Soft X-ray Detector Developments at Berkeley
Motivation and Activities

- **Soft X-ray light sources at Berkeley (Today: ALS, Tomorrow: NGLS)**
- Direct soft X-ray detection - Charge Coupled Devices
  - Emphasis on speed or special properties
- Specialized processing for soft X-ray detectors
  - Thin entrance windows, thinned sensors, laser machining, ...
- Other technologies - e.g. Silicon-on-Insulator, CMOS APS, ...
- Data reduction and processing

- High repetition rate ($\geq$ MHz)
- Tunability
- Coherence
- Seeded operation

~250 - 1,250 eV (fundamental)

**CW FEL Array**

ALS

NGLS
X-ray Detection in Silicon

- High efficiency up to ~8 keV X-rays
- Readout noise limited for soft X-rays

Absorption and Transmission as functions of energy and thickness for different materials (Si, Ge, GaAs).

Energy [eV]

- 100 nm, 50 nm, 10 nm

Absorption/
Transmission
LBNL CCD

- 3-phase CCD structure
- Poly gate electrodes
- Buried p-channel
- Transparent rear window

At $V_{\text{SUB}} = 115$ V, $\sigma_D = 3.7 \pm 0.2$ µm

- Thick (up to 650 µm) high-resistivity Si
- Fully depleted
- Direct X-ray detection

- n-type (p-channel) for enhanced radiation resistance
Soft X-rays - t not T

- Fully-depleted detector needs
- High resistivity bulk
- (thin) conductive contact
- Back illuminated

- Want low temperature implant
  - < melting point of Al interconnect
  - Process (e.g. CMOS)
  - Thin
  - Implant

![Graph showing energy vs. thickness for 90% QE](image-url)
# Low Temperature Thin Contact Development

<table>
<thead>
<tr>
<th>Process</th>
<th>Window thickness</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low energy implantation + 500 C annealing</td>
<td>1,000-2,000 Å</td>
<td>Process dependent, several SOI prototypes functional</td>
</tr>
<tr>
<td>Low energy implantation + laser annealing</td>
<td>400-700 Å</td>
<td>Several SOI prototypes functional after processing</td>
</tr>
<tr>
<td>a-Si contact deposition by sputtering</td>
<td>300 Å</td>
<td>Prototypes functional after processing, high leakage</td>
</tr>
<tr>
<td>In-situ doped poly (ISDP)</td>
<td>100-200 Å</td>
<td>Standard MSL process - high temperature process</td>
</tr>
<tr>
<td>Molecular Beam Epitaxy</td>
<td>50-75 Å</td>
<td>Developing in-house capability - R&amp;D</td>
</tr>
</tbody>
</table>

## Example
- **50 µm thick SOI**
- **850 nm laser**
CCDs

- Original integrated circuit scientific imager
- Noiseless, lossless charge transfer
- (Relatively) Large conversion gain with low $C_{FD}$, $\Delta V = q/C_{FD}$
- (Relatively) Low noise [CDS]
- Large area (wafer scale), small pixel devices possible
- But slow (parallel exposure, serial readout)
CCDs are Wonderful

But they are slow:
Parallel exposure
Serial readout

Solution:
Parallel readout
Conventional → (almost) Column-Parallel CCD

- (a) CP-CCD allows:
  - keeping Source Follower
  - wire bonding (pitch)
- Need to fit multiple transistors
- Conventionally, “outside” of imaging footprint
- Where to put these transistors?
(almost) Column-Parallel CCD

- Prototype: 480 x 480, 30 μm pixels → 96 outputs
- Constant area taper
- Metal strapping
- 300 μm output pad pitch

2006/7
16-Channel Custom Readout IC

Preamp  Multi-Gain Integrator  CDS  Pipelined ADC

- Gain 8, 2, 1
- 12+1 bit ADC
- Covers 15 bit range
- 300 μm input pad pitch

0.25 μm CMOS - 2006
FastCCD 1.0 - 1st Demonstrations

Techniques enabled or enhanced
Microdiffraction - Today and Tomorrow - ALS BL 12.3.2

X-ray CCD camera

FastCCD Example: solder grain

KB optics

Sample on x-y stage

Monochromatic or white light

6.2 hrs. with conventional phosphor/CCD detector

3 orders of magnitude increase in speed at 200 fps

Tin melting ~232 C
Sudden grain rotation and splitting before melt?

Nobumichi Tamura, Martin Kunz, Kai Chen, Rich S. Celestre, Dionisio Doering, Tae Sung Kim, Peter Denes, Patric Gruber, Andy Minor, Daniel Kiener
Fast Energy-resolved Laue Diffraction

- FastCCD at high readout rate → single photon counting (spectroscopy)
- Heterogeneous samples
- Fast alternative to monochromator energy scan

Potassium Titanyl Phosphate KTiOPO$_4$ (or KTP)

![Image of a diffraction pattern with labeled energy levels and intensity graphs.](image-url)
Soft X-ray Ptychography - ALS BL 9

- Implemented ptychography at 750 eV
- Wet cell
- $2 \times 10^3$ photons/(10 nm)$^3$/second
- 50 MB/second 4 TB/day

(N. Huse, LBL-UXSL)

Scanning Diffraction

D. Doering et al. SRI2012 P. Denes
Nanosurveyor - COSMIC

Last week:
ALS BL 5.3.2 STXM
Photon Correlation Spectroscopy - APS BL 8-ID

XPCS Example – 71nm radius latex spheres in glycerol at ~-20 deg C
(Data courtesy of Suresh Narayanan and Alec Sandy)
RSXS system for ALS/LCLS

