Snowmass2021 - Letter of Interest

Charge-Coupled Device Technology Development for Future Dark Energy and Dark Matter Studies

Thematic Areas: (check all that apply □/■)

■ (IF1) Quantum Sensors
■ (IF2) Photon Detectors
■ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
□ (CF3) Dark Matter: Cosmic Probes
■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
□ (CF7) Cosmic Probes of Fundamental Physics
□ (Other) *[Please specify frontier/topical group]*

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Abstract: The current generation of Dark Energy and low-mass Dark Matter detectors critically rely on HEP-developed charge-coupled devices (CCDs). These capabilities will be further improved for future experiments with investment in three technologies: (1) sub-electron noise Skipper amplifiers for detecting single photons, (2) transferring fully depleted CCD manufacturing to modern, 200 mm-wafer foundries, and (3) development of CCDs using germanium as the substrate instead of silicon.

Discussion

The fully depleted charge-coupled device technology that was originally developed at LBNL[1] was successfully implemented in the DOE Stage III Dark Energy Camera[2] as well as the BOSS and eBOSS spectrographs[3]. Large format, 4k $\times$ 4k CCDs from LBNL with improved performance compared to the DECam CCDs have been installed in the DESI red and near-infrared spectrographs[4] along with blue-sensitive CCDs from STA and the University of Arizona Imaging Technology Lab (ITL) . The camera for the Vera C. Rubin Observatory (formerly the LSST) will use 100 μm thick, fully depleted CCDs that were commercially produced[5]. DESI and the camera for the Rubin Observatory are DOE Stage IV Dark Energy projects.

Fermilab and LBNL have developed fully depleted, Skipper CCDs that achieve deep sub-electron noise performance[6]. These CCDs are the baseline detector for the DAMIC-M, SENSEI, and OSCURA direct dark matter detection projects. The enhanced red response of the thick, fully depleted CCDs is the main advantage of these devices for DOE astrophysics applications, while the ability to deplete standard thickness wafers, i.e. 650 μm thick for 150 mm wafers, allows for a factor of 2.6 $\times$ more mass per equivalent-size astronomical CCD that are typically 250 μm thick for the LBNL imagers.

Many of the aforementioned CCDs were fabricated at Teledyne DALSA Semiconductor with finishing for back illumination at either LBNL or the ITL. The remainder of the CCDs were produced by e2V. Teledyne DALSA Semiconductor has announced the end of foundry support for CCD development. In order to provide CCDs for future experiments new foundries must be identified, and the fully depleted and blue-sensitive CCD technologies must be transferred to the foundries. The latter is already underway. The DALSA foundry processes 150 mm diameter wafers, but to avoid near-term obsolescence it will be necessary to transfer the fully depleted CCD technology to the more modern 200 mm foundries. To date we have identified two potential foundry partners, and are able to procure the 200 mm diameter, high-resistivity, float-zone wafers needed for this work. Some of the challenges noted to date are the change to step-and-repeat lithography with both smaller field sizes and reduced depth of focus when compared to the projection lithography used at DALSA, and the need for technology developments to allow for back illumination. This initial work for fully depleted CCDs on 200 mm wafers is part of the OSCURA DOE funding, but more support will be needed to produce devices suitable for astronomical imaging applications. It is likely that the enhanced capabilities of the 200 mm foundries will lead to improvements in CCD noise performance, although significant R&D will be required.

In terms of silicon CCD design efforts, faster readouts for the Skipper CCDs are required in order for the technology to be applied to astrophysics imaging and spectroscopy applications. This is covered in more detail in the LOI from A. Drlica-Wagner *et al*. Faster readout of Skipper CCDs is also needed for Quantum Information Sciences work for which LBNL and Fermilab are collaborating on CCD development.

On the longer time frame, CCDs made on Germanium substrates could potentially greatly improve the near-infrared response from the silicon limit of about $\lambda \approx 1$ μm to about 1.4 - 1.5 μm. Lincoln Laboratory has produced Ge CCDs[7], and LBNL is also pursuing R&D on Ge devices including the development of high-purity, 150 mm diameter Ge wafers with PHDS Co. This work is not easily transferred to commercial foundries due to contamination concerns related to processing on Ge substrates, and the lack of commercial interest to date implies that the proof-of-principle R&D work is best suited for non-commercial facilities such as the MIT Lincoln Labs Microelectronics Laboratory and the LBNL MicroSystems Laboratory.

References

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