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Detector commissioning for the CDMS-II final run at the Soudan Underground Laboratory

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Abstract

CDMS-II uses detectors known as Z-sensitive ionization phonons (ZIPs) to search for weakly interacting massive particles (WIMPs), a very promising candidate for the dark matter in the universe. The most recent data run utilized 12 ZIP detectors (six Ge and six Si) running for $\frac{1}{2}$ year at the Soudan deep underground laboratory (780 m below surface), resulting in the current world's highest sensitivity to WIMP–nucleon coherent interaction [D.S. Akerib, et al., Phys. Rev. Lett. 93 (2004) 211301]. The CDMS-II experiment is approved to run 30 ZIPs until summer 2007 and its goal is to another order of magnitude increase in sensitivity to WIMPs. We present the detector preparation steps leading to the production of the CDMS-II detectors to be used in this final run.

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1. Introduction

CDMS uses simultaneous ionization and phonon measurements to detect weakly interacting massive particles (WIMPs). CDMS WIMP discrimination is based on the fact that the ionization yield in a semiconductor substrate depends strongly on the type of the interaction; a nuclear-recoil (e.g., WIMP) event in a Ge substrate produces ~3 times less ionization than an electron-recoil (most of the radioactive background) event with the same recoil energy. However for the events which occur very close to the geometrical boundaries of the detector (in particular in the few micron 'dead-layer' close to the ionization electrodes) part of the charge created by the recoil could be lost [1]. Hence, a surface electron-recoil event can mimic a WIMP signal, thereby degrading the discrimination efficiency.

CDMS-II solves this problem by measuring the athermal phonons produced in the primary interaction before they randomize and eventually reach equilibrium. These phonons carry the information necessary to reconstruct the history of the event including the impact position in the detector, i.e., to identify the "dead-layer" events.

2. Z-sensitive ionization phonons (ZIPs) fabrication

Fig. 1 shows a schematic of a ZIP detector with its corresponding readout electronics. ZIPs [2] are crystals of

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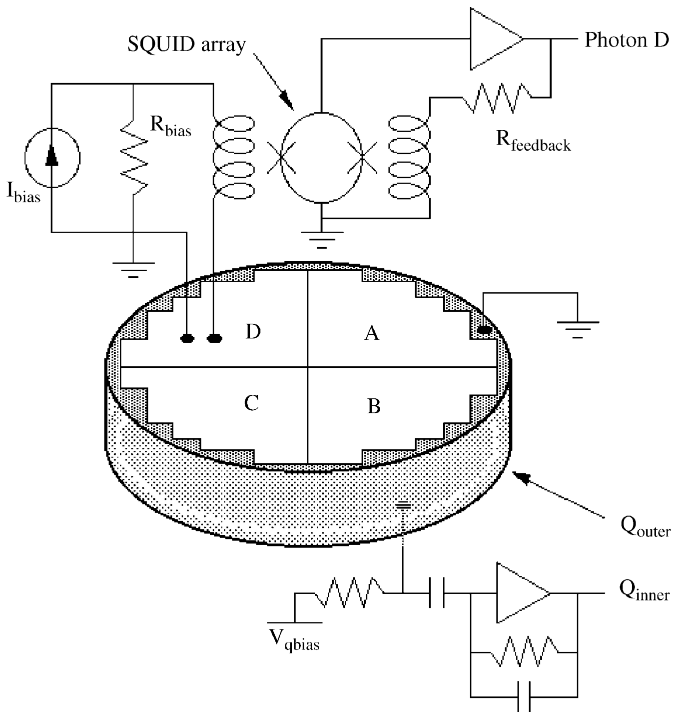

Fig. 1. Schematic of a ZIP detector with its corresponding readout electronics. The four quadrants on the top face are individual phonon sensors. The bottom face is divided into an inner charge electrode separated with a 1 mm gap from an outer guard-ring.

Ge or Si, polished into discs 76 mm in diameter and 10 mm thick. Both faces of the detector have metallized Al grids to function as the ionization electrodes for the charge readout, and photolithographically patterned tungsten transition edge sensors (TESs) on one face to perform the phonon energy measurement. The phonon sensor face of ZIPs is divided into four quadrants, and each quadrant includes 1036 tungsten (W) TESs uniformly distributed and electrically connected in parallel. As each quadrant has its individual electronic readout, the relative amplitude and timing of the four phonon pulses provide a 2D position reconstruction of events. The timing parameters of each phonon signal contain information on the position of the events. In particular, the rise time and delay of the phonon signal of events occurring close to the faces of the ZIPs are shorter than the events occurring in the bulk of the detector [3].

