Diamond Sensors

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DOE BES Neutron & Photon Detector Workshop
Diamond for Light Sources

- In May 2011, the APS held the 4th “Diamond for Modern Light Sources”
  - Monochromators
  - Kineform lenses
  - Windows
  - Fluorescent Screens
  - Beam monitors (BPMs)

- In May 2012, the NSLS held “X-Ray Beam Position Monitors”
  - Five talks mentioned diamond sensors

- European Synchrotrons (Soleil, ESRF, DESY) leading the way
  - The only “real” commercial device is from Dectris, out of PSI
  - Much of this talk is from talks by J. Morse (ESRF), M. Pomorski (CEA Saclay)
Motivation

New Sources and New Applications require new diagnostics

- Position of beam on sample at nanoscale
  - 10 nm resolution, 100 µm from sample for nanoprobe

- Alignment of Insertion devices and complex optics
  - 5-crystal monochromator for NSLSII HSX

- Flux, position and beam shape for high flux endstations
  - Protein Footprinting (XFP at NSLS II) has no diagnostic option
  - Damping wiggler beamlines will saturate ion chambers (ISS) – in this case the diamond may be both diagnostic and detector

- Fast timing diagnostics for pump-probe science
  - Resolve position and flux for each pulse in custom bunch structures
  - Diagnostics for FEL beams at kHz-MHz rep rates

NSLS II needs many of these to be available now!
Why Diamond?

- **Phenomenal Material**
  - High *thermal* conductivity and low CTE: can take the heat
  - High *transmission* for manageable thicknesses; vacuum-compatible and compact (20 µm has same signal as 6 cm IC)
  - Wide band, indirect **gap**: need not operate in the dark or with cooling (unaffected at 300 C); **no photo-recombination based saturation**.
  - Radiation Hard (unchanged* by 18 months in the white beam)
  - High **speed** capable (compared to ion chamber)

- **Single and polycrystalline synthetic diamonds are options (N<5 ppb)**
  - Poly is cheaper and available on wafer scale, but smaller CCD
  - Single is limited in size (4.7x4.7 sq mm typical), but CCD > 1 mm

- **Considerable interest:**
XBPMs
Basics

fast ionization chamber approach  
transient current signals in sc and pc CVD

induced signal proportional to the deposited energy  
(factor \(\sim 13 \text{ eV/e-h if CCE=100\%}\))

diamond position sensitive detectors for X-ray beam monitoring

pixel, strip
- large sensitive area
- beam position and profile

quadrant
- fast
- only 4 channels

resistive electrode
- large sensitive area
- only 4 channels

- sophisticated electronic
- pixel size limits position resolution

- small sensitive area
- beam size dependence

- speed limited by RC

Michal Pomorski - Diamond Sensors Laboratory, DMLS workshop @ Argonne National Laboratory, 05-06 May 2011
Responsivity vs Photon Energy

$$S = \frac{1}{W} e^{-t_{metal}/\lambda_{metal}} \left(1 - e^{-t_{dia}/\lambda_{dia}}\right) CE[v, F]$$

Platinum M edge feature due to loss of photons absorbed by incident contact not field dependent

Maximum S of 0.07 A/W => w = 13.3±0.2 eV

Loss of photons through diamond reduces S for hv >5 keV

C K edge feature is field dependent, caused by incomplete carrier collection for carriers produced near incident electrode – electrons diffuse into incident contact and are lost

J. Keister and J. Smedley, NIM A 606, (2009), 774
Response vs Flux and Bias

“Clean” Single Crystal

- Ion chamber Calibration
- Calorimetric Calibration
- Fit, $w = 13.4 \pm 0.2$ eV

Polycrystalline

- Ion chamber Calibration
- Calorimetric Calibration
- Fit, $w = 13.8 \pm 1.0$ eV

Response to incident flux linear over 11 orders of magnitude

Under 0.1 V/µm required for full collection

Diamond Current (mA) vs Voltage (V)

- 300 µm thick plate

- 210 µm thick plate
Oxygen terminated diamond
Either Bias

After high flux
Negative bias

Response maps with 19 keV photons, bias at 80% Duty Cycle, 1kHz square wave
Relation to Threading Dislocations

White beam topography shows locations of dislocations in the diamonds.

There is a strong spatial correlation between dislocations and PC regions.

