Delta-doped Imagers for UV and EUV Applications

Shouleh Nikzad, T.J. Jones, , S.T. Elliott, T.J. Cunningham, P.W. Deelman, A.B.C.Walker a, and H.M. Oluseyi a , Center for Space Microelectronics Technology, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 aDepartment of Physics, Stanford University, Stanford, CA 94305

Abstract

The large imaging format, high sensitivity, compact size, and ease of operation of silicon-based sensors have led instrument designers to choose them for most visible-light imagers and spectrometers for space-based applications, and this will probably remain the case in the near future. In fact, technologies presently under development will tend to strengthen the position of silicon-based sensors. CCD-CMOS hybrids currently being developed may combine the advantages of both imagers and new high-gain amplifiers and could permit photon-counting sensitivity even in large-format imagers. Back-illumination potentially enables silicon detectors to be used for photometry and imaging applications for which front-illuminated devices are poorly suited. Successful detection by back illumination requires treatment of the back surface using techniques such as delta doping.

Delta-doped CCDs were developed at the Microdevices Laboratory at the Jet Propulsion Laboratory in 1992. Using molecular beam epitaxy, fully-processed thinned CCDs are modified for UV enhancement by growing 2.5 nm of boron-doped silicon on the back surface. Named delta-doped CCDs because of the sharply-spiked dopant profile in the thin epitaxial layer, these devices exhibit stable and uniform 100% internal quantum efficiency without hysteresis in the visible and ultraviolet regions of the spectrum. In this paper we will discuss, the performance of delta-doped CCDs in UV and EUV, and the response of these devices to low-energy electrons for electron-bombarded CCD (EBCCD) applications. Recent activities on the extension of delta doping to other imaging technologies will also be presented.

Introduction

The large format, high resolution, low noise, and technological maturity of CCDs renders these devices as detectors of choice for many scientific applications. Standard frontside-illuminated CCDs do not respond in the UV because of short absorption of UV photons in the CCD frontside circuitry. Untreated back-illuminated silicon CCDs have limited sensitivity to radiation with short penetration depth (e.g., UV photons and low-energy particles), due to the surface depletion caused by the inherent charge in the native oxide. Because of surface depletion, internally-generated electrons are trapped near the irradiated surface and therefore cannot be transported to the detection circuitry. This surface potential can be eliminated by low-temperature molecular beam epitaxial (MBE) growth of a delta-doped layer on the silicon surface. This effect has been demonstrated through achievement of 100% internal quantum efficiency for UV photons detected with delta-doped CCDs [Hoenk92].

Figure 1 schematically shows the structure of a delta-doped CCD. A 2.5 nm delta-doped silicon layer is grown on the back surface of thinned, fully-processed CCDs at low-temperature. Processing of delta-doped CCDs has been described previously [Hoenk92, Nikzad94]. Delta-doped CCDs have been extensively tested and have shown 100% internal quantum efficiency in the ultraviolet and visible parts of the spectrum indicating that the deleterious backside potential well responsible for the detector dead layer has been effectively eliminated. Because the delta-doped layer is incorporated directly into the silicon lattice, the modified CCDs are robust enough to withstand direct deposition of anti-reflection coatings for further enhancement of total quantum efficiency.

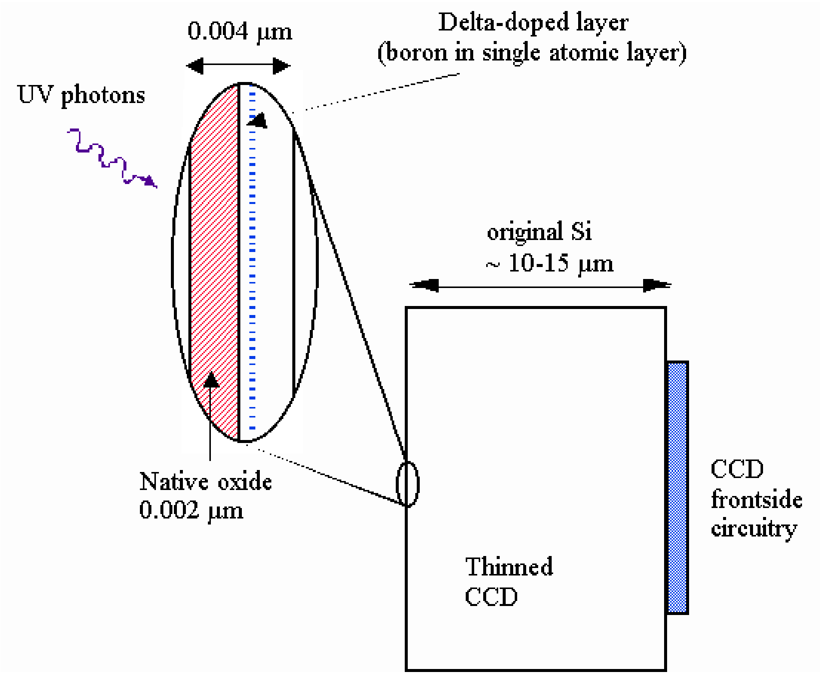

Figure 1.

UV and EUV Characterization of Delta-doped CCDs

The quantum efficiency (QE) of delta-doped CCDs in the UV and visible regions of the spectrum has been extensively measured. Figure 2 shows the typical quantum efficiency in the 250-700 nm region of the spectrum and an example of enhancement of the total QE by direct deposition of antireflection coatings of single layer HfO_2 [Nikzad94]. The solid line in figure 2 is the silicon transmittance which represents 100% internal quantum or the maximum QE that can be obtained without addition of antireflection coatings. We have also measured the QE of delta-doped CCDs in the far UV nm region of the spectrum. It was shown in these measurements that the delta-doped CCD shows 100% internal QE throughout the entire 120-700 nm waveband. Figure 2 also shows the characterization of delta-doped CCDs into the EUV. The EUV measurements were performed using a beam line at the Stanford Synchrotron Radiation Laboratory. These measurements show very high sensitivity in the EUV range of the spectrum.

