Coherent Diffraction Imaging

Ross Harder aka “The Imposter”
34-ID-C
Advanced Photon Source

https://tinyurl.com/y2qtrz7c

Compact Objects (CDI)

Non-compact samples (Ptychography)

Acknowledgments:
Prof. Ian Robinson (BNL)
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Visibility of fringes is a direct measure of the coherence of a beam. If beam is coherent across the spacing of the slits a Fourier Transform of the slit structure is observed downstream.
COHERENCE

longitudinal coherence

transverse coherence
COHERENCE

longitudinal coherence

\[ \Delta \lambda \]

transverse coherence

\[ d \]

\[ w_c \]

\[ z \]

\[ 0.5 \text{ um or 1.5 fs} \]

\[ \text{Si (111)} \]

\[ 34-ID-C \text{ 50m} \]

\[ 25 \times 70 \text{ um @ 9 keV} \]

\[ l_c \sim \frac{\lambda^2}{\Delta \lambda} \]

\[ \tau_c \sim \frac{\lambda^2}{c \Delta \lambda} \]

\[ w_c \sim \frac{\lambda z}{d} \]
Coherence: Laser Speckle

A. L. Schawlow "Laser Light"
Scientific American, 219 (3), p. 120, (1968)

Laser Speckle: Interference pattern arising from randomly distributed scatterers
Stars are big, but very far away. As a result, their light has a high transverse coherence. As the light propagates through the atmosphere our eye detects a portion of the coherent diffraction.
First Speckle: Exner, 1877 (using candle light)


First Speckle Photo: von Laue, 1914 (using arc discharge lamp)

M. von Laue: Sitzungsber. Akad. Wiss. (Berlin) 44, 1144 (1914)

Courtesy Prof. Oleg Shpyrko (UCSD)
First X-ray Speckle:

\[ I \propto |F(q)|^2 \]
WHY USE SYNCHROTRON RADIATION?

Synchrotron sources offer:

- Brightness (small source, collimated)
- Tunability (IR to hard x-rays)
- Polarization (linear, circular)
- Time structure (short pulses)

Source brightness is the key figure of merit for coherent imaging

\[ B = \text{photons/source area, divergence, bandwidth} \]

\[ F_c \sim \lambda^2 B \]
COHERENT X-RAY REFERENCES


X-RAYS, TWO EXTREMES FOR STRUCTURAL STUDY:

X-ray Imaging (Shadowgraphs)
- Inhomogeneous, non-periodic materials
- Limited spatial resolution (~0.001 mm)

X-ray Diffraction (Scattering)
- Is particularly sensitive to periodicity in the sample (Crystals)
- Atomic resolution (unit cell)

Roentgen, Nobel 1900

Von Laue, Nobel 1914
Bragg & Bragg, Nobel 1915
IMAGING REGIMES WITH COHERENT X-RAYS

X-ray beam

near-field Fresnel

absorption radiograph

phase contrast

2a

z \sim \frac{a^2}{\lambda}

in-line holography

far-field Fraunhofer

z \gg \frac{a^2}{\lambda}

cohherent diffraction

Kagoshima (1999)

Jacobsen (1990)

Miao (1999)
REFRACTIVE INDEX AND CONTRAST IN THE X-RAY REGION

\[ n = 1 - \delta - i\beta = 1 - \frac{r_e}{2\pi} \lambda^2 \sum n_i f_i(0) \quad A = A_0 \exp(-inkt) \]
\[ k = \frac{2\pi}{\lambda} \]

- Absorption contrast: sensitive to \( \text{Im}(n) \)
  \[ \sim 4\pi\beta(x,y)t/\lambda \]

- Phase contrast: sensitive to \( \text{Re}(n) \)
  \[ \sim 2\pi\delta(x,y)t/\lambda \]

Absorption contrast:
sensitive to $Im(n)$
\[ \sim 4\pi\beta(x,y)t/\lambda \]

Phase contrast:
sensitive to $Re(n)$
\[ \sim 2\pi\delta(x,y)t/\lambda \]
Polarized X-rays give sensitivity to electron spin in PtCo

CDI IN BRAGG GEOMETRY:
IMAGING DISPLACEMENT FIELD
(STRAIN)

Displacement field $u(r)$:

Coherent X-ray Diffraction measures:

$$
\tilde{\rho}(r) = \rho_{G_{hkl}}(r) \exp \left[-iG_{hkl} \cdot u(r)\right]
$$

Strain is a gradient of $u(r)$, the phase component of the complex-valued density.
TRADITIONAL MICROSCOPY:

Object Plane  Detector Plane

Lens-less Imaging:

