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Novel multi-channel skipper-CCD packages for dark matter searches

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Ana Martina Botti[a,*] **and Claudio Chavez**[a]

[a] *Fermi National Accelerator Laboratory, PO Box 500, Batavia IL, 60510, USA*

E-mail: abotti@fnal.gov, cchavez@fnal.gov

The next generation of skipper Charge Coupled Device (skipper-CCD) experiments for rare-event searches will bring new challenges for the packaging and read-out of the detectors. Scaling the active mass and simultaneously reducing the experimental backgrounds in two orders of magnitude will require a novel high-density Silicon-based package, that must be massively produced and stored. In this work, we present the design, first production, and testing of multi-channel Silicon packages with photon shielding, along with the outlook for the next steps towards producing 1500 wafers that will add up to a 10 kg skipper-CCD detector.

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*Speaker

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1. Skipper-CCD for rare-event searches

Skipper-CCDs [1, 2] is a promising technology to exploit in rare events and new physics experiments where sensitivity to low-energy processes is required. However, several are the challenges to building a successful setup for this; controlling the environmental background has become one of the main difficulties in these experiments. The cosmic radiation leaves tracks in the CCDs that need to be removed from any analysis. Furthermore, when a high number of charges is transferred from a pixel to the serial register, electrons may get caught in silicon impurities or bleed to nearby pixels, and later on, be reconstructed as single- or few-electrons events. Even though this noise is distinguishable and is removed by rejecting areas in the CCD around high-energy events, it reduces drastically the active mass of the detector. In addition, environmental photons and electrons also leave signals in the CCD that maybe be similar to that expected from a dark-matter particle interaction. Deploying the setup in an underground facility is necessary to reduce the cosmic muon flux, and the implementation of copper, lead, and/or aluminum vessels helps to shield the CCD from the remaining environmental radiation.

Other sources of background are originated in the detector itself. The silicon thermal noise is the main theoretical contribution in this sense producing single-electron events. However, it may also produce two- and three-electron events as a result of the spatial pile-up of dark counts. We control this effect by cooling the detector down and reducing the exposure between reads. In addition, particle interaction in the partial charge collection layer [3] may also be a source of low-energy backgrounds. This layer consists of a volume in the silicon bulk where the dopant concentration is higher and, in turn, increases the recombination probability. This has been proved to be an important source of background in dark-matter experiments [4], and can be improved with a backside treatment to reduce the thickness of this layer.

The Sub-Electron-Noise Skipper-CCD Experimental Instrument (SENSEI) is the first experiment in implementing Skipper-CCDs for new physics searches. Using a prototype sensor with an active mass of about 0.1 g the SENSEI collaboration has been able to establish world-leading limits for dark matter in the sub-GeV mass region [5, 6]. These limits were significantly improved with a more recent run using a scientific grade CCD with about a 2 g active mass deployed underground with 230 m.w.e of overburden [7], and later on with the first science run at SNOLAB (6000 m.w.e.) using about 12 g of skipper-CCDs [8]. SENSEI is expected to reach an active mass of 100 g.

The Dark Matter in CCDs (DAMIC) experiment uses traditional CCDs with a resolution of about two electrons and an active mass of about 42 g to search for dark-matter interactions. The latest DAMIC results were obtained in a run of about 45 days with 6000 m.w.e of overburden producing leading limits in the MeV region [4, 9]. DAMIC(-M) is currently upgrading to skipper-CCDs and is expected to achieve a total active mass of 1 kg in the next three years [10]. In addition, the Observatory of Skipper CCDs Unveiling Recoiling Atoms (OSCURA) project, is developing a Skipper-CCD detector with a total mass of 10 kg to be comissioned by 2027 [11].

We show the expectations for the SENSEI final design (solid cyan line), DAMIC-M (solid red line), and OSCURA (solid blue line) in figure 1 for dark matter interacting through a light (left) and heavy (right) mediator, assuming a zero background for channels with two or more electrons. Current SENSEI results are shown in a cyan shade [5–7]; DAMIC at SNOLAB [9], XENON10, XENON100, XENON1T [12–14], DarkSide-50 [15], EDELWEISS [16], and SuperCDMS [17]

