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Abstract The SuperCDMS collaboration is presently operating a 9 kg Ge payload at the Soudan Underground Laboratory in their direct search for dark matter. The Ge detectors utilize double-sided athermal phonon sensors with an interdigitated electrode structure (iZIPs) to reject near-surface electron-recoil events. These detectors each have a mass of 0.6 kg and were fabricated with photolithographic techniques. The detector fabrication advances required and the production yield encountered are described.

Keywords Dark matter · Cryogenic detectors · Transition edge sensors

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1 Introduction

The cryogenic dark matter search (CDMS) collaboration is presently performing the SuperCDMS Soudan experiment in the search for dark matter using 15 Ge detectors at the Soudan mine. These detectors utilize our latest advances in double-sided photolithographically-patterned phonon sensors (Fig. 1), where the athermal phonons are absorbed in Al collection fins and the signal is read out using W transition edge sensors (TESs). The improved background surface event rejection using ionization electrodes interdigitated with the phonon sensors, the 'iZIP' concept, has been reported before, [1] with the performance of these detectors at Soudan described in Ref. [2] Here we will discuss their fabrication and production yield in comparison [3] to the ZIP detectors of CDMS II.

2 Fabrication Flow Chart

The iZIP detector production is similar to that used for the CDMS II detectors [3], except now there are athermal phonon sensors on both faces of the Ge substrate. Figures 2, 3, 4 show the modified flow chart for their fabrication. We established that

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the most efficient route was to perform the photolithographic steps in parallel, namely the photoresist developing and metals wet etching occur for both faces simultaneously.

In Ref. [3] we described the transition for SuperCDMS to the use of contact rather than stepper aligners and the associated advantages. The generic iZIP phonon sensor design reduces the surface area coverage of the phonon sensors, thus previous demands on the Al fins' surface area coverage and the number of TESs connected in parallel are relaxed. And the width of the individual TESs can be increased, which allows us to use the same photoresist for the TES wet-etching (Shipley 1813) as the initial fin-layer patterning. This resist is robust against the hydrogen peroxide wet-etching required for the W TES patterning, and eliminated the need to use the adhesion promoter AP-400 [3].

An amorphous Si layer is needed to protect the underlying Ge substrate during the wet etching steps for the metals, but once the phonon sensors are complete (Fig. 3) it is desirable to remove this slightly conductive film in between the ionization bias and phonon sensor (ground) rails. We had performed investigations of different

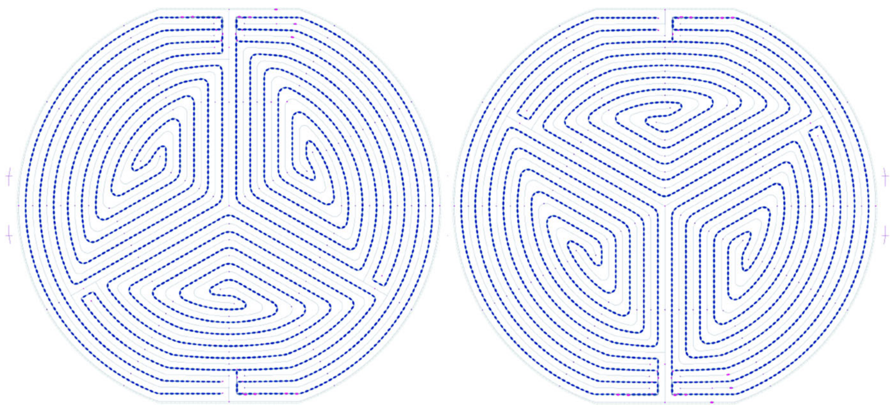

Fig. 1 Mask design for the ∅ 76 mm Ge iZIP detectors deployed in SuperCDMS Soudan. The wider ribbons contain the athermal phonon sensors which also serve as the ionization signal ground. The very *narrow lines* in between are the biased ionization electrodes. The four athermal phonon readout channels on each crystal face are arranged with an outer phonon readout channel containing two rings of phonon sensors surrounding the inner three phonon readout channels (Color figure online)