Courtesy Prof. Oleg Shpyrko (UCSD)
FIRST DEMONSTRATION OF CDI WITH X-RAYS

diffraction pattern  reconstruction

COHERENT DIFRACTIVE IMAGING:

Y. Takahashi et al.,
LARGE-FORMAT, SINGLE-PHOTON SENSITIVE X-RAY CCD CAMERAS OPENED THE DOOR TO COHERENT X-RAY IMAGING

Fairchild Peregrine 486 CCD Camera

- 4K x 4K pixel array (61.4 mm square area)
- 15 μm pixels, 100% fill factor
- Back-illuminated for up to 80% QE
- Readout noise < 5 e- at 50 Kpixels/s
- Dynamic range > 86 dB in MPP
- 6 s readout with four on-chip amplifiers
- Pixel binning for more rapid readout
- Peltier-cooled to -50 C for low dark current
Hi Resolution Imaging (CCD)?

At APS 34-ID-C:
9.25 hours of scanning
38 minutes of x-ray exposure

~7nm data

Rainbow color map (still) considered harmful
PIXEL ARRAY DETECTORS: REVOLUTIONIZING COHERENT IMAGING

A Three Layer Hybrid Device

- **Diode layer** → converts x-rays to photocurrent.
- **ASIC layer** → custom signal processing electronics.
- A layer of **metallic interconnects** (bump bonds) between corresponding pixels on the diode and ASIC layers.

D. Schuette, S. Gruner (Cornell)

Pilatus 6M detector (PSI/Dectris)

**PADs can be read out in ~1 ms (CCDs take seconds!)**

**PAD pixels are 55-150 µm. (CCDs are 12-24 µm)**
Hi Resolution Imaging (PAD)?

Quad Timepix GaAs sensor

700nm gold crystal
3 degree rocking curve
25 minute measurement
15 sec movie (1X APS-U measurement)
Coherent Diffraction from Crystals

$|\text{Fourier Transform}|^2$
Coherent Diffraction from Crystals

$|\text{Fourier Transform}|^2$
Measuring 3D CXD

\[ Q = k_f - k_i \]

Silver Nano Cube (111)

3D Ag Nano Cube

Yugang Sun and Younan Xia,

(Received 3 July 1952)

Shannon (1949), in the field of communication theory, has given the following theorem: If a function \( d(x) \) is known to vanish outside the points \( x = \pm a/2 \), then its Fourier transform \( F(X) \) is completely specified by the values which it assumes at the points \( X = 0, \pm 1/a, \pm 2/a, \ldots \). In fact, the continuous \( F(X) \) may be filled in merely by laying down the function \( \sin \pi aX/\pi aX \) at each of the above points, with weight equal to the value of \( F(X) \) at that point, and adding.

Now the electron-density function \( d(x) \) describing a single unit cell of a crystal vanishes outside the points \( x = \pm a/2 \), where \( a \) is the length of the cell. The reciprocal-lattice points are at \( X = 0, \pm 1/a, \pm 2/a, \ldots \), and hence the experimentally observable values of \( F(X) \) would suffice, by the theorem, to determine \( F(X) \) everywhere, if the phases were known. (In principle, the necessary points extend indefinitely in reciprocal space, but by using, say, Gaussian atoms both \( d(x) \) and \( F(X) \) can be effectively confined to the unit cell and the observable region, respectively.)

For centrosymmetrical structures, to be able to fill in the \( |F|^2 \) function would suffice to yield the structure, for sign changes could occur only at the points where \( |F|^2 \) vanishes. The structure corresponding to the \( |F|^2 \) function is the Patterson of a single unit cell. This has twice the width of the unit cell, and hence to fill in the \( |F|^2 \) function would require knowledge of \( |F|^2 \) at the half-integral, as well as the integral \( h \)'s. This is equivalent to a statement made by Gay (1951).

I think the conclusions which may be stated at this point are:

1. Direct structure determination, for centrosymmetric structures, could be accomplished as well by finding the sizes of the \( |F|^2 \) at half-integral \( h \) as by the usual procedure of finding the signs of the \( F \)'s at integral \( h \).

2. In work like that of Boyes-Watson, Davidson & Perutz (1947) on haemoglobin, where \( |F|^2 \) was observed at non-integral \( h \), it would suffice to have only the values at half-integral \( h \).

The extension to three dimensions is obvious.