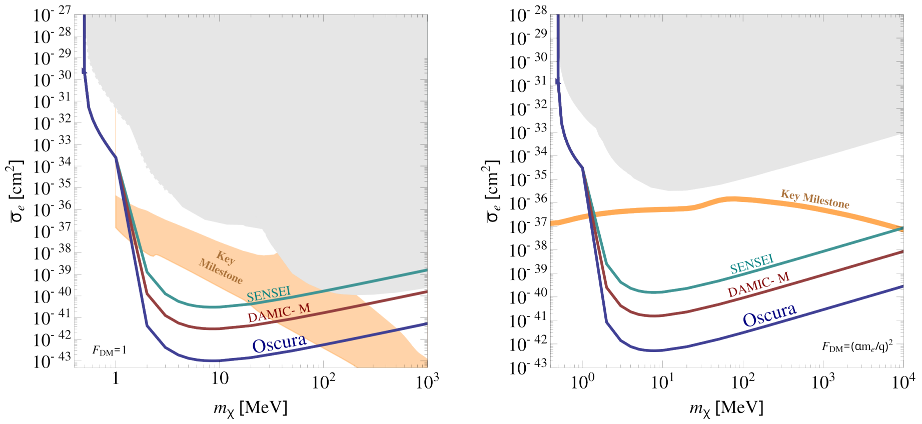

Figure 1: Projected sensitivities for SENSEI, DAMIC-M and OSCURA. The cyan shades represent the limits set by the SENSEI prototype, while the grade shades represent the limits set by DAMIC, XENON10, XENON100, XENON1T, DarkSide-50, EDELWEISS, and CDMS-HVeV. Figure adapted from [18].

results are shown in a gray shade. In orange, we present the theoretical milestone scenarios, which will be broadly explored with the next generation of Skipper-CCD detectors.

2. Low-background package for multi-kilogram experiments

The OSCURA experiment aims for a total sensitive mass of 10 kg. Given the typical pixel dimensions of a Skipper-CCD for dark-matter detection (15 µm × 15 µm × 675 µm) and assuming a Silicon density of 2.33 g / cm^3, OSCURA mass requirement translates into a total of 28 gigapixels. To reach its sensitivity goal, the experiment requires a background level below 0.01 dru. This is only possible if the background contribution of the radioactive material close to the sensor (such as those in the electronic components, flex cables, etc.) is understood and mitigated. Furthermore, to avoid single electrons from dark current (10^{-6} e^-/pix/day [18]) piling up into multiple-electron events that add to the dark-matter signal background, it is necessary to attain a maximum read-out time of 2 hr. Then, the detector can be operated with sub-electron resolution (read-out noise below 0.15 e^-) if segmented in 24000 channels. The CCD size and form factor are trade-offs defined by the fabrication yield criteria and the requirements previously described: a bigger sensor with a higher active volume and number of channels will be more likely to have a fabrication defect. We defined the CCD dimensions at 1278 × 1058 pixels, which gives a yield higher than 90%. We thoroughly discuss the requirements for the OSCURA experiment at [18].

We devised the CCD package to read 24000 channels, having one channel per sensor, in 2 hours with a read-out noise of about 0.15 e^- and a background goal of 0.01 dru. We present the high-density, multiple-channel and low-background packages in Fig. 2. The multi-chip module (MCM) is the basic unit of the OSCURA experiment. It consists of a 6" substrate (left panel) with traces that connect the CCD pads to a flex cable, and in turn, to the read-out electronics. Each module can accommodate 16 CCDs and a resistance temperature detector for temperature monitoring. On the top of the wafer, traces corresponding to the video outputs of each CCD and reverse bias voltage are located. At the bottom, the hubs to connect the remaining CCD pads are found. The clocks and operating voltages are shared within the 16 CCDs and distributed through one trace. On the right, we placed the pads to connect the flex cable (right panel) as far as possible from the CCDs, to avoid the radiation produced in the Kapton tape impinging on the sensors.

The purpose of the package is to ensure that only low-background silicon is located adjacent to the active volume of the CCD, with a small portion of the flex circuit meeting the necessary requirements determined from simulations. Both the flex circuit and the sensors are bonded to the carrier silicon wafer. For the Oscura experiment, a total of 1500 Multi-Chip Modules (MCMs) are required. Fig. 2 on the right illustrates the construction of a Super Module (SM) consisting of 16 MCMs, utilizing a support structure made of custom ultrapure electro-deposited copper. Additionally, the SM incorporates copper shielding to protect the sensors from radiation within the first few centimeters. To achieve an active mass of 10 kg, the OSCURA experiment requires 100 SMs, each of which will be processed with one channel of a low-threshold acquisition board [19]. To this aim, we implemented two steps of analog multiplexed electronics between the super module and the low-threshold acquisition board; we present the concept for the OSCURA read-out electronics in [20]. The analog multiplexing stages process the low-level video outputs from each CCD into a signal with a high signal-to-noise ratio that is then read with the low-threshold acquisition board.

