X-ray Detector Development at LBNL

\[ r_e = \frac{1}{4\pi\varepsilon_0} \frac{e^2}{mc^2} \sim 10^{-15} \text{ m} \quad \sim 10^{-10} \text{ m} \quad \sim 10^{-8} \text{ m} \quad R_E = \frac{c}{\sqrt{4\pi G \rho}} \sim 10^{26} \text{ m} \]

Elementary particles
Atoms
Proteins, Molecules
Universe

P. Denes
Acting Director Engineering Division
Deputy Director for Engineering, Advanced Light Source

0.25 μm ATLAS pixel chip
Laboratory Focus and Vision

Mission and Overview

FY 2006 Non-DOE Funding: $111M

FY 2006 Non-DOE Funding: $55.3M
FY 2006 Dept. Of Homeland Security: $2.6M
Evolution

Spectroscopic detectors
- High-purity Ge
- Nuclear medicine
- Gas detectors

Tracking detectors
- Si Strips
- Si pixels
  - CCD (astro)
  - hybrid (particles)

Imaging detectors
- Spectroscopic pixels
- Monolithic pixels
How did we get into this?

Charged particle tracking:
Measure positions
\[ R = \frac{p}{qB} \quad \delta p/p \sim \delta R/R \]
CDF / DØ / BaBar ATLAS
Pixel Detectors for Particle Physics

Originally CCDs
Then hybrid pixels

- 1996 - SLD Vertex Detector
- $3 \times 10^8$ pixels
- 96 3.2 MPix 20 μm CCD
- 120 Hz collision rate
- <1 Hz readout rate
ATLAS Pixel

46,080 pixels
50 x 400 μm²

2007 ATLAS Pixel Detector
LHC Pixels

Two large projects to develop hybrid pixel detectors

Synchrotron Spinoffs
CMS → PSI → Pilatus
ATLAS → LBNL →
Bring silicon valley expertise to silicon strips
Class 10 cleanroom
• completed 1989
LBNL 2k x 4k CCD:
Blue: H- at 656 nm  Green: SIII at 955 nm  Red: 1.02 μm
Thick, Fully Depleted CCD

At $V_{\text{SUB}} = 115 \, \text{V}$, $

\sigma_D = 3.7 \pm 0.2 \, \mu\text{m}$

S. Holland
Thick, Fully Depleted CCD

Quantum Efficiency Measurements

- LBNL B6135.7.7: ~250 um thick (-140C)
- Commercial CCD: ~20 um thick

Wavelength (nm)
Improve Blue Sensitivity

Delta doping High purity P-channel Arrays: R&D

California Institute of Technology

N-type delta doping process for high purity substrates was developed.
Process extended to devices and optimized on 1k x 1k p-channel CCDs.
Delta doped large format p-channel CCDs.
AR coating developed in house.
Excellent QE, dark current, CTE, and uniformity observed.

Delta-doped p-channel CCD, LBNL 1k x 1k

2K x 4K Array in the MBE
The West is Red

SNAP
SuperNova/Acceleration Probe

Dark Energy and the Accelerating Universe
SNAP Readout

CRIC 1
Floating-point FE

CRIC 2
⊕ Pipelined ADC

CRIC 3
⊕ Digital Calibration / Control

CLIC
HV DI CMOS
Programmable voltages
Programmable clock patterns
### “Detectors” at Berkeley Lab

<table>
<thead>
<tr>
<th>Enabled by</th>
<th>Microelectronics</th>
<th>Materials</th>
<th>Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Examples</strong></td>
<td>CCDs&lt;br&gt;Strip detectors&lt;br&gt;Pixel detectors</td>
<td>Scintillators&lt;br&gt;Other semiconductors (Ge, CZT, ...)</td>
<td>TPCs&lt;br&gt;Large Č detectors&lt;br&gt;Optical detectors</td>
</tr>
<tr>
<td><strong>Initial Uses</strong></td>
<td>HEP (tracking)&lt;br&gt;Various (astro)</td>
<td>NP (γ spectroscopy)&lt;br&gt;BER/NIH (PET)</td>
<td>HEP, NP, BES&lt;br&gt;(accel. diag.)</td>
</tr>
<tr>
<td><strong>Emerging Uses</strong></td>
<td>BES (x-ray, e-)&lt;br&gt;Biology “DHS”</td>
<td>Other medical “DHS”</td>
<td>“DHS”</td>
</tr>
</tbody>
</table>
Consensus:
- fast, 2D detectors
- moderate size/number of pixels in most cases
- Majority soft x-ray
- some hard x-ray
- some low energy electrons

Workshop on Advanced Detectors
October 16, 2009

This year’s workshop was structured similarly to the 2007 workshop: a 1st half discussing detector technologies and capabilities, and a 2nd half surveying needs at the ALS.