- 360 degrees rotation in horizontal scattering plane
- 90 degrees rotation in vertical scattering plane
- -30 degrees operating temperature (water cooling)
- ~480X480, 30μm square pixels
- 200fps (max) readout
Time Evolution of Charge / Spin Ordering

Qulify samples on ALS BL 8.0
cFCCD - RSXS Endstation

1st light - Jul. 2010

Ship to SLAC June 17th 2010
Spin Ordering (SO) – The Movie

Fast melting and slow recovery of spin ordering around 50K
(shot-by-shot readout to correct time jitter and intensity fluctuation)

Aug. 2010 - 28 mJ/cm²
FastCCD 2.0 - 1k Frame Store

- 1,920 x 960 30 µm pixels
- Can operate as 2k CCD
- Or 1k CCD with electronic shutter

- 200 fps
- <500 µs shutter
1K Frame Store FastCCD Systems
~dozen systems for ALS and APS (XFEL, LCLS and NSLS-I/II)

- Improved readout chip – fCRIC2
- New buffer chip – for higher speed

J. Joseph, P. McVittie et al.
Performance (ALS BL 5.3.1)

Cu fluorescence

\[ K_{\alpha} \quad 8.05 \text{ keV} \]
\[ K_{\beta} \quad 8.91 \text{ keV} \]

Peak position vs X-ray energy

\( \sim 22 \text{ eV/ADU} \)

Noise distribution:
\( <\text{Noise}> = 90 \text{ eV} \)
(25 electrons)

T = -50°C, exposure time = 20 ms, \( V_{\text{SUB}} = 50 \text{ V} \).
All spectra for single pixel events
Evolution of CCD Readout

Conventional CCD

<table>
<thead>
<tr>
<th>4-port</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial readout</td>
</tr>
<tr>
<td>$10^0$ fps</td>
</tr>
</tbody>
</table>

- Slow $V_{\text{CLOCK}}$
- Fast $H_{\text{CLOCK}}$
- Fast ADC
- Multi-stage CCD output

or
Evolution of CCD Readout - (a)CP-CCD

- Slow $V_{CLOCK}$
- Fast $H_{CLOCK}$
- Fast ADC (ASIC)
- Single-stage output

FastCCD
(almost)Column Parallel

$f^{CRIC}$ (custom 0.25 µm CMOS readout IC)

$10^2$ fps

Buffered output
$t_R \sim 100 \text{ ns} \rightarrow \sim \text{ns}$

Gain $\sim 30\%$ signal

16-channel buffer chip
chip-to-chip wirebond

0.35 µm HVCMOS - 2011

B. Zheng et al.  SRI2012 P. Denes
Challenge: Fast $V_{\text{CLOCK}}$ with reasonable power

Highly parallel digitizers

Very Fast CCD
Column Parallel
HIPPO (custom 65 nm CMOS readout IC)
>$10^{3-4}$ fps

Fast $V_{\text{CLOCK}}$
Faster $H_{\text{CLOCK}}$
Faster ADC (ASIC)
No SF Output

“$\triangle$” $\Leftarrow$ G $< 1$
RESET
VFCCD - CCD

- 50 μm pitch for chip-to-chip wire bonding
- Aim for 10,000 MPix / s
HIPPO: High-Speed Image Pre-Processor with Oversampling

1 4-Channel Cell...

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Value</th>
<th>Units</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>12</td>
<td>Bits</td>
<td></td>
</tr>
<tr>
<td>Sampling Rate</td>
<td>80</td>
<td>MS/s</td>
<td></td>
</tr>
<tr>
<td>Full Scale</td>
<td>1</td>
<td>Volts</td>
<td>$V_{pp}$-differential</td>
</tr>
<tr>
<td>Noise (ADC)</td>
<td>200</td>
<td>μV-rms</td>
<td>LSB is 250 μV</td>
</tr>
<tr>
<td>Noise (Full)</td>
<td>1.4</td>
<td>LSB</td>
<td></td>
</tr>
<tr>
<td>Linearity</td>
<td>10</td>
<td>Bits</td>
<td>Differential</td>
</tr>
<tr>
<td>Circuit Pitch</td>
<td>50</td>
<td>μm</td>
<td>match CCD</td>
</tr>
<tr>
<td>Serial Output</td>
<td>480</td>
<td>Mb/s</td>
<td>dual data rate</td>
</tr>
</tbody>
</table>

10 MHz x 4 (40 MHz) + CDS (80 MHz)

65 nm CMOS - 2011
**Fine-pitch CCD for Spectroscopy**

"Conventional" 4-port CCD

- Anticipate <4 e− noise can be obtained at 50 - 100 kHz readout
  - $2880 \times 640 = 1.8 \times 10^6$ pixels
  - 4 ports $\rightarrow$ $4.6 \times 10^5$ pixels / port
  - $\sim5$ (10) second readout at 100 (50) kHz
Summary

- Fully-depleted, thick CCDs as X-ray detectors
  - Obtain speed by parallelism
- Thin contacts required
  - Low temperature process required post metalization

Other monolithic structures we work on:
- Bulk CMOS APS (thinned, implanted) for SXR
- Silicon-On-Insulator

Data volumes will grow immensely
- Eu XFEL, NGLS, further developments at storage rings
- Compression and “pre-analysis” becoming part of detector development
Who:
Technical Staff: J. Bell, J. Eames, B. Holmes, J. Stirklunen, R. Witharr, G. Zizka

Students: H. Bovenzi, S. Facchinetti, TS Kim, B. Niasari, S. Schindler, B. Zheng

Together with:
ALS Experimental Systems Group
ALS Scientific Support Group
APS Beamline Technical Support Group
National Center for Electron Microscopy

Engineering Division
Electronic Systems Group
Integrated Circuit Design Group
Microsystems Laboratory
Physics Division