ZIPs are manufactured on the Stanford Campus at the Stanford Nanofabrication Facility (SNF). The fabrication process is a modified two-layer CMOS process for both sides of the detector. A pre-screening of the detector at 77 K is performed for the obvious failures during the fabrication process before being delivered to the test facilities for a detailed cryogenic test.

3. Detector testing and characterization

The two ^3He–^4He dilution-fridge test facilities at UC Berkeley and Case Western Reserve University are responsible for testing the performance of each new ZIP detector.

After fabrication, the W transition temperature (T_c) is systematically slightly too high, or not uniform enough, for optimal performance. A process was developed whereby the W T_c distribution would be mapped, and then the detectors would be subjected to ion implantation with ^{56}Fe ions to "compensate" the W T_c gradient. The same process will also lower the T_c to a more acceptable range [4]. During the first test of the ZIPs, the T_c, I_c and I–V of each of the four phonon sensors are evaluated in order to define the ion-implantation map. Fig. 2 shows a set of I–V curves obtained at different temperatures for one detector channel before implantation. After the implantation, the detectors are again examined in the test facilities. A satisfactory performance at this stage validates the detector for future installation in the experiment. We then study the dynamic performance of the detectors by looking at pulse data with calibration neutron, γ and β sources. The goal of this study is to define the WIMP signal region in the parameter space of ionization and phonon pulse characteristics [5].

4. Cold electronics, installation

Each phonon sensor is read out by a SQUID array (100 elements) based amplifier functioning at 600 mK. The SQUID array chips are fabricated by the CDMS-II collaboration (NIST). The primary stage of the charge amplifiers (measuring the ionization signal) is a field effect transistor (FET) heat sunk to a 4 K bath and self-heated to 130 K when functioning. Two FETs and four SQUID arrays are put together in a single card (a "SQUET") to become one ZIP cold electronic pre-amplification unit.

Sets of six detectors are stacked vertically in a single "tower". The "towers" are then subject to a thorough

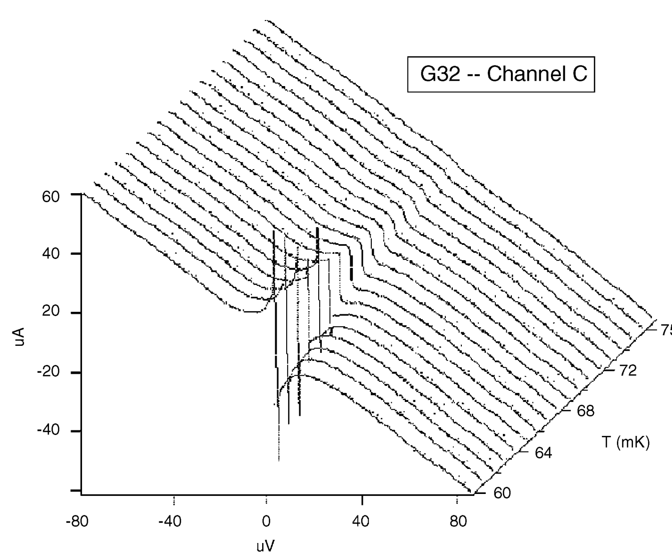

Fig. 2. The temperature variation of I–V curve for one phonon sensor. The x-, y- and z-axis, respectively, report bias voltage, sensor temperature and the sensor current. With this set of curves we can estimate the I_c and T_c of each sensor.

Fig. 3. (Right) A CDMS tower. The lower part of the copper cylinder is a stack of six detectors. The upper part is the housing for the readout cables. These Nb/Ti wires are heat sunk to 600, 50 and 10 mK. (Left) The CDMS-II five towers after installation in the Soudan underground refrigerator.

cryogenic checkout against any electrical continuity failure, before being delivered to the Soudan underground refrigerator lab to be installed for the WIMP search experiment.

CDMS-II has produced five working towers with a total of 19 Ge and 11 Si detectors. The towers are now installed in the Soudan underground refrigerator facility (Fig. 3) and currently cooled to $<50\,\mathrm{mK}$.

5. Conclusion

Operating with 12 ZIP detectors, CDMS-II has the highest sensitivity to WIMP–nucleon coherent interactions [6]. Since the previous run with 12 ZIPs, 18 more detectors have been produced along with corresponding cold electronics. The new 30-detector CDMS-II run is in progress, and will run for a period of 2 years. The goal is to increase the CDMS-II sensitivity by a further factor of 10.

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