Funded by Strategic LDRD, a very fast pseudo column parallel CCD has been developed for a number of synchrotron research areas. This was based on CCD technology developed for SNAP, and modified so that 10 columns are read out into individual ASIC channels. This massively parallel architecture speeds read out compared to typical scientific CCDs up to a factor of 100. It also has the advantage of being based on thick Silicon, offering therefore sensitivity from the IR to the hard x-ray regions. In collaboration with the APS, this chip has been built into a camera, and tested on several experiments at ALS and APS. At the ALS, the prototype has been tested on 12.3.2 for hard x-ray microdiffraction and 9.0.1 for soft x-ray ptychography.

ARRA funds to deliver FastCCD systems to ALS beamlines were received in 2009, and a new BES Detector R&D program was also funded. For this workshop, the goals were to review the needs for FastCCD systems as well as performance specifications and to see what are the needs for the future which R&D can address.

Technologies:
- FastCCD experience at ALS: D. Doering
- FastCCD experience at ALS: J. Weizsäcker
- Silicon-on-Insulator: D. Contarato
- Thin window, fully depleted detectors: C. Tindall

Needs at the ALS:
- T. Tykacaak: STXM
- M. Marcus: micro-XAS
- P. Heimann: ultrafast
- S. Marchesini: CXDI
- N. Tamura: micro-diffraction
- A. MacDowell: tomography
- A. Scholl: PEEM
- Y-D Chuang: x-ray fluorescence and scattering
- A. Bostwick: photoemission
- S. Clark: high pressure
- S. Roy: Coherent scattering
FastCCD - maximize impact, direct (or indirect) detection

**Concept - late 2003**

- **Direct x-ray detector**
  - X-ray photoconverts in silicon
  - Collect the photoelectrons
  - (Much more signal)

- **Canonical x-ray detector**
  - X-ray photoconverts in phosphor
  - Photoelectron ionizes $\rightarrow$ scintillation photons
  - Photons bounce around in phosphor and get distorted in fiber
  - Photons photoconvert in CCD
  - Collect the photoelectrons

**Original specs:**
- $\geq$ 100 frames / s
- 15 bit dynamic range
- 8 bit resolution
- sparse scan
FastCCD - maximize impact, direct (or indirect) detection

Concept - late 2003

CCD - 2006/7 (LDRD)
- Metal-strapped gates (first time at LBL)
- Constant-area “taper”
- Output stages on 300 μm pitch
- LDRD version: 480 x 480
- 30 μm pixels

Readout ASIC - 2006 (LDRD)
- 16 channels
- 300 μm pitch
- 15 bit dynamic range
- Correlated Double Sampling
- 1 MHz/channel
- > 200 frame/sec
FastCCD - 2nd ½ of 2008: Integrate and Characterize

Characterize on 5.3.1

Calibrate with fluorescence photons. 200 μm thick, but E > 10 keV certainly detectable (ε < 1)

Initial single γ energy resolution
FastCCD - 1st ½ of 2009: First tests at APS and ALS

Argonne - January 2009
๏ Jan ’09 x-ray tube (lab) tests at ANL
๏ Jul ’09 1st beam at 8-ID
๏ Nov ’09 2nd beam at 8-ID

Berkeley - May 2009
๏ FastCCD on micro-diffraction BL 12.3.2
Microdiffraction - Today and Tomorrow

X-ray CCD camera

KB optics

Sample on x-y stage

Monochromatic or white light

Example: solder grain

2.7 min. with FastCCD (at 20 Hz - disk write limited for this test)
6.2 hrs. with MAR133

3 orders of magnitude increase in speed at 200 fps

Nobumichi Tamura, Martin Kunz, Kai Chen, Rich S. Celestre, Dionisio Doering, Tae Sung Kim, Peter Denes, Patric Gruber, Andy Minor, Daniel Kiener
Soldering ... an example

Tin melting ~232 C
Sudden grain rotation and splitting before melt?
Fast Energy-resolved Laue Diffraction