Figure 2: (left) Design of the Multi Chip Module (MCM) with 16 sensors mounted on a 150 mm silicon wafer. (right) Super Module (SM) with 16 MCMs supported and shielded with electroformed copper. Picture extracted from from [11].

The most abundant material in the volume surrounding the sensors is that of the substrates, the closest objects to the CCDs. Since their contribution to the background radiation will be significant, it is of utmost importance to select an ultra-low-background material. High-resistivity Silicon, as used in the CCDs, is one of the first options to assure a low background. In addition, we build the Flex with the minimum amount of polyimide (Kapton) and with a single-layer circuit.

3. Fabrication of Silicon MCMs

The first production of silicon packages was performed at the Center for Nanoscale Materials at Argonne National Laboratory (ANL) through a user proposal; the fabrication processes and recipes definition was a joint effort between FNAL and ANL.

We performed the first tests using 6” ultra-high-resistivity Silicon wafers with 675 μm thickness produced by Topsil (model FZ-HPS/HiRES). To isolate the Silicon from the conductive metal, we deposit a 390 nm silicon dioxide (SiO_2) layer with about 4% uniformity using an AJA dielectric sputtering system operated at 400°C. We present a picture of the wafer after the SiO_2 deposition on the top left panel in Figure 3. For the next step, we used an AJA Metal sputtering system that allowed us to deposit a 450 nm Aluminum layer on top of the SiO_2. A picture of the wafer after the sputtering is shown on the top right panel in Figure 3. After baking the wafer for 5 minutes at 130° in an oven to release the moisture, we spun a 1 µm layer of SPR-955 photoresist and baked it for 2 minutes at 90 degrees on a hotplate. We then used a Heidelberg MLA 150 Maskless Lithography tool to expose the photoresist according to the MCM design. The exposition took about 30 minutes and a 50 seconds development using Microposit^{TM} MF^{TM}-CD-26 Developer followed. On the bottom left panel of Figure 3, we present a picture of the wafer with the patterned photoresist right after the development. Next, we wet etch the wafer using aluminum etchant type A at 40°C until the tracks appeared (about 2.5 minutes). As we display in the bottom right panel of Figure 3, the photoresists successfully protected the aluminum traces while the etchant removed the rest of the metal. We finally cleaned the remaining photoresists with Microposit^{TM} Remover 1165.

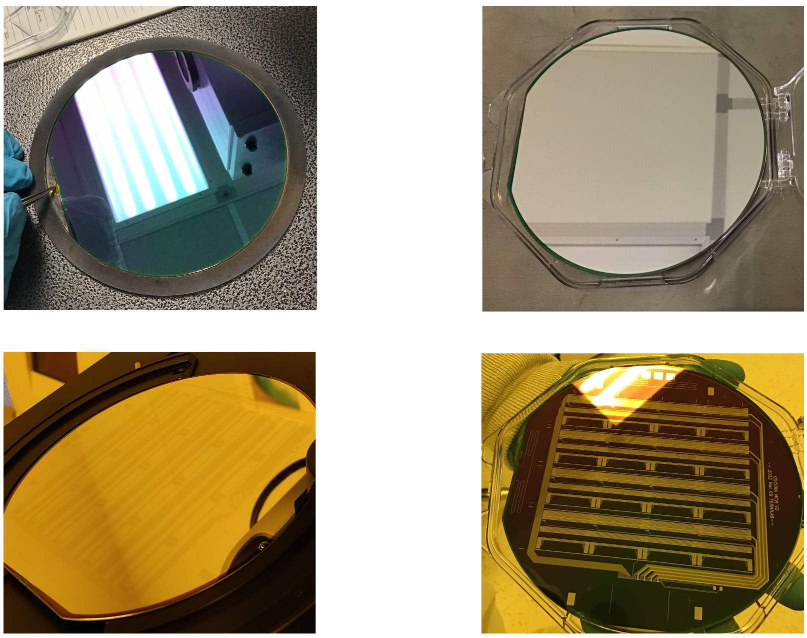

Figure 3: Pictures of the Silicon wafer after each step of production. (Top-left) SiO_2 deposition. (Top-right) Aluminum deposition. (Bottom-left) lithography and development. (Bottom-right) aluminum etching.