References


Critical sampling

\[ |A_q| = \left| \sum_{0}^{N} \rho_n e^{-iqr_n} \right| \]

Nyquist Freq = \(1/(2\times\text{bandwidth})\)

Intensity is under sampled
Oversampling 2x

N/2 equations
N/2 Unknown densities
N/2 Known Densities (zero)

$$|A_q| = \left| \sum_{0}^{N} \rho_n e^{-iqr_n} \right|$$
Input Output Algorithms

Reciprocal Space Constraints
- Experimental Amplitudes
- Oversampled
- Thresholded
- ZeroPadded

Direct Space Constraints
- Support
- Total Energy
- Mixing previous iterates.
- Positivity

R. W. Gerchberg and W. O. Saxton *Optik* 35 237 (1972)
Input Output Algorithms

Reciprocal Space Constraints
- Experimental Amplitudes
- Oversampled
- Thresholded
- ZeroPadded

Direct Space Constraints
- Support
- Total Energy
- Positivity

Mixing old and new iterates.

\[ \mathcal{F} \]

\[ \mathcal{F}^{-1} \]

R. W. Gerchberg and W. O. Saxton *Optik* 35 237 (1972)
Input Output Algorithms

Reciprocal Space Constraints
- Experimental Amplitudes
- Oversampled
- Thresholded & ZeroPadded

Direct Space Constraints
- Support
- Total Energy
- Mixing old and new iterates
- Positivity

Error Reduction
\[ u_i^{(n)} = \begin{cases} 
\tau_i^{(n)} & i \in \text{Support} \\
0.0 & i \notin \text{Support} 
\end{cases} \]

Hybrid Input-Output
\[ u_i^{(n)} = \begin{cases} 
\tau_i^{(n)} & i \in \text{Support} \\
\tau_i^{(n-1)} - \beta \tau_i^{(n)} & i \notin \text{Support} 
\end{cases} \]

FFT

FFT\(^{-1}\)


R. W. Gerchberg and W. O. Saxton *Optik* 35 237 (1972)

Input Output Algorithms

Reciprocal Space Constraints
- Experimental Amplitudes
- Oversampled
- Thresholded
- ZeroPadded

Direct Space Constraints
- Support
- Total Energy
- Mixing old and new iterates.
- Positivity

Hybrid Input-Output

$\mathbf{u}_i^{(n)} = \begin{cases} 
\tau_i^{(n)} & i \in \text{Support} \cap |\varphi_i| \leq \varphi_{\text{max}} \\
\beta \tau_i^{(n)} & i \notin \text{Support} \cup |\varphi_i| > \varphi_{\text{max}} 
\end{cases}$


Monitor Reciprocal Space Error

Chi Square

Iteration

Amplitude

23nm

[Graph and images depicting data analysis and visualization]
GENETIC/GUIDED ALGORITHM

Random start → HIO/ER → Fitness = 0.01
Random start → HIO/ER → Fitness = 0.3
Random start → HIO/ER → Fitness = 0.8
Random start → HIO/ER → Fitness = 0.05
Random start → HIO/ER → Fitness = 0.7
Random start → HIO/ER → Fitness = 0.65
Random start → HIO/ER → Fitness = 0.5

Fitness metrics
Reciprocal Space Error
Sharpness (sum pho^4)
...

Cross the population with the best.

Cross Sqrt(a*b)
...


A.I. CDI
Atomistically Informed Coherent Diffraction Imaging
TRAINING THE NEURAL NETWORK

Training:
180,000 examples generated
20,000 held back for validation
1,000 used for testing

NEURAL NETWORK THAT LEARNS IMAGE RECONSTRUCTION

A
Input intensity

B
True object

C
Predicted object

D
True phase

E
Predicted phase
3D Ag Nano Cube

Yugang Sun and Younan Xia,
3D Strain Map in ZnO

(a) (0,1,1) (0,-1,1) (1,0,1) (-1,0,1) (-1,1,1) (1,-1,1)

(b) 3D strain map with color scale from -2.8 to 2.8 radians.

(c) Schematic showing the crystal and X-ray beam setup.

(d) Micrograph showing a 2μm scale bar.
3D Strain Map in ZnO

\[ u_j = \xi_{ji} q_{ki} \phi_k; \quad \xi_{ji} = (q_{kj} q_{ki})^{-1} \]
3D Strain Map in ZnO

\[ \epsilon_{ij} = \frac{1}{2} \left( \frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right), \quad \tau_{ij} = \left( \frac{\partial u_j}{\partial x_i} - \frac{\partial u_i}{\partial x_j} \right) \]
Patterned Gold Nanocystal Samples
Multiple reflection reconstructions
Multiple reflection reconstructions

(11-1)
Multiple reflection reconstructions
Multiple reflection reconstructions
Multiple reflection reconstructions

(1/3 1/3 5/3)

