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Radiation-tolerant, red-sensitive CCDs for dark energy investigations

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Abstract

We describe the development of thick (200–300 μm), fully depleted p-channel, charge-coupled devices (CCDs). The advantages of these CCDs relative to conventional thin, n-channel CCDs include: high quantum efficiency over a wide range of wavelengths, extending into the near-infrared; negligible fringing at long (~900–1000 nm) wavelengths; improved radiation tolerance; and a small point-spread function controlled through the application of the bias voltage. These visible-to-near-infrared light detectors are good candidates for the next generation of large focal-plane mosaics under development for dark energy measurements. The Dark Energy Survey has selected these CCDs for the focal plane of a new camera being designed for the Blanco 4 m telescope at CTIO in Chile. They also meet all the requirements for the visible-light detectors for the SuperNova/Acceleration Probe, a satellite-based experiment designed to make precision measurements of dark energy.

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Keywords: Charge-coupled devices; P-channel; Fully depleted; Diffusion; Radiation tolerance

1. Introduction

The development of photodetectors has a long history at Lawrence Berkeley National Laboratory (LBNL) [1–4]. The LBNL charge-coupled device (CCD) is a back-illuminated device based on a traditional three-phase charge transfer and a buried channel. But unlike conventional CCDs that employ an n-channel to collect electrons from a thin (10–20 μm thick) epitaxial layer, the LBNL CCD has a p-channel implant that collects holes from a fully depleted, high-resistivity n-type silicon substrate, typically 200–300 μm thick. The depletion is achieved through application of a bias voltage to a thin backside conductive layer, underneath a two-layer anti-reflective (AR) coating. Because the AR coating is insulating, and for convenience in packaging and deployment, the bias voltage is applied from the front side through an undepleted region around the periphery of the device. Floating p^+ guard rings drop the bias voltage to a grounded guard ring enclosing the active area [5].

LBNL CCDs have been selected for a new 0.5 gigapixel camera designed by the Dark Energy Survey (DES) team for the 4 m Blanco telescope at the Cerro Tolo Inter-American Observatory (CTIO) [6]. This camera will deploy 62, 2k × 4k format CCDs with 15 μm pixels. DES will carry out a 5000 square-degree survey in five filters to study dark energy. The selection of LBNL CCDs for DES was mainly driven by the high quantum efficiency in the near-infrared, in order to optimize sensitivity for distant, highly red-shifted objects.

The SuperNova/Acceleration Probe (SNAP) is a space-based dark-energy mission with a focal plane populated by a mosaic of silicon and HgCdTe detectors [7]. SNAP will measure the evolution of dark energy with Type Ia supernovae and gravitational weak lensing. In the SNAP baseline design the focal plane has 36 LBNL CCDs, with 10.5 μm pixels in a 3.5k × 3.5k format. The selection of LBNL CCDs for SNAP was motivated by the enhanced near-infrared sensitivity, the improved radiation tolerance

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and the well-controlled charge diffusion, resulting in a small point-spread function (PSF) that is commensurate with the pixel size.

2. Quantum efficiency

The most obvious advantage for thick, fully depleted CCDs is the enhanced quantum efficiency (QE) at long wavelengths. As the photon energy approaches the silicon band gap, the photon interaction length rapidly increases, until silicon becomes completely transparent at 1050 nm (at 140 K). A thick device is more efficient in the red, and has greatly reduced fringing from multiple reflections that can occur when the device thickness is less than the absorption length [8]. The QE in silicon at long wavelengths is a function of the operating temperature, decreasing at lower temperatures due to the reduction of phonon-induced tunneling [9]. LBNL CCDs are typically operated at cryogenic temperatures (~140 K) in order to reduce dark current to negligible levels (~1e$^-$/pixel/h). At this temperature, the measured QE is 95% at 900 nm [10]. The QE at short wavelengths is similar to that of conventional thin CCDs, and depends mainly on the properties of the AR coating. An R&D program is underway with the Jet Propulsion Lab (JPL) to apply a "delta-doped" AR coating using molecular beam epitaxy (MBE) to LBNL CCDs in order to enhance the QE below 400 nm [11].

3. Radiation tolerance

Another important advantage of the LBNL CCDs for space applications is their radiation tolerance. Due to the use of boron as a dopant in the n-channel instead of phosphorous, the formation of the single phosphorous vacancy "E-center" defect is reduced, while the formation of the most probable divacancy defect is suppressed [12]. This improved radiation tolerance relative to conventional n-channel CCDs has been demonstrated in proton irradiation studies [12,13], and will result in much better charge-transfer efficiency (CTE) after exposure to the galactic and solar proton flux in space.

4. Diffusion

Recent advances in the engineering of the channel stop and guard ring structures in the LBNL CCD have resulted in devices that can withstand bias voltages exceeding 200 V without breakdown [14]. This advance enables full depletion of devices 650 μm thick, with interesting applications to soft X-ray detection. The application of a high substrate bias voltage also increases the velocity of the hole motion from the backside to the front-side pixel well, thereby reducing the charge transit time. Lateral charge diffusion is proportional to the charge transit time, and is thus proportional to the device thickness and inversely propositional to the square root of the bias voltage [15]. The rms PSF in a 200-μm-thick LBNL CCD was measured to be 3.7 μm at a bias voltage of 115 volts [16], meeting the SNAP PSF requirement, which is derived from detection of the subtle effects of galaxy shear for weak lensing studies.

5. Conclusions

Highlights of the R&D program to develop thick, fully depleted p-channel CCDs for use in particle cosmology experiments have been presented. These devices will enable the next generation of astronomical surveys to carry out precision measurements of dark energy.

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