Novel multi-channel skipper-CCD packages for the OSCURA† experiment

Ana Martina Botti* and Claudio Chavez
CPAD Workshop 2022
Nov 29 - Dec 2, 2022

* Fermi National Accelerator Laboratory · abotti@fnal.gov
† Observatory of Skipper CCDs Unveiling Recoiling Atoms · https://astro.fnal.gov/science/dark-matter/oscura/
Dark-matter direct detection

- **Weakly interacting massive particles:**
  - Favoured by ΛCDM
  - Experimentally accessible

- **Light dark matter:**
  - New theoretical models
  - New enabling technologies (semiconductors, cryogenics, noble gases, etc)

- **Search for sub-GeV dark matter in Silicon:**
  - e- recoils
  - Nuclear recoils
  - Absorption
Light dark matter in Silicon

Light-DM mass range:
- 1-1000 MeV for e\(^{-}\) recoil
- 1\(\sim\)1000 eV for absorption
- 0.5\(\sim\)1000 MeV Nucleus recoil (Migdal effect)

Sensitivity to 1,2,3 e\(^{-}\) signals needed: Skippers-CCD can do this!

Expected spectrum from benchmark models (e\(^{-}\) recoil)

R. Essig et al, JHEP 05 (2016), 046
First Skipper-CCD prototypes

- New generation Charge Coupled Devices (CCD)
- Readout noise ~ 0.1 e⁻
- Energy threshold ~1.1 eV (Si bandgap)
- Designed at LBNL MSL
- Parasitic run, optic coating and Si resistivity ~10kΩ

Instrument:
- System integration done at Fermilab
- Custom cold electronics
- Firmware and image processing software
- Optimization of operation parameters

Charge-coupled devices (CCD)

Main goals
- First DM detector with Skipper-CCDs
- Validate technology for DM and ν detection
- Probe DM masses at the MeV scale (e - recoil)
- Probe axion and hidden-photon DM masses > 1 eV (absorption)

DM-Nucleus scattering
DM-electron scattering

Channel stops
Vertical clocks
Horizontal clocks
Serial register
Sense node
Skipper CCD read-out

1. **pedestal** integration.
2. **signal** integration.
3. **charge** = **signal** – **pedestal**.
4. **Repeat** N times.
5. **Average** all samples.

Then, both high- and low-frequency noise is reduced.
Skipper-CCD read-out noise

Standard CCD mode: charge in each pixel is measured once

New Skipper CCD: charge in each pixel is measured multiple times

Readout-noise: 3.5 e RMS

Readout-noise: 0.06 e RMS
Perspectives: skipper CCDs and Dark Matter

SENSEI 100g (5 dru)  DAMIC-M 1kg (0.1 dru)  OSCURA 10kg (0.01 dru)

2021  2024  2027

Many challenges to scale the mass and reduce the background in two order of magnitude!

The Oscura Experiment
arXiv: 2202.10518
Chavarria (arXiv:2210.05661)
OSCURA Collaborators

New generation Charge Couple Devices (CCD) at LBNL MicroSystems Lab

Energy threshold ~ 1.1 eV (Si bandgap) and readout noise ~ 0.1 e

Main goals:
- First DM detector with Skipper-CCDs
- Validate technology for DM and ν detection
- Probe DM masses at the MeV scale (e - recoil)
- Probe axion and hidden-photon DM masses > 1 eV (absorption)
OSCURA package

10 kg skipper-CCDs:
- 24000 channels/devices (28 GPix)
- 1500 multi-chip modules (MCM) with 16 CCDs each
- 94 super modules with 16 MCMs each

Read-out:
- High-density package (This talk)
- Multiplexer + SENSEI electronics (see C. Chavez’s talk)
- ASICs (see T. England talk)

Background goal (0.01 dru):
- Silicon based pitch adapter (This talk)
- Aluminum shielding (This talk)
- Low-background materials