- FastCCD at high readout rate → single photon counting (spectroscopy)
- Fast alternative to monochromator energy scan
- Promising - larger detector area needed

Potassium Titanyl Phosphate KTiOPO$_4$ (or KTP)
Diffractive Imaging, Holography and Ptychography on BL 9.0.1

Stefano Marchesini and a cast of thousands
Scanning Diffractive Imaging

Plan

Beam
Energy: 750 eV
$\lambda=1.65$ nm
$E/\Delta E=500$;

Pinhole: D=6 $\mu$m wide, 2 $\mu$m thick Au
Distance Pinhole-ZP $D_{pz}$: ~1 m
Beam size (to first min): 670 $\mu$m
Scanning Diffractive Imaging

T. Warwick

Beam
Energy: 750 eV
\( \lambda = 1.65 \text{ nm} \)
\( E/\Delta E = 500 \);

Pinhole: D=6 \( \mu \text{m} \) wide, 2 \( \mu \text{m} \) thick Au
Distance Pinhole–ZP \( D_{pz} \): ~1 m
Beam size (to first min): 670 \( \mu \text{m} \)
Ptychography

Energy: = 750 eV
Focus = 300 nm
Flux (phot/s) = 4 \times 10^7
Oversampling = x 9.6
max resolution = 9 nm

10 nm should be possible in near future

03/2009 Draft

08/2009 Deploy

08/2009 Measure
Prototype FCCD at APS
Prototype (front-illuminated)
Final mechanical / thermal verification

- cFCCD for LCLS Hutch 2 (delivery early 2010)
- cFCCD for BL 9.0.1
- cFCCDs with new devices
Continued (New) CCD LDRD

FY09 LDRD Wafer 
*In fabrication now*

New Output stages 
Version with a hole 
1k Frame store

New Output stages 
Version with a hole 
1k Frame store
LSST-like Prototype

2k x 3k x 10.5 μm pixels
ARRA-funded FastCCDs

- 8 systems
- 2009 workshop:
  - 1k Frame Store
  - “hole” option
- ATCA-based DAQ
- Delivered in 2 yrs.

**Advanced Light Source Accelerator Improvement and Equipment**

Berkeley Lab’s Advanced Light Source (ALS) is receiving $11.3 million to help it maintain its position as one of the world’s premier soft x-ray light sources. The ALS is a national user facility serving more than 1,900 scientists annually doing research in a wide variety of fields, from biology and earth science to the study of optics and semiconductors; they use the light sources to examine structures on the atomic and molecular level.

First, the ALS will receive $5.8 million to acquire sextupole magnets to increase brightness by a factor of two to three, keeping the ALS at the cutting edge of soft x-ray science. Second, ALS will receive $2 million to construct and install an elliptically polarizing undulator to provide a new x-ray source for the femtosecond soft x-ray beamline 6.0-2, effectively doubling the capacity of this facility by enabling soft and hard x-ray branchlines to operate simultaneously. This will allow new research on complex materials, such as superconductors, nanostructures, and transition-metal oxides.

Third, ALS will receive $2 million to equip its beamlines with advanced CCD-based detectors developed at the ALS to enhance the reach and productivity of the beamlines. Lastly, ALS will receive $1.5 million to develop a unique superconducting magnet for a beamline, allowing experiments leading to novel insights into the magnetic structure of engineered magnetic nanostructures and materials not accessible by any other technique.
Needs Addressed with ARRA FastCCDs

STXM

μXRF, μXRD, μXAS

Ptychography

Scanning μDiffraction

Photon in / photon out

Photoemission (phosphor)

XPCS

High Pressure Melting

Tomography
Next Steps - CCDs

- Original idea: biggest bang/$ - improve CCD readout
  - Faster readout, but with no degradation of performance
  - Wide dynamic range
  - **FastCCD** - 100 X faster (because 100 X more parallel)

- Learned in the meantime
  - **Direct detection** enables spectroscopy
  - *Really* want to detect single photons
  - Lower dynamic range (but good SNR) higher speed

FastCCD = (a)CP-CCD

VeryFastCCD =
  - CP-CCD (metal strapped, so 25 - 30 μm pitch)
  - Faster ADC

- Go from 100 fps to 10,000 fps
  - Requires development of DAQ and firmware processing
  - In progress now
Direct detection – R&D