The second layer consisted of a SiO_2 coating that works as passivation to protect the aluminum tracks from scratches and prevent shorts during and after the assembly. This layer must have openings at the positions of the pads where the CCDs are connected. To this aim, we deposit a 490 nm SiO_2 layer using the AJA dielectric sputtering system operated at 275°C; because of the aluminum layer, we could not bake the wafer at a higher temperature. We performed an HMDS treatment to help the photoresist adhere to the SiO_2 and spun 1 µm of SPR-955. We proceeded with the lithography and development in the same way as for the aluminum layer. In this case, the design only included the positions of the pads for the openings. We then used a dry etching Oxford Plasmalab 100 tool to remove the SiO_2 from the pads, after which we removed the remaining photoresist with 1165. Finally, we used an e3511 ESI Plasma Asher to remove any residue.

Having the first wafers produced, we defined the assembly process at FNAL. The first step was to glue the flex cables that connect the silicon substrate pads to the readout electronics. To this aim, we design tools that allow us to hold the silicon wafer on a tray and then use alignments gadgets. The flex cable is manually placed using aligning plates to match it with the multi-chip module pads. Having the cable fixed we apply Pyralux® laminate at the end of the flex and hold it with the clamping bar to ensure that uniform pressure is applied. Then, we put the entire assembly setup inside an oven at 191°C for 3.5 hours. After that, we remove the fixture from the oven, uninstall the clamp, and check for proper gluing of the flex cable onto the Silicon substrate module.

The second assembly step is to glue the CCDs onto the silicon substrate. For this purpose, we designed a tool that allows the simultaneous placement of up to four CCDs. The CCD positioning tool consists of a hollow bar with four pockets and four valves to put and individually fix each CCD. To prevent the glue from flowing onto the wire-bond surface on the substrate pads, we use double-sided Kapton® tape, which we place on each of the CCD edges. As in the previous step, we fix the silicon substrate on the fixture plate by applying a vacuum. Then, we place the CCD bar on top of the wafer using one set of alignment pins; the assembly of the CCDs is performed from the devices near the cable and then proceeding outwards. Once the positioning bar is aligned, we apply a small force at each CCD so these are held in place by the double-sided tape. We release the vacuum on the positioning bar for all CCDs and lift the tool from the locating pins. This procedure is repeated for all four columns until the 16 CCDs are attached to the wafer with the double-side Kapton® tape. We then apply Epoxy (Master Bond EP30-2) under each of the CCDs, mid-way between the two tape locations. We wait at least 36 hours for the glue to cure. The package at this states, which consists of the Silicon substrate with the flex cable and 16 glued CCDs, is displayed on the left panel of Figure 4.

The final step in the assembly procedure consists of wire-bonding the pads inside the multi-chip module, and between the module and CCDs. To this aim, we use a Hesse Mechatronics BJ820 fully automatic fine wire wedge bonder, that allows us to connect the pads with 25 µm aluminum wires. A picture of connected pads inside the multi-chip module is presented in the middle panel of Figure 4. It is worth noting how the passivation layer on the silicon substrate is well aligned to the aluminum layer, as the pad openings appear as a thin line around the pad. For completeness, we show in the right panel of Figure 4 wire bonds between the CCD pads and the Silicon substrate. The CCD edge and the overflowed Epoxy can be seen.

4. Optical and infrared shield

As discussed above, the skipper-CCDs for Oscura will be operated in a LN2 pressure vessel. For a run on the surface and without any shield, we measure light generated in LN2 at a rate of $R_{LN2,1e^-} = 0.013\ e^-$/pix/day using a SENSEI skipper-CCD. For this measurement, the background around 10 keV was $\sim 10^4$ dru, six orders of magnitude above the Oscura background target of 0.01 dru. Assuming that light generation in LN2 scales with the background rate at higher energies, we estimate the light generated by LN2 in Oscura to be $R^{0.01\text{dru}}_{LN2,1e^-} \sim 10^{-8}\ e^-$/pix/day. This is below the expected thermal dark current in the Oscura sensors and it is not expected to contribute to the experimental background.

However, since the geometry and CCD packaging used to measure light generation in LN2 are not identical to the planned Oscura design, we are working to implement a light shield to ensure