C. Chavez et al. Sensors 22 (2022) 11, 4308
F. Chierchie et al. arXiv:2210.16418
1st silicon prototypes

User proposal approved at Argonne National Laboratory

Based on SENSEI pitch adapters (at PNF/Chicago):
- 675 um hires 6 in Si substrate
- 500 nm SiOx insulation
- 500 nm Al circuit
- 500 nm SiO2 passivation

Image: SENSEI detector and pitch adapters produced at PNF

Silicon fabrication at ANL

Insulation layer:
➔ AJA dielectric sputtering system at 400°C
➔ 390 nm SiO₂

Aluminum layer:
➔ AJA Metal sputtering system
➔ 480 um Al on SiO₂
➔ 1um SPR-955 + Heidelberg MLA 150
➔ CD-26 developer + Al Type-A wet etcher

Passivation layer:
➔ AJA dielectric sputtering system at 275°C
➔ 390 nm SiO₂
➔ Oxford Plasmalab 100 dry etching
➔ e3511 ESI Plasma Asher (EOP)
Assembly and first tests

Tools developed for assembly and testing at FNAL

Assembly Process:
- Glue flex cable with laminate
- Glue CCDs with EPoxy
- Wire bonds

Testing:
- Electrical (shorts and impedance)
- Reverse bias
- Cold (with multiplexed read-out electronics)
Issues and outlook

Clock coupling in video out
➔ Thicker insulation seems to help

Long recovery time
➔ Reduce resistivity
➔ Reduce capacitance

Next steps
➔ Thicker SiO2
➔ Thicker metal (Al/Au)
➔ Intrinsic Si
➔ Change design rules
CCD aluminum shielding

Cooling down
  ➔ CCDs in LN2
  ➔ LN2 scintillates
  ➔ Cherenkov

Imagine throwing the CCD in a Cherenkov tank!

Image: CERN courier (The Pierre Auger Observatory)
CCD aluminum shielding

Lift-off process at ANL:
- 1um SPR-955 + Heidelberg MLA 150
- Temescal FC2000 E-Beam Evaporator
- 50 nm Al + 1165 remover

Testing:
- Expose to LED
- Expose to environmental radiation
- Some things to understand (but success in 1st try!)

Next steps:
- Extra cleaning
- Try different thickness
- Test with different wavelengths

Very important step for X-ray detection with skipper-CCDs!
Summary

- **OSCURA**: 10 kg skipper-CCD for light dark matter detection; major effort from most institutions working with skipper-CCDs
- Background goal of **0.01 dru** is the main challenge
- **24000** read-out channels/devices
- First high-density package achieved (working ceramic version). First **Silicon** prototypes produced at **ANL**
- Great improvement in first two versions

- Signal coupling and recovery time needs to be improved (**clear plans on how to**)
- Further prototypes at **ANL** (and probably **PNF**)
- Preliminary engagement with **production facility** to process **1500** wafers
- First production of CCDs with **Aluminum shielding** at ANL. First tests were **successful** (more are coming)
- Al shielding opens a door for **X-ray detection** with skipper CCDs (beyond OSCURA)
Backup slides
Skipper-CCD read-out noise

![Graph showing the relationship between empty pixels distribution and RO time per pixel.](image1)

![Image showing a data point with annotations: "empty pixels", "muon", and "X-ray").](image2)
Skipper-CCD resolution

(Almost) Empty CCD

Front-illuminated CCD
Skipper-CCD for photo detection

D. Rodrigues et al., NIMA A 1010 165511

Charge per event for 55Fe x-ray source

Compton scattering spectrum in Silicon with 241Am γ-ray source
Setup @ MINOS

- 230 m.w.e.
- Previous vessel + extra shielding
- T ~ 135 K + vacuum
- LTA board
Skipper CCD read-out

Multiple sampling of same pixel without corrupting the charge packet.
Pixel value = average of all samples
Suggested in 1990 by Janesick et al. (doi:10.1117/12.19452)
Background sources: detector

Exposure dependent
- Dark current ($10^{-5} \text{ e}^-/\text{pix/day}$ at 135 K)
- Amplifier light ($10^{-1}$ to $10^{-5} \text{ e}^-/\text{pix/day}$)

Exposure independent
- Spurious charge ($10^{-2}$ to $10^{-5} \text{ e}^-/\text{pix/image}$)