Reminder - p-i-n diode detector

Photo-conversion

\[ \Rightarrow \text{photon penetrates entrance window} \]
\[ \Rightarrow \text{photon is absorbed in depth } T \]

\[ N_Q = \frac{E_Y}{\varepsilon} \]
\[ \sigma^2_N = F \cdot \frac{E_Y}{\varepsilon}, \ F=Fano \ factor \]

<table>
<thead>
<tr>
<th>Material</th>
<th>Si</th>
<th>Ge</th>
<th>GaAs</th>
<th>Diamond</th>
</tr>
</thead>
<tbody>
<tr>
<td>\varepsilon [eV]</td>
<td>3.6</td>
<td>3.0</td>
<td>4.4</td>
<td>13.1</td>
</tr>
<tr>
<td>F</td>
<td>0.12</td>
<td>0.13</td>
<td>0.10</td>
<td>0.08</td>
</tr>
<tr>
<td>\rho [g/cm^3]</td>
<td>2.3</td>
<td>5.3</td>
<td>5.3</td>
<td>3.5</td>
</tr>
<tr>
<td>95% @ 8 keV</td>
<td>200 µm</td>
<td>85 µm</td>
<td>85 µm</td>
<td>3 mm</td>
</tr>
</tbody>
</table>

Si ideal for most of ALS
Good Stuff!

X-ray absorption in 300 μm of Silicon with native oxide
Importance of Depletion

**Fully depleted detector**
- No recombination
- Charge drifts to collection electrode
- PSF $= 0$

**Undepleted detector**
- Diffusion + recombination
- Bad PSF

**Partially depleted detector**
- All effects
- PSF and charge collection depend on site of photoconversion

**Charge collection**
- drift - all charge drifts directly towards anode
- diffusion - charge goes into $4\pi$
- recombination - no charge collected
Entrance Window

X-ray absorption in thin windows

Minimize this dead space for soft x-rays

SNAP (optical) CCD

Thinned, back-illuminated CCD: laser annealed, partially depleted
Thick, back-illuminated fully depleted detector: thin contact needed
Low Temperature Window Process

- LBNL ISDP (S. Holland) - high temperature
- R&D - LBNL Low T. (C. Tindall) - just below* Al melting (*sometimes!)
- R&D - JPL (S. Nikzad) δ-doping

Measurements on pin diode
Successfully implanted SOI

- SIMS data for the implanted contact on PIN diodes after annealing @ 500°C
- Expect detection threshold of 500 eV for 0.1 μm thick contact
The Problem with Pixels

Need to connect

Old Fashioned Solution
Monolithic detectors based on CMOS: CCDs

CCD Pixel IQ: 0

Current Solution
Bump-bonded hybrid pixels

Hybrid Pixel IQ: High
Silicon-on-Insulator

Channel Length \( L/k \)

Conventional SOI to reduce capacitance to substrate

Attempt at the “lab” level:
- High resistivity substrate
- Contact/implant through BOX

IBM 0.18 μm SOI CMOS

BOX (SiO₂)
Silicon-on-Insulator

50 nm CMOS / DI
200 nm SiO₂
200 μm high ρ Si

International collaboration
- Started in context of ILC
- Led by KEK, using Oki

CMOS on thick, fully-depleted, high-resistivity, detector-grade silicon
SOI R&D

- LDRD-supported for ILC FY05-07
  - US/Japan funds
  - Analog and digital pixels
- BES detector R&D for xrays
- Start testing on 5.3.1
- femtoPix
SOI (in the ILC Context) Demonstrates 1 \( \mu \text{m} \) Resolution

Scan with laser
vary power to simulate different S/N
cross-check with e\(^{-}\) beam
Issues

Still an “R&D” process

Back-gating:
Channel sees gate and back-gate potential

Solutions:
Design improvements
Light p-spray

BOX poses radiation hardenss challenges

1st SOI Chip
Recent Results

- SOImager
- Thinned to 50 μm
- LBNL low-temperature implant (C. Tindall)
- δ-doping next

![SOImager Image]

![Graphs showing signal vs. Vdep for different Vdep values]
femtosecond Beamlines 6.0.1/2

An Example

- 4 kHz femtosecond laser system
- In-Vacuum Undulator
- Hard x-ray branchline (2-8 keV)
- Soft x-ray branchline (200 - 1800 eV)
- Hard x-ray hutch
- Crystal monochromator
- Soft x-ray monochromator