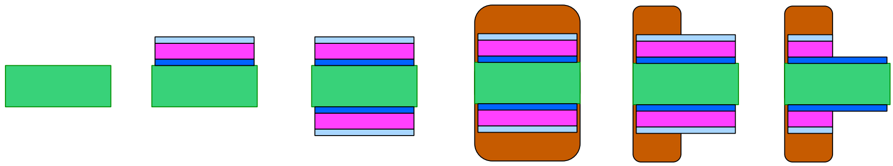

Fig. 2 Fabrication flowchart for SuperCDMS iZIP detector fabrication (geometry heavily distorted). As described in Ref. [3], the ∅ 76 × 25.4 mm thick Ge substrates (*green*) are cleaned prior to loading for thin-film depositions. A trilayer of 40 nm thick amorphous Si (*dark blue*), 300 nm Al (*magenta*) , and 30 nm W (*light blue*) is deposited on both faces of the substrate. After unloading, a 1.6 µm thick photoresist layer (*brown*) is applied to both faces. The photoresist layers on both faces are exposed to the Al 'fin-layer' masks. Then they are developed, baked, and the metal layers wet-etched [3] simultaneously (Color figure online)

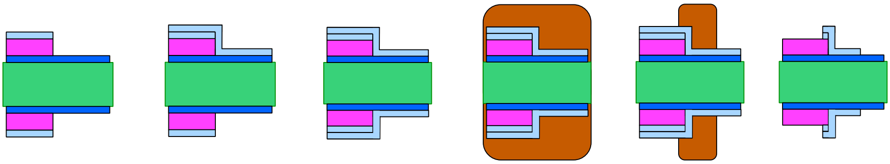

Fig. 3 After stripping of the photoresist, the Ge substrate receives a second W film deposition (40 nm thick) on both faces that will become the TESs. The films are patterned with TES-layer masks and all the unprotected W is wet-etched away, leaving the TESs and the 30 nm thick W trap interface between the TES and Al fins (Color figure online)

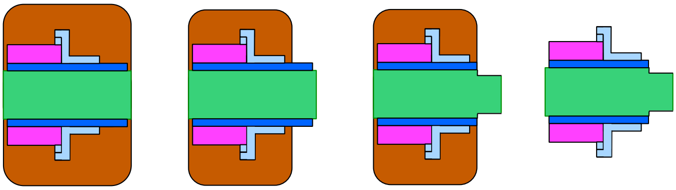

Fig. 4 Both faces are recoated with photoresist, exposed to the Ge-trench mask, and developed. The unprotected amorphous Si between the phonon sensors and ionization bias electrodes is dry-etched away, including several hundred nm of underlying Ge substrate (Color figure online)

CHF_3, O_2, SF_6 combinations before with results almost identical to those reported by Legtenberg et al. [4] For the iZIP detectors deployed in SuperCDMS Soudan we used a recipe of CHF_3 (40 sccm) and O_2 (20 sccm) at 150 mTorr. There was no sidewall slope requirement, instead there was concern that any polymer residue could be conductive or introduce shot noise to the ionization measurement. Hence the presence of a significant oxygen content in the recipe to remove carbon. We were unable to find a recipe that was selective to etch the amorphous Si but not the Ge, thus we accepted that significant etching of the Ge substrate would occur once the amorphous Si layer had been etched. The significant oxygen content of this recipe also etches the photoresist but for the etch times used only half of this resist gets removed, the amorphous Si is etched off, and the underlying Ge is etched to a depth that varies radially from 200 to 300 nm for the central region of the detector to 600–900 nm towards the perimeter.

3 Mask Revisions

The iZIP detector design underwent several revisions prior to starting production for SuperCDMS Soudan. Improvements were made to the wire-bonding pads and track layout to improve visibility during visual inspections. A final round of R&D was required to improve the iZIP detector charge collection stability performance [5] (and discussed further in Sect. 5) and increase the permissible applied ionization biases from ∼2.5 to ∼5 V. The maximum electric fields in the iZIP detector occur near the narrow ionization bias (Q) electrodes. The width of this electrode was minimized to reduce its contribution to the detector capacitance, and thermalization of the athermal phonon signal. The initial mask designs for SuperCDMS Soudan had a charge electrode width

Table 1 Contributing factors to the overall detector production yield for SuperCDMS Soudan

Factor	Before	After	Yield (%)
Crystal voids	29	27	93
Shaping chips	27	24	89
Photolithography	24	23	96
Ion implantation	23	21	91
Ionization performance	21	15	71
Totals	29	15	51

The before and after columns list the number of Ge crystals considered

of 8μm (Mask v.4) but ionization breakdown was a limiting factor in the production yield so the Q electrode width was relaxed to 40μm and used for half the detectors deployed at Soudan (Mask v.5). The radial geometrical definition of the inner fiducial volume for the ionization readout was not changed and remained 73 %. The center-line to center-line separation between the Q electrodes and phonon sensors (ground electrodes) varies around the design but is typically ∼1.2 reducing to 1.0 mm near the major flats (see Fig. 1).