We can use this!
Temporal Response, Hard X-rays


- X28C (non-PC)
- APS 11-ID-D (PC)
- APS 11-ID-D (non-PC)
Temporal Response, Soft X-rays

Voltage (V) vs Time (ns)

-0.015 to 0.000

-0.010

-0.005

0.000

0.005

0.010

0.015

0.8 MV/m

0.4 MV/m

0.3 MV/m
Contact Fabrication

Lift-off lithography:

- allows complex geometric designs for metal contacts: can implement many designs on single mask, electrode features to < 1μm

...but non-standard work on small samples

→ surface preparation, hot acid cleaning and post-clean handling

→ lithography: spin resist edge ‘beading’

~100nm Al contacts on 30 and 100μm diamonds
OSU-Kagan

(capability developed for CERN RD-42)

~100nm Al contacts on 100μm plates
INEX, UK

ESRF-DESY-OSU XBPM and microdosimetry mask set, 2010

Slide Courtesy John Morse, ESRF
BNL Diamond Lithography

Platinum grid contact
(50 µm spacing, full image 2x2 mm)

Wire-bonded Pt patterned contact
providing position sensitivity across device
(50 µm spacing for smallest stripe, full image 3x3 mm)

Contacts fabricated by optical lithography at the BNL CFN
Diamond BPM Types - BNL

1. Circuit Board Mounted
   - Pt metallization
   - wire-bonded electrodes
   - LEMO connectors

2. Application specific - X-Ray fluorescence (X27)
   - Ag diamond metallization
   - Ceramic board
   - 1 cm wide (compact)
   - Ag traces.

3. White BPM (X25)
   - Mini-gap undulator
   - ~100W incident power
   - Large beam
Compact Diamond Mounting - ESRF

ESRF-ID21 Fluorescence Microscopy beamline: *limited space, operation in dirty vacuum and in air*

IBM-etched e6 single crystals 4.2 x 4.2mm², *thicknesses 30 & 100μm*

Rogers multilayer PCB, microcoax wire leadouts

direct mounting of diamond to PCB and ...

Al electrode contacts and wire bonding (Kagan – OSU 2010)

ID21 beamline installation

homogeneous response map for 3/3 samples tested, no signal ‘hot spot’ defects

<0.1pA leakage current at 2Vμm⁻¹

vertical streaks are from beam I₀ normalization errors during scan

Slide Courtesy John Morse, ESRF
Position Response of Diamond Quadrant Devices

For large beamsize (>50µm), device ‘crossover response’ is simply the line integral across the beam intensity profile.

Electrometer measurements, i.e. signal integration time >> charge carrier drift time.

For a small beam (<5µm), crossover response is ~independent of beam size:

- convolution of photoelectron thermalization range
- and lateral charge diffusion occurring during carrier drift.

Slide Courtesy John Morse, ESRF
Example position noise data

Representative position calibration and noise data, RMS position noise for \(~40\times40\ \mu\text{m}^2\) white beam size (\(~100 \text{ mW/mm}^2\)) in current mode, 0.1 s integration.
Quadrant Device, Electrometer Readout: Time Scans

ESRF ID21 FZP microfocus beam tracking 1sec/point: vertical beam jumps on synchrotron e-beam refills

2010 data, $4 \times 10^9$ ph/sec at 7.2keV (FZP → K-B mirror)
14(18)nm vertical (horizontal), 1sec integration
33(48)nm, 0.1 sec integration

X-ray flux $\sim 10^8$ ph/sec at 7keV (FZP optic):
$\sim 20$fC in diamond per X ray bunch
$\sim 10$nA ‘dc equivalent’ signal current

Slide Courtesy John Morse, ESRF
Electronics options

• Electrometers & oscilloscopes
• Current amplifiers, V-F & counters
• ANL “quadem” system developed for foil BPMs – already EPICS integrated
• Pulse readout with FPGA system
• “Pulsed bias” for thermal load management and trap clearing
• Libera Brilliance at DESY
  – Uses existing eBPM readout
  – Less sensitive to “persistent current” due to low readout bandwidth
  – Up to 10 kHz readout

Area under pulse was used to calculate vertical axis

$G_X$ and $G_Y$ were calculated by using:

\[
X = G_X \frac{(Q_B + Q_D) - (Q_A + Q_C)}{Q_A + Q_B + Q_C + Q_D} \quad Y = G_Y \frac{(Q_A + Q_B) - (Q_C + Q_D)}{Q_A + Q_B + Q_C + Q_D}
\]

Position noise was calculated by taking the standard deviation of the residuals and multiplying by $G$

- Includes all noise sources, including actual beam wander
Position Stability at 11-ID-D, APS

Ring Structure at APS 11-ID-D
- 24 bunches spaced 153 ns apart
- Takes 3.68 µs to complete one orbit
- Beam size 15 µm x 0.8 mm
- Measured the position of the first bunch continuously
- +400V on quad (~2 MV/m)
- Recently acquired 324 mode

Short term stability

Long term stability
Ring Structure at APS 11-ID-D

- Ring mode “hybrid fill, top up”.
- 102mA total, 16mA in first bunch, 86mA in remaining pulse train.
- Separated by 1.594 µs
- Ratio of ring currents matches very closely to measured charge ratio
  - Current Ratio: 86mA/16mA = 5.38
  - Measured Q Ratio: 0.91nC/0.17nC = 5.35
Position Stability at 11-ID-D, APS