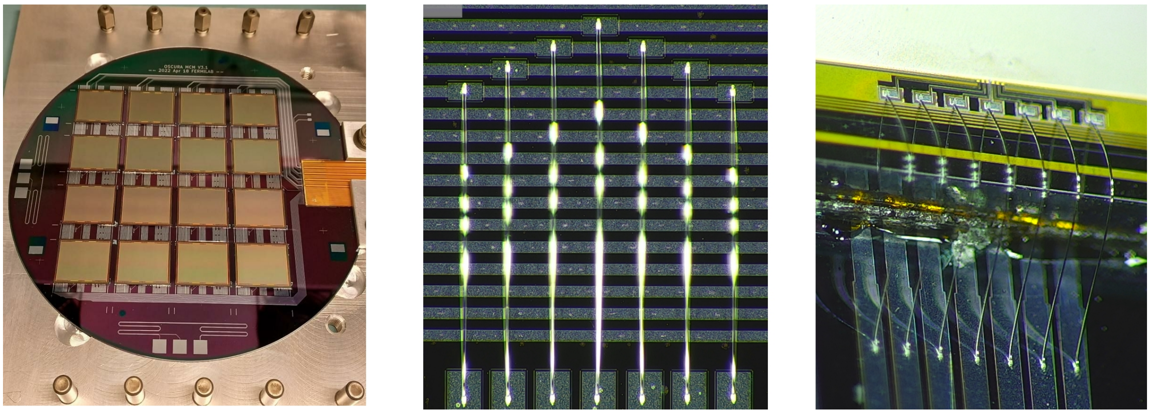

Figure 4: Pictures of an MCM after assembly. (Left) silicon wafer with 16 CCDs and flex cable, still on the assembly tray. (Middle) aluminum wire-bonds between pads on the Silicon package; the SiO_2 openings for pad connection can be seen as a thin line around the pads. (Right) wire bonds between a CCD and the Silicon wafer.

ionization events from visible and near-IR light are a subdominant background. We set the goal to suppress 99% of the light hitting the surface of the Oscura sensors.

We deposited a 50 nm aluminum layer on top of the active area of Oscura prototype skipper-CCDs using a maskless lithography tool (Heidelberg MLA 150) and an electron beam evaporator (Temescal FC200). Within the first tests we produced a prototype with a shaped aluminum layer on top of each quadrant, as shown in Fig. 5 (left). This picture shows the Oscura prototype skipper-CCD with the wire bonds between the pads and the flex cable that connects the sensor to the readout electronics. Fig. 5 (right) shows an image taken with the upper half of the CCD after 30 min of exposure. Electron, X-ray, and muon tracks are uniformly distributed in the active area, while the background light is ~95% suppressed under the aluminum shield with respect to the overscan. Although the process implemented to produce this device is not optimal since the beam evaporator can damage the CCD, the result sufficed as proof of concept for the next fabrication step. A thicker aluminum layer can be safely incorporated as a part of the sensor production and will guarantee the light suppression goal.

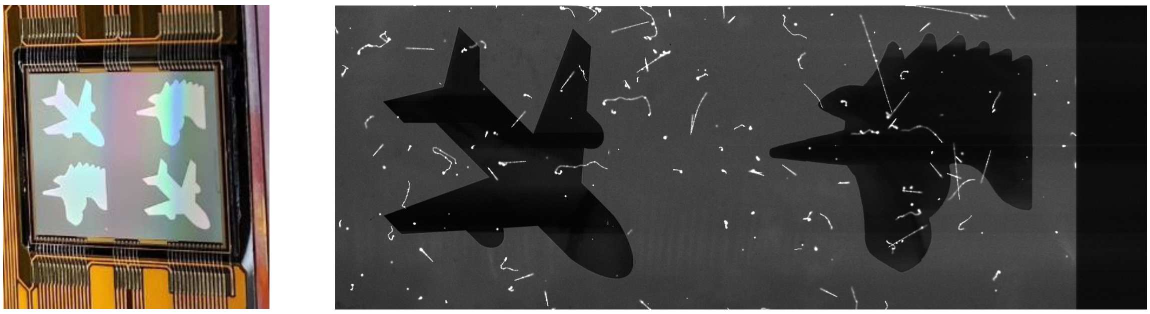

Figure 5: Oscura prototype skipper-CCD with an aluminum shield to probe the background light suppression potential of a 50 nm metal layer. Left) Picture of the sensor with an aluminum plane- and unicorn-shaped layer on top of each quadrant. Right) Image acquired using the upper half of the Oscura skipper-CCD after 30 minutes exposure.

5. Summary and outlook

In this work, we presented the design, production, assembly, and testing of a novel Silicon-based package for multi-kilogram skipper-CCD detectors. The collaboration between ANL and FNAL allowed us to produce the first functional package. The tests performed to characterize its electrical properties showed a signal distortion associated with the track's resistivity and capacitance that did not allow for sub-electron detection. However, we have proposals for improvement that include thickening both the SiO_2 and metal layers. We expect to try different metal deposition, such as vaporization or electrical plating, that will result in thicker metal layers, and in turn, lower track resistivity. Even though the first produced wafers did not fulfill the requirements for a multi-kilogram skipper-CCD detector, it allowed us to define the process design basis for the production of 1500 packages.

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