200 fs pulses
But low flux - $10^5 \gamma/s/0.1\%$ BW

Millions of dollars invested
- in hardware
- in time to make this work

Detector used for last decade

Perkin Elmer C30902: single element APD, $100
**femtoPix**

A pixel

- **4,000 frames / sec.**
  - 2 kHz laser on
  - 2 kHz laser off
- **CDS**
- **Firmware processing**
- **Submission Jan. ’10**

17.5 μm pixel
World's 1st 3D SOI in 3D process now
**Monolithic Detectors for Electron Microscopy**

- **TEAM 1K**
  - 400 frame/s
  - 9.5 μm pixels
  - 0.35 μm CMOS
  - Single e⁻ S/N ~15

- **Silicon dumbbells**
  - single 2.5 ms exposure

- **6 e⁻**

---

- National Center for Electron Microscopy
- Advanced Light Source
- The Molecular Foundry
Boron Nitride (a la Graphene)

Individual 2.5 ms exposures

Summed
Next Steps (e−)

TEAM 2K
- 100/400 frame/s
- 9.5 μm pixels
- 0.35 μm CMOS
- Reticle Scale

HHMI
- 5 μm pixels
- 0.18 μm CMOS

R&D - SOI for low voltage EM
(LEEM, PEEM, SPLEEM, LVTEM, ...)

May '09

Sep '09
R&D Directions (1)

**Dumb detector**
- Today: $10^2$ Hz
- Soon: $10^3.5$ Hz
- Tomorrow: $10^5$ Hz

**Clever detector**
- Soon: FPGA

**Brilliant detector**
- Tomorrow: FPGA -> GPU
- Future: FPGA -> GPU

Archival Storage
Current and Future Light Sources

ALS Today
ALS with sextupoles
ALS “ultimate”

NGLS

FLASH
LCLS

NSLS-II

NGLS

FLASH
LCLS
Next Generation Light Source

<table>
<thead>
<tr>
<th>Beamlines</th>
<th>BL 1</th>
<th>BL 2</th>
<th>BL 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>chicaned and seeded radiators</td>
<td>seeded, time-bandwidth limited</td>
<td>SASE</td>
</tr>
<tr>
<td>Feature</td>
<td>x-ray pump / x-ray probe with fs resolution</td>
<td>pump/probe with adjustable delay (THz - UV pump)</td>
<td>potential for seeding</td>
</tr>
<tr>
<td>Pulse Duration</td>
<td>250 as - 25 fs</td>
<td>250 as - 50 fs</td>
<td>1 - 50 fs</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>10 - 100 kHz</td>
<td>10 - 100 kHz</td>
<td>≤ 1 MHz</td>
</tr>
<tr>
<td>Peak Power</td>
<td>10 - 100 MW</td>
<td>1 GW</td>
<td>1 GW</td>
</tr>
<tr>
<td>R&amp;D Options</td>
<td>EEHG HHG option</td>
<td>EEHG HHG option</td>
<td>≫1 MHz</td>
</tr>
</tbody>
</table>

Science

<table>
<thead>
<tr>
<th>BL 1</th>
<th>BL 2</th>
<th>BL 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>multidimensional spectroscopy</td>
<td>ultrafast dynamics</td>
<td>inelastic and coherent scattering</td>
</tr>
<tr>
<td>x-ray pump / x-ray probe</td>
<td>inelastic scattering</td>
<td>diffractive imaging</td>
</tr>
<tr>
<td>species-selective intramolecular dynamics</td>
<td>species-selective tomography</td>
<td></td>
</tr>
</tbody>
</table>

High rep-rate source 2.5 GeV SC CW LINAC
(My) Ideal Soft X-ray Detector

In 10 years, $10^5$ fps

- Monolithic
- (or µ-bump) (?)
- Ever more processing
- Stitched (?)

- Radiation hardness
- Entrance window
- SNR
- Speed

- UHV

Missing (but needed)
- Z (hard x-rays)
- Radiation hardness
- Spectroscopy
- Large area
- ...

Thin Window

50 µm Si

Gain
Questions?

Grateful acknowledgements to:
ALS Experimental Systems Group
ALS Scientific Systems Group
APS Beamline Technical Support Group
Electronic Systems Group
Integrated Circuit Design Group
MicroSystems Laboratory
National Center for Electron Microscopy
Physics Division
Engineering Division