National Aeronautics and Space Administration

Modeling and Analysis for Process Qualification of Delta-doped UV and UV/Optical Silicon Detector Arrays

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Program: FY22 R&TD Strategic Initiative
Strategic Focus Area: UV Spectroscopy - Strategic Initiative Leader: Margaret A Frerking

Objectives: To analyze detector data using physical models of delta-doped detector surfaces and to apply the results of this analysis to develop optimized delta-doping processes and structures.

Background: The recent Astro2020 decadal survey, Pathways to Discovery in Astronomy and Astrophysics for the 2020s, identified time domain astronomy and astrophysics as key scientific challenges for the next decade. JPL's delta-doped detector enable the stability and sensitivity required by these missions over a wide spectral range, spanning soft X-rays through the UV, visible, and near infrared. The unique capabilities of 2D-doped detectors will be particularly important in the advancement of silicon detectors to address technology gaps for NASA's Great Observatories.

Approach and Results: Starting with Morley Blouke's model of thinned CCDs, I developed an algorithm for calculating QE(T) in weakly passivated detectors, and then applied this model to analyze QE(T) in delta-doped detectors and to derive requirements for strong surface passivation in space-relevant radiation and thermal environments. The strength of surface passivation is parameterized in terms of energy, as opposed to earlier surface passivation models based on the strength of the near-surface electric field. The QE(T) model proved useful in comparing the effects of temperature, epilayer doping, and Si-SiO2 interface traps on the stability of various surface passivation technologies. Using nextnano++ software to model the near-surface band structure of thinned detectors, I determined that the root cause of temperature-dependent QE was damage to the detector during processing using chemical-mechanical polishing, and proposed etching the surface to remove the damage. Based on my search of the literature, I recommended using the Takizawa "slight etch" method. Test growths on wafers processed using this method showed nanoscale surface roughness based on reflection high energy electron diffraction data. To solve this problem, I identified an NH4F etching process that produces atomically flat Si(100) surfaces. This solved the problem of nanoscale roughness. Based on my computations of delta-doped surfaces, I also recommended changing the MBE layer structure by adding a third delta layer as close as possible to the MBE-detector interface. The optimized process and MBE structure were used to fabricate delta-doped CCD201 detectors. QE measurements performed by Open University showed that optimized delta-doped CCD201 detectors exhibited near-100% internal quantum efficiency that was stable and uniform across the detector. In a direct comparison with a Te2v UV-enhanced CCD97, the data show that the optimized delta-doped CCD201 detectors have 2x to 3x higher quantum efficiency than state-of-the-art Teledyne e2v CCDs.

Significance/Benefits to JPL and NASA: The R&TD research was significant in having achieved the stated objectives by using data and theory to identify the root cause of observed low and temperature-dependent quantum efficiency in some delta-doped detectors, inventing optimized processes and structures, and successfully demonstrating optimized delta-doped CCD201 detectors with stable, near- 100% internal quantum efficiency. These achievements represent a significant and timely advance in JPL's silicon detector technologies for three reasons. First, the Astro2020 decadal survey highlights the importance of detector stability for meeting NASA goals in ultra-precise photometry and time-domain astronomy. Second, JPL's models and published data show how and why Teledyne e2v's UV-enhanced CCD passivation process is unstable. Whereas NASA requirements call for stability better than 1%, the quantum efficiency of Teledyne detectors is unstable upon exposure to ultraviolet light – the instabilities are surprisingly large, such that exposure to ultraviolet light at 200nm causes the QE to change by factors of 1.5x to 2x. Third, NASA recently announced selections for MIDEX step 1 studies, in which the Caltech-led Ultraviolet Explorer mission was selected. UVEX is a UV survey mission that will perform time domain astronomy measurements in the near and far ultraviolet.

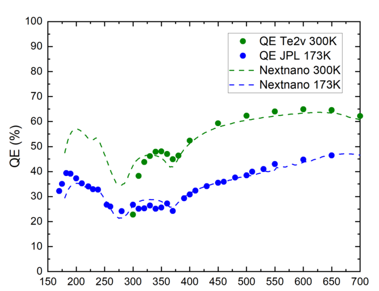

Figure 1. Band structure calculations and QE(T) models show that CMP damage comprises a very shallow distribution of traps with integrated density on the order of $5x10^{13}cm^{-2}$.

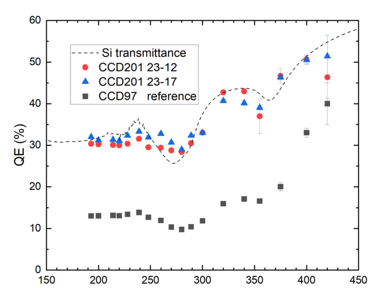

Figure 2. Measured quantum efficiency of delta-doped CCD201 detectors in comparison with a Te2v UV-enhanced CCD97.

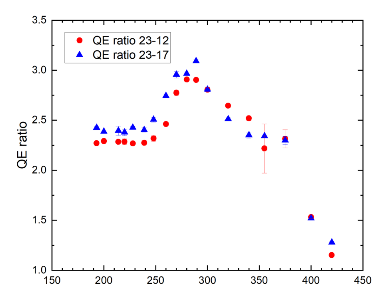

Figure 3. The delta-doped detectors exhibited nearly 100% charge collection efficiency over the range measured, with 2x to 3x higher UV QE than Te2v's state-of-the-art UV-enhanced CCD97.

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