(1/3 1/3 5/3)
Multiple reflection reconstructions

\[(1/3 \ 1/3 \ 5/3)\]
Multiple reflection reconstructions

\[ \varphi = q \cdot u(r) \]
Vector Displacement Field of Gold lattice

Produced by combining reconstructions from (11-1) (020) (-111)
**BCDI TODAY**

Operando Nanoscale Imaging

Dislocation dynamics in Li-Ion battery


**Liquid Catalysis**

Dislocation dynamics in the hydriding phase transformations of Pd


Imaging Lattice Dynamics
Laser Pump - CXD Probe@LCLS

\[ S(\tau) = \sum_{n=1}^{N} A_n \exp \left( -\frac{\tau}{\tau_{d,n}} \right) \cos \left( \frac{2\pi}{T_n} \left( \tau + \tau_{0,n} \right) \right) + C_n. \]

600 pm “breathing modes”

Crystal A
101 ps and 241 ps

Crystal B
90 ps and 256 ps

Ultrafast three dimensional imaging of lattice dynamics in individual gold nanocrystals
Ultrafast three dimensional imaging of lattice dynamics in individual gold nanocrystals
Comparison of projected displacements from experiment and molecular dynamics simulations. Orthogonal slices from the image corresponding to a delay time of +110 ps (top) which is compared to orthogonal cut slices from a cylinder simulated with molecular dynamics (bottom). A time of +14 ps was selected for the comparison as it is a comparable delay time to the data taking into account the relative dimensions.

Ultrafast three dimensional imaging of lattice dynamics in individual gold nanocrystals
Ptychography (to fold) - Scanning CDI for extended object

 Courtesy Dr. Junjing Deng (APS)
Ptychography (to fold) - Scanning CDI for extended object

Courtesy Dr. Junjing Deng (APS)
Ptychography (to fold) - Scanning CDI for extended object

Courtesy Dr. Junjing Deng (APS)
Ptychography

**Exit surface wave field:** \( \psi(r) = P(r)O(r) \)

\[
O(r) = \frac{\sum P^*(r - r_j) \psi_j(r)}{\sum_j |P(r - r_j)|^2}, \quad P(r) = \frac{\sum O^*(r + r_j) \psi_j(r + r_j)}{\sum_j |O(r + r_j)|^2}
\]


Spatial resolution: \( \delta = \frac{\lambda}{\theta} = \frac{\lambda z}{N\Delta} \)


Ptychographic iterative engine (PIE)

Courtesy Dr. Junjing Deng (APS)
At which plane ptychographic images are reconstructed

$$\psi(r) = P(r)O(r)$$

Ptychography always produces images at the sample plane.

The resolution is not limited by the beam size.

Characterization of focusing optics.

Propagation   Sample plane
Simultaneous ptychographic and fluorescence microscopy.

The deconvolution process involves first resampling the elemental maps from the step scan where $I_p$ is the intensity measured with resolution in the sample plane and the overlap between probe positions allow imaging beyond the resolution of the X-ray optics. The reconstructed transmission function amplitude (a) & in the sample plane and the overlap between probe positions allow imaging beyond the resolution of the X-ray optics. The reconstructed transmission function amplitude (a) & in the sample plane and the overlap between probe positions allow imaging beyond the resolution of the X-ray optics. The reconstructed transmission function amplitude (a) & in the sample plane and the overlap between probe positions allow imaging beyond the resolution of the X-ray optics. The reconstructed transmission function amplitude (a) & in the sample plane and the overlap between probe positions allow imaging beyond the resolution of the X-ray optics. The reconstructed transmission function amplitude (a) & in the sample plane and the overlap between probe positions allow imaging beyond the resolution of the X-ray optics. The reconstructed transmission function amplitude (a) & in the sample plane and the overlap between probe positions allow imaging beyond the resolution of the X-ray optics. The reconstructed transmission function amplitude (a) & in the sample plane and the overlap between probe positions allow imaging beyond the resolution of the X-ray optics.

$2$ the pixel size of the reconstructed probe, $2$ the pixel size of the reconstructed probe, $2$ the pixel size of the reconstructed probe, $2$ the pixel size of the reconstructed probe, $2$ the pixel size of the reconstructed probe, $2$ the pixel size of the reconstructed probe.

$1$ to $1$ the probe amplitude. $1$ to $1$ the probe amplitude. $1$ to $1$ the probe amplitude. $1$ to $1$ the probe amplitude. $1$ to $1$ the probe amplitude. $1$ to $1$ the probe amplitude. $1$ to $1$ the probe amplitude. $1$ to $1$ the probe amplitude.