Ring Structure at APS 11-ID-D
- Ring mode “hybrid fill, top up”.
- Tracked the singlet bunch position every 11 turns (40 µs) for 15 hrs
- Singlet bunch has a peak current density of 200 A/cm²
- Traditional alignment feedback works on average current -> looking primarily at pulse train, not at singlet
X25 White Beam Position Monitor

• Installed 13.6 m from undulator at X25
• Large (6x1 mm$^2$) beam; up to 100 W, 11W absorbed
• Two 100 µm thick E6/DDL single crystal diamond plates tiled side-by-side
• Selected with topography
• Custom 4-channel current amplifier
• Up to 760 mA observed
• Position noise:
  Better than 0.5 x 0.05 µm

Transmission-mode diamond white-beam position monitor at NSLS
J. Synchrotron Radiation, 19, 381-387 (2012)
Monitor Calibration

XBIC Map

Bias Calibration

Position Calibration

Current (mA)

Operating Voltage

Upstream w/BPM

Downstream w/BPM

Bias (V)

Contrast

y position

z position

G_y = 1.70 mm

G_z = 0.27 mm

Distance (mm)
2\textsuperscript{nd} Monitor

Diamond Current (A)

Power Absorbed by Diamond (W)

Ion chamber Calibration
Calorimetric Calibration
Theory, $w = 13.3$ eV

- $X$ Current (normalized)
- $Y$ Current (normalized)

Distance (mm)

Distance (mm)
Monitor Results

Beam position changes with undulator gap
Extent of motion is a function of e-beam position
Needs Assessment

• High flux monitoring (e.g. NSLS II: ISS, XFP, XPD, CHX, others)
• White beam monitoring of beam center of mass, not just wings (e.g. machine, insertion device diagnostics, white beam beamline endstation sensor)
• Robust sensor (long lifetime in operation)
• Fast “timing” response (e.g. APS hybrid mode)
• Compact sensor (replace gas ion chambers)
• Low impact on beam quality (coherence)
• Nanoscale position resolution, close to sample
R&D Areas

• **Diamond material quality improvement**
  – Screening diamonds for threading dislocations
  – Readout strategies and contacts that mitigate material nonuniformity

• Effects of diamond processing on material quality (particularly with very thin polished devices)

• Spatial uniformity of diamond response and dependence on material quality and processing

• Impact on x-ray beam coherence (scattering, dependence on diamond quality)

• Determining the charge transport limit in diamond and the max measurable peak flux (LCLS)

• Heat load management (for sensor mounting)
• ‘proof of principle’ now well established for intensity and position measurements of (monochromatic) synchrotron beams using quadrant devices with both electrometer and RF readout

also results from white beams (high thermal power): BNL tests, Smedley et al. talk

• to obtain stable, non-injecting contacts, sub-surface damage of crystal from abrasive polishing must be eliminated, with deposition of metal made after scrupulous surface cleaning

• CVD crystal quality (local high density areas of threading dislocations) remain the major concern for device yield → high leakage currents, signal hot spots...

...no progress in crystal defect quality of commercially available e6 ‘detector grade’ samples over past ~7 years
R&D Areas

• Electronic contact options (blocking vs. injecting, metal vs. low-Z), measurement of Schottky barrier
• Effects of carrier diffusion on performance (soft x-rays, determination of ultimate position resolution obtainable)
• Pixilation of devices (beam imaging)
• Position resolution for nano-focused beams
• Mitigating effects of Bragg peaks for spectroscopy BLs
• Instrumented windows (small single- and large poly-crystalline diamond)
• Real-time pulse-by-pulse readout electronics
• Compact packaging
Summary

• New Sources and New Applications require new diagnostics
  – Nanoscale, High Flux, Timing/pump-probe, compact “at-sample”
• Diamond is a remarkable material:
  – Flux linearity demonstrated over 11 orders of magnitude
  – Calculable, reliable responsivity \( w = 13.3 \text{ eV} \)
  – Low absorption (lowest Z semiconductor), High Thermal Conductivity
• BNL effort could form the core of a resource/hub for US synchrotrons
  – Materials Science (XPS, IR, NEXAFS, XRD, Topography), Lithography, testing, diamond screening, fabrication, electronics development
  – Devices tested at APS and ALS as well as across 16 NSLS beamlines
  – Strong NSLS II demand, commercialization underway for some devices
  – Collaboration with ANL for readout development
• R&D needed in several areas
  – Better diamonds (larger, fewer dislocations), new electrical contacts (underway with CNM), smaller features, custom designs for spectroscopy
  – Our strategy has been to use the user facilities to make better devices

Thank you!
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Facilities:
NSLS, APS, ALS, CNM, CFN

SBIR Partner:
Sydor Instruments, LLC

SBIR Phase I awarded for FY2012.
Currently gathering requirements for white beam and sample position configurations.
User requirements will drive commercial development in 2013

Publications of particular interest:
E. Muller et al., J. Synchrotron Rad. 19, 381-387 (2012)
Beam Damage? Detector Lifetime?

After 18 months in white beam