4 Production Time-Scales and Yield

The detector fabrication for SuperCDMS Soudan commenced in July 2010 with the final detectors completed in August 2011 to give a payload of 15 detectors, 0.6 kg each. Table 1 lists the contributing factors to the overall detector production yield. The first two factors contribute to an estimate of the initial number of Ge crystals required. Errors during photolithography can usually be recovered either during photolithography (but increasing fabrication time) or a repolishing of the crystal. The subsequent factors in Table 1: (any) required ion implantation or ionization testing, impact costs and time-scales significantly.

Crystal voids are probably due to fast crystal growth [6], their presence at the surface during polishing could compromise the photolithography of the phonon sensors so additional time is required to ‘polish through’ these defects. Two crystals were eventually rejected from the Soudan SuperCDMS project as a ‘defect free’ layer in the vicinity of the desired crystal thickness could not be found. Germanium is a fragile, brittle, material and any shaping or polishing subcontracted activities are usually done on a ‘best efforts’ basis. Thus some loss of material during these activities is unavoidable, and may be sufficiently extensive that the iZIP design photolithography can not be performed. Three crystals were lost for those reasons. One crystal was rejected during photolithography and repolished. Again, a balancing act is required to optimize resources for photolithography, polishing, subsequent packaging and surgery. Contributing factors to overall production yield should be not judged in isolation.

In an earlier article on CDMS II detector production [3] we described improvements to controlling the W T_c, which is now lower and more uniform than during CDMS II production. This removed the need for multiple masking steps for Fe ion implantation of the W TESs. However some detectors for SuperCDMS Soudan had T_c ∼100 mK and we wished to implant them down to the goal ∼80 mK without measuring the W T_c before-hand. The dosage estimates were based on other measured detectors from the same production batch or witness wafers. This tactic to speed up the detector qualification for Soudan resulted in the loss of two detectors whose subsequent T_c ended up to too low. We believe that the Balzers deposition system used has reached the limit of its reproducibility and uniformity and is being phased out and replaced with more modern machines, which have the feature of a load-lock system for our large crystals.

5 Ionization Performance of Electrode Structure

As introduced in Sect. 3 and listed as the final factor in Table 1, a major difficulty encountered in SuperCDMS Soudan iZIP production was the ionization performance of the Ge detectors. The extremely poor ionization breakdown performance of some Ge crystals removed their consideration for re-use with the v.5 mask but the improved performance of several other crystals with the improved mask indicated that the earlier Q-electrode width was a contributing factor. During production the iZIP fabrication recipe itself did not change, including the final dry-etching depth of the Ge 'trenches' between the electrodes.

To speed up the testing program a dilution fridge in Minneapolis was commissioned with simplified wiring and readout to qualify the detectors, followed by commissioning of a large He-3 cryostat at Stanford. This reduced the burden on the primary test facilities and allowed more rapid feedback. Although the base temperature of the He-3 cryostat was low enough to study some the Ge crystal properties of interest [7] we found that it was only able to reject 75 % of the detectors whose ionization performance was subsequently rejected at the primary test facilities. It would be desirable to identify further straight-forward diagnostic tests to qualify the Ge crystals.

We have observed a close correlation between the detector's ionization performance at the primary test facilities (namely the ionization breakdown thresholds and stability/drift of the partitioning of the ionization signal between electrodes [5]) and the stability of the iZIP performance in the Soudan experiment. The ionization performance of iZIP detectors fabricated for SuperCDMS Soudan can be classified into four categories: those that are stable (between LED flashings or electrode grounding resets) for more than 10 h, around 3 h, only 2 h, and rejected from Soudan deployment. Of those known to be in the 2–3 h stability category from the primary test facility studies, the He-3 studies have so far been unable to discover a non-ionization signal test that could identify them.

6 Conclusions

We have demonstrated that large-mass double-sided athermal phonon sensors can be fabricated with high yield and deployed for a dark matter search. Ongoing investigations of the ionization collection performance for larger 100 mm diameter Ge substrates have been reported before [8], along with the background rejection performance of this technology [2], and position us well for a future 200 kg scale Ge dark matter search.

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