By propagating the reconstructed X-ray waves through the sample we can quantify the distance of the sample from the focal plane. Line profiles through the focal waist (log scale) (a) and through focal series with resolution does not increase the spatial resolution of the images but rather ensures smooth variation between pixels in the rescaled image.

Iterative deconvolution of the point spread function of X-ray fluorescence data was done using bilinear interpolation after low pass filtering the data. The bilinear interpolation is approximately 24 hours to complete. The reconstruction was easily identifiable at the conclusion of the second iteration and convergence was achieved after just a few hundred iterations.

The forward problem of image formation in the X-ray fluorescence microscope can be formulated as a discrete convolution with two native length scales, $\mu m$ aperture was scanned across the sample whilst simultaneously recording the X-ray fluorescence spectrum. The probe was then deconvolved using the modified residual norm steepest descent algorithm (MRNSDA) as implemented in the “Parallel Iterative Deconvolution” ImageJ plugin.

No additional constraints were used on the amplitude or phase of any of the wavefields. The probe was then deconvolved using the modified residual norm steepest descent algorithm (MRNSDA) as implemented in the “Parallel Iterative Deconvolution” ImageJ plugin.

The resulting images were then scanned across the sample and at each point in the scan a photon counting pixel array detector [23] (2562 55 m pixels) located 1.34 m downstream of the focus recorded a far-field diffraction pattern as an energy dispersive silicon drift diode measured the fluorescence yield and strong absorption by the sample itself. The transmitted X-rays however are sensitive to the complementary contrast mechanisms of the two techniques. The soft X-ray fluorescence from low-Z biomass elements (C,N,O) are difficult to detect due to low fluorescence.

The transmitted X-rays pass through a knife edge scan, was much larger than the outermost zone width. The focused beam was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2. The sample was imaged several regions of a gold spoked “star” resolution pattern, Fig. 2.

Making ptychography colorful

- Combination of Ptychography & Fluorescence

- **Frozen-hydrated samples**: closer to natural state, reduce radiation damage
- **Fluorescence**: quantitative elemental composition
- **Ptychography**: structure information with high resolution


Courtesy Dr. Junjing Deng (APS)
• Frozen-hydrated *Chlamy.* Alga
• Ptychographic image resolution: ~18 nm
• Fluorescence image resolution: ~100 nm
• Complementary information helps with sample analysis


Courtesy Dr. Junjing Deng (APS)
• Frozen-hydrated *Chlamy. Alga*
• Ptychographic image resolution: ~18 nm
• Fluorescence image resolution: ~100 nm
• Complementary information helps with sample analysis
Extended to 3D

P

Ca

Cl

K

S

Ptycho

Courtesy Dr. Junjing Deng (APS)
Ptychographic spectroscopy
-- like STXM XNEAS analysis, but with higher resolution and more information (both absorption and phase) from refractive index

Adapted from D. Shapiro, et al. Nat. Photon. 8, 765 (2014)
GDFE LAYERED MAGNETIC FILMS

\[ E_{tot} = \int \left[ e_{ex}(m) + e_{an}(m) - \mu_0 H_{ex} \cdot M + \frac{1}{2} \mu_0 H_d^2 \right] dV \]

A. Tripathi, O.S. et al., Proc Natl Acad Sci USA 108, 13393 (2011)
MAGNETIC CONTRAST MECHANISM

Off-resonance: ●

Gd M₅ edge

Counts [Arb. Units]

Energy [eV]

On-resonance: ●

A. Tripathi, O.S. et al., Proc Natl Acad Sci USA 108, 13393 (2011)
REAL SPACE RECONSTRUCTION

Magnetic structure (exit wave)

Illumination Function

A. Tripathi, O.S. et al., Proc Natl Acad Sci USA 108, 13393 (2011)
REAL SPACE RECONSTRUCTION

Magnetic structure (exit wave)

Illumination Function

A. Tripathi, O.S. et al., Proc Natl Acad Sci USA 108, 13393 (2011)
A. Tripathi, O.S. et al., Proc Natl Acad Sci USA 108, 13393 (2011)
INCREASING FIELD

A. Tripathi, O.S. et al., Proc Natl Acad Sci USA 108, 13393 (2011)
Nanoscale Strain in SiGe film devices

SURFACE DIFFRACTION COHERENT IMAGING

- Image local surface structure
- Steps and step dynamics during film growth or interfacial reactivity
- Nanoparticle nucleation
- Defect distributions, particularly at interfaces
- Combined with x-ray micro fluorescence

APPLY FOR COHERENT IMAGING BEAMTIME @ APS!

Bragg CDI

Ptychography

Tomography

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https://www.aps.anl.gov/Users-Information