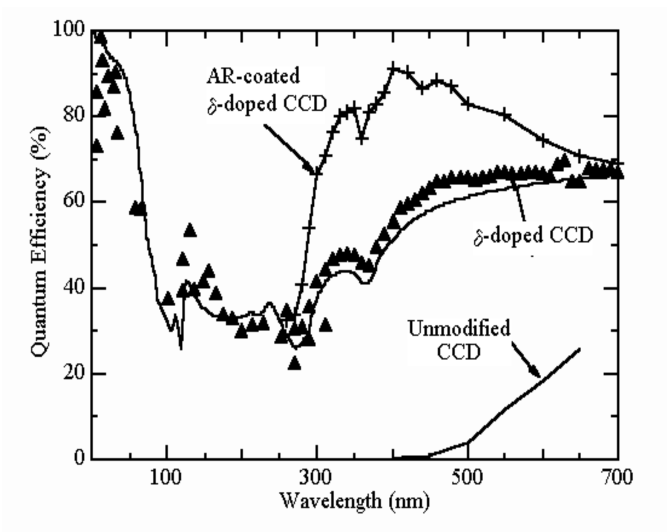

Figure 2.

Applications in astronomy require stable device performance. Figure 3 shows quantum efficiency data over a three-year period. No degradation of the device quantum efficiency was observed. Note that while exposed to various vacuum chambers and temperature cycles for these measurements, in between measurements this device was kept at room temperature and was not kept under vacuum or inert environments. The device stability with respect to its history of illumination or quantum efficiency hysteresis has also been examined in collaboration with Dr. J. Trauger. For these measurements, the device was exposed to ultraviolet light for several seconds. The exposure time was then increased by a factor of 100. Returning to the original exposure time showed identical quantum efficiency for the delta-doped CCD, and essentially no quantum efficiency hysteresis was measured in this device.

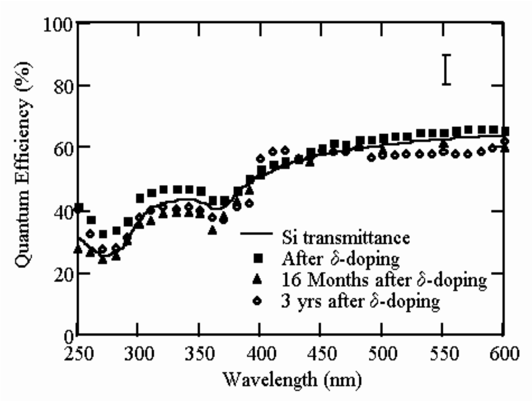

Figure 3.

Low-energy Electron Detection with Delta-doped CCDs and EBCCD Applications

Similar to UV photons, low-energy particles deposit a significant fraction of their energy within a few nanometers of the surface, therefore, frontside-illuminated or untreated back-illuminated CCDs cannot detect low-energy particles. The 100% internal quantum efficiency of delta-doped CCDs in the UV indicate that electrons generated near the surface of delta-doped CCDs are detected efficiently. This indicates that delta-doped CCDs can potentially be used as imaging devices for low-energy particles.

We have measured the response of delta-doped CCDs to electrons in the 50-1500 eV energy range using both an indirectly-heated cathode electron source in a custom UHV chamber and in a scanning electron microscope [Smith96, Nikzad97, Nikzad98]. All devices were fully-characterized using UV illumination prior to the electron measurements. Figure 4 shows the electron quantum efficiency of a delta-doped CCD plotted as a function of incident energy in the 200-1000 eV range. The high gain and low-energy cutoff of delta-doped CCDs as shown in the figure indicates that delta-doped CCDs are good candidates for use in EBCCD applications.

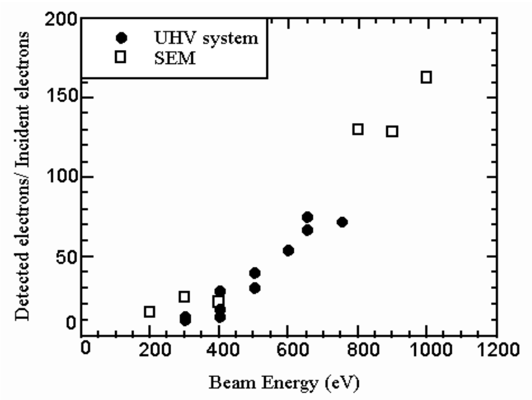

Figure 4

Delta doped High Resistivity Detectors

We are developing two new detectors that extend the delta-doping technology to high resistivity detectors in collaboration with Dr. S. Holland at Lawrence Berkeley National Laboratory. High-resistivity silicon detectors can be depleted through the entire wafer thickness with modest fields (~100 V). Combining the large volume and full depletion capability of high resistivity detectors with delta doping allows detection of UV photons that have shallow absorption lengths as well as higher energy photons (such as low energy x rays) with long absorption lengths. We are developing delta doping for both p-type (hybridized with CMOS readout) and n-type monolithic high resistivity detectors. The preliminary measurements in the p-type detector have shown sensitivity to UV photons and indicating that the detector is successfully delta doped. Further work in quantifying these results and development of the n-type detector is underway.

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