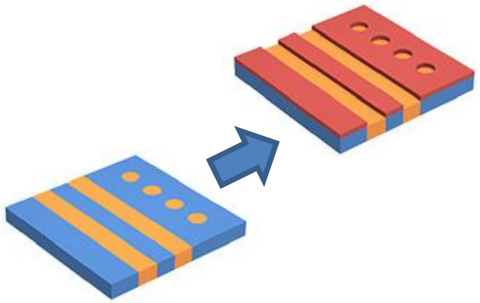
- Median control
  - Stochastic control

  New strategies

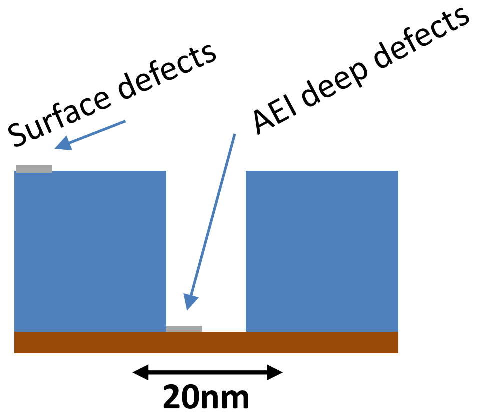


- Patterning
  - Selective patterning

  New errors



Defect Review & CD metrology



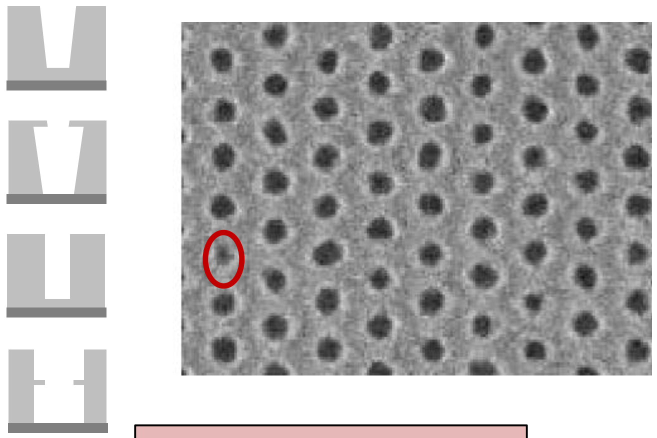
Defects at bottom of Via

Issue:

- Defect deep in feature cannot be reviewed by SEM

EUV imaging answer:

- EUV optical penetration in gives phase visibility to bottom-of-contact items



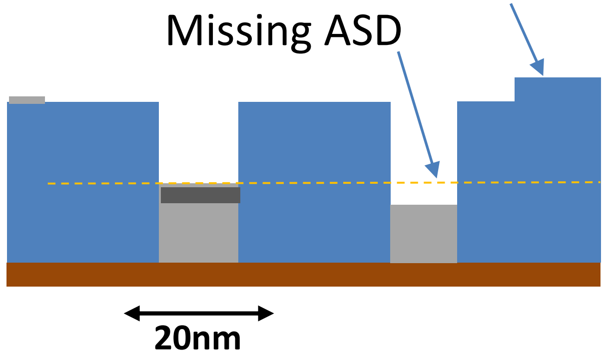
Stochastic defects

Issue:

- Many critical defects are random
- Median CD not sufficient

EUV imaging answer:

- Image large FOV
- Measure direct distribution



Topographic defects

Issue:

- Height/coating defects not measureable with SEM

EUV imaging answer:

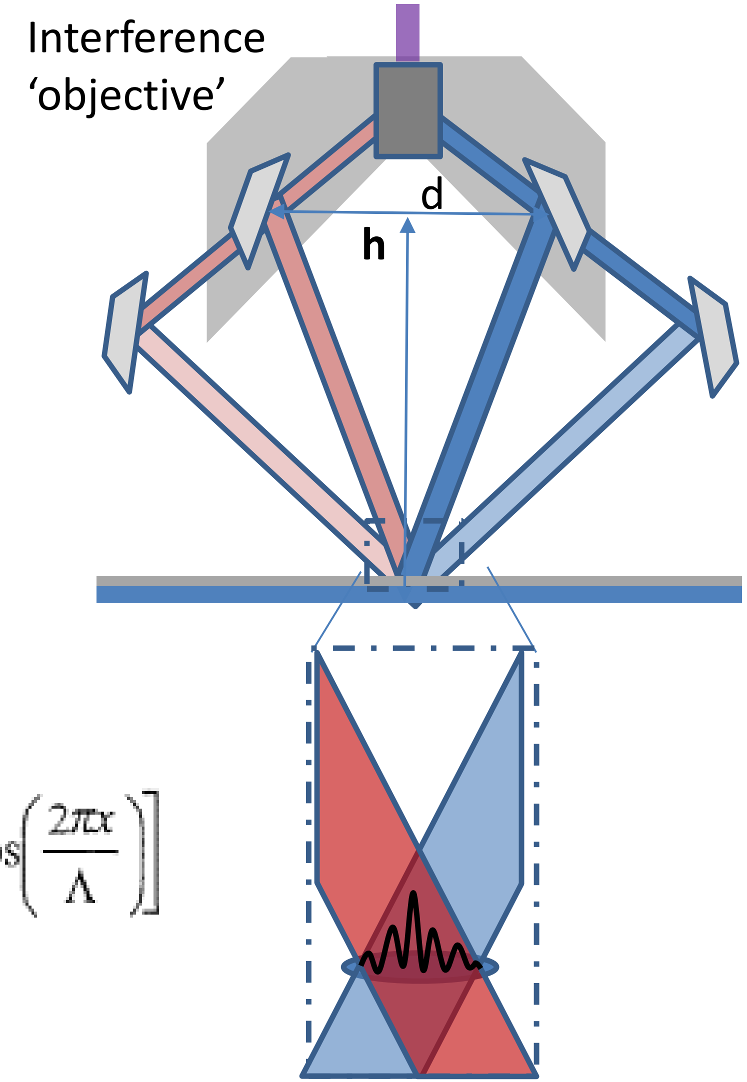
- Direct height via phase
- Sensitive to selective deposition variation