Single electron rate reduced by optimizing operation parameters
- Read-out mode: continuous vs expose
- Voltage configuration
- Amplifier off while exposure

Background sources: environment

High-energy:
- Air shower muons
- Nuclear decays
- x/γ-rays

Low-energy:
- IR photons
- Halo and transfer inefficiency
- Compton scattering
- Charge collection inefficiency
Background goal

DC (e-/pix/day)

- General purpose CCD setups. No IR cover. At sea level. Output transistor ON.
- SENSEI prototype surface run (low resistiv. Si) and CONNIE experiment (high resistiv. Si). ~ IR cover. At sea level. Output transistor ON.
- SENSEI prototype run (low resistiv. Si). ~ IR cover. At MINOS (100m underground).
- DAMIC experiment run (high resistiv. Si). ~ IR cover. At SNOLAB (2km underground). Output transistor ON.
- SENSEI expectation with high resistivity Si. IR cover. At SNOLAB (2km underground). Output transistor OFF.

Latest SENSEI published result: $1.6 \times 10^{-4}$ e-/pix/day

### Dark Current

<table>
<thead>
<tr>
<th>$[e^{-}\text{pix}^{-1}\text{day}^{-1}]$</th>
<th>$\geq 1e^{-}$</th>
<th>$\geq 2e^{-}$</th>
<th>$\geq 3e^{-}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-3}$</td>
<td>$1 \times 10^8$</td>
<td>$3 \times 10^3$</td>
<td>$7 \times 10^{-2}$</td>
</tr>
<tr>
<td>$10^{-5}$</td>
<td>$1 \times 10^6$</td>
<td>$3 \times 10^{-1}$</td>
<td>$7 \times 10^{-8}$</td>
</tr>
<tr>
<td>$10^{-7}$</td>
<td>$1 \times 10^4$</td>
<td>$3 \times 10^{-5}$</td>
<td>$7 \times 10^{-14}$</td>
</tr>
</tbody>
</table>

Background estimations for 1 year and 100 g.

**Blue:** discovery channel (background free)

**Red:** modulation or limits
### The Sensei Experiment

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td>Demonstrate sub-electron resolution</td>
<td></td>
</tr>
<tr>
<td>2018</td>
<td>DM search with proto-SENSEI (0.1 g) at surface</td>
<td></td>
</tr>
<tr>
<td>2019</td>
<td>DM search with proto-SENSEI at MINOS (230 m.w.e.)</td>
<td></td>
</tr>
<tr>
<td>2020</td>
<td>DM search with science grade (~2 g) at MINOS</td>
<td></td>
</tr>
<tr>
<td><strong>Ongoing</strong></td>
<td>Production (100g) + commissioning at SNOLAB (6000 m.w.e.)</td>
<td></td>
</tr>
</tbody>
</table>

**GUINEA PIG 2022 · Sep 8, 2022**
Summary: from prototype to science grade

Active mass ~ 0.1 g
0.019 gram-day exposure
0.14 e- RO noise
(800 samples)
SEE ~ 1.14 e-/pixel/day

Active mass ~ 0.1 g
0.069 gram-day exposure
0.14 e- RO noise
(800 samples)
SEE ~ 0.005 e-/pix/day

Active mass ~ 2 g
19.926 gram-day exposure
0.14 e- RO noise
(300 samples)
SEE ~ 1.6x10^-4 e-/pix/day
SENSEI @ SNOLAB

- Science-grade skipper-CCDs achieved
- Packaging and electronics also achieved
- Phase 1 system @ SNOLAB
- Vessel deployed at SNOLAB (during the pandemic!!!)
- First 10 CCDs deployed

Towards a 100 g skipper-CCD detector:
- Produce ~ 50 devices
- Packaging at Fermilab
- Testing
- Deliver and deploy at SNOLAB

→ 10000 dru (MINOS standard shield): proto-SENSEI
→ 3000 dru (MINOS extra shield): first science grade skipper
→ 5 (ultimate goal) dru (SNOLAB): SENSEI 100 g