Interferometric printing for resist qualification

- Multi-resolution printing of lines at 10-40nm pitch
- Variable contrast across aperture and as a function of printed pitch
- Variable contrast in envelope function

- Cost and throughput allow
  - Point or use qualification
  - Aging tests
  - Post manufacture testing

  All without need for a full EUV system

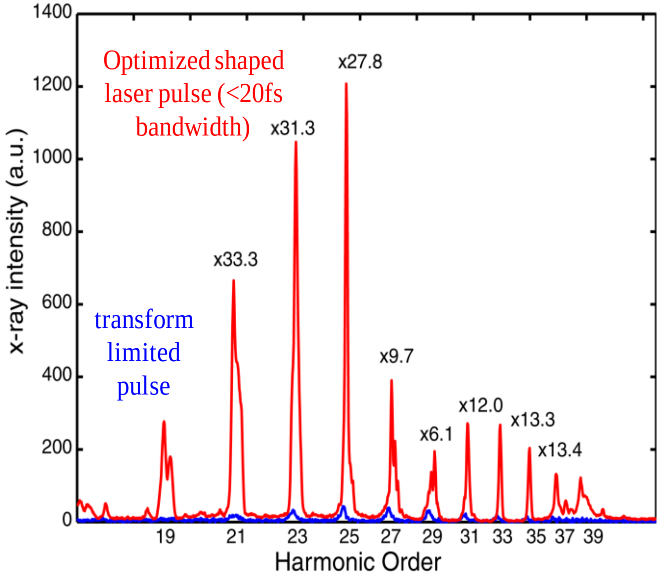


$$I(x)=\frac{1}{2}\left[1+\cos\left(\frac{2\pi x}{\Lambda}\right)\right]$$

What is next

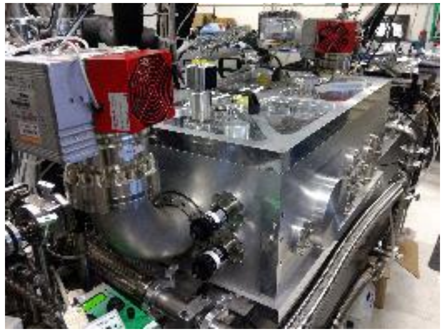
Where next: 100x faster image, 10,000 faster solution time

More photons (uW)



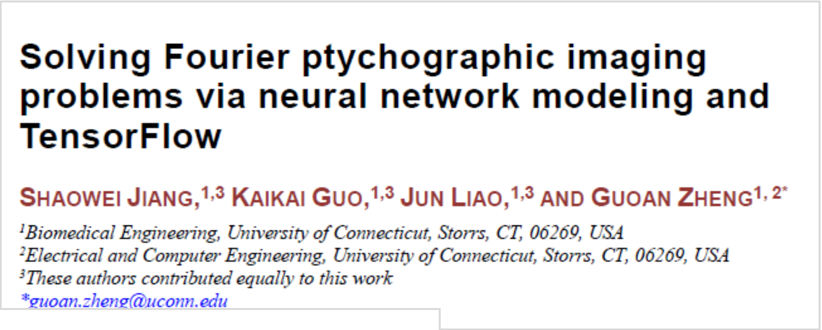
HHG can improve by 10-30x
Top: Randy Bartels

Better Systems



Better Software

Ptychography is uniquely good for DL/NN:
→Clear forward solution/model
→high amount of data
→computationally difficult inversion



Solving Fourier ptychographic imaging problems via neural network modeling and TensorFlow

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Deep learning-based super-resolution in coherent imaging systems

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(many, many articles)

What is next: finishing

- There is incredibly useful science that can be uncovered with HHG
- It takes *doing* and *completing*