Ultrastable and Uniform EUV and UV Detectors

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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. 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. Generally, back illumination requires treatment of the back surface 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, our in-house thinning capability, bonding approaches for producing flat focal plane arrays, and in-house capabilities of directly applied antireflection coatings. Recent activities on the extension of delta doping technology to other imaging technologies will also be presented.

Introduction

The large format, high resolution, low noise, and technological maturity renders CCDs 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 frontside circuitry of CCDs. 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 positive 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 Si surface. This effect has been demonstrated through the achievement of 100% internal quantum efficiency for UV photons detected with delta-doped CCDs.

Figure 1 schematically shows the structure of a delta doped CCD. A 2.5 nm delta-doped Si 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 part of the spectrum indicating that the deleterious backside potential well responsible for the detector dead layer has been effectively eliminated [Hoenk92, Nikzad94]. 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 enhanced UV quantum efficiency.

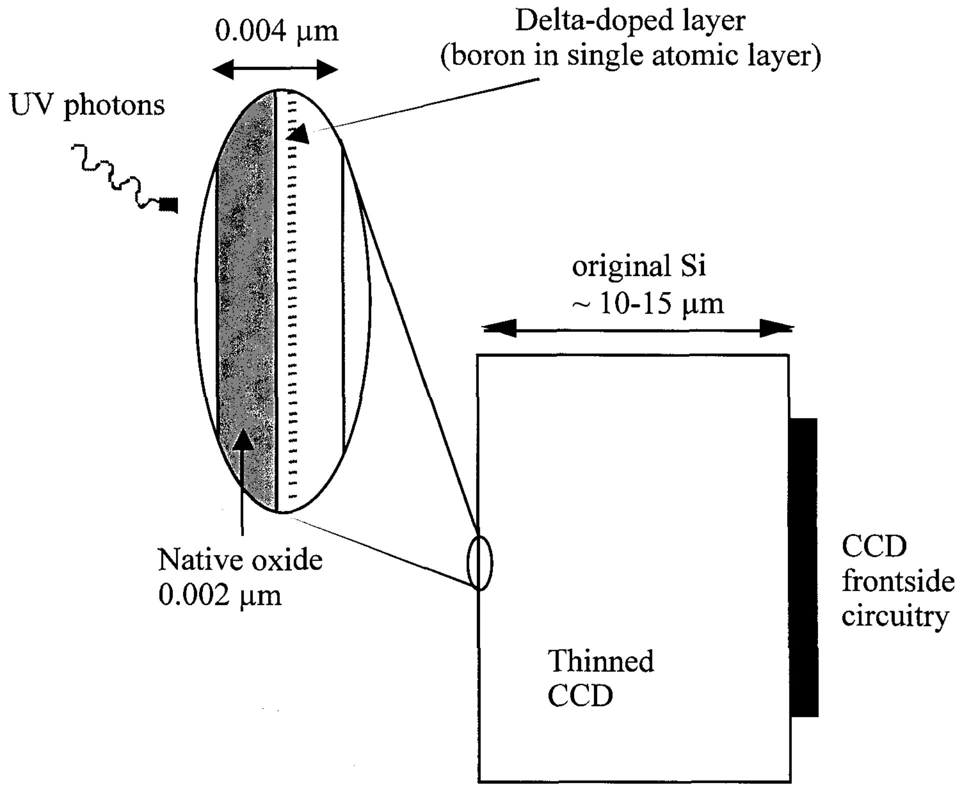

Figure 1. Cross section schematic of a delta-doped CCD. The epitaxially-groan delta-doped layer on the back surface of a thinned CCD places a high density of boron atoms approximately 0.5 nm below the silicon epilayer surface and protected by an oxide overlayer.

UV and EUV Characterization

The quantum efficiency (QE) and stability 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 the enhancement of the QE in the 300-400 nm region by direct deposition of single layer HfO_2.[2] The solid line in figure 1 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 121.6-310 nm region of the spectrum. It was shown in those measurements that the delta-doped CCD shows 100% internal QE throughout the entire 120-700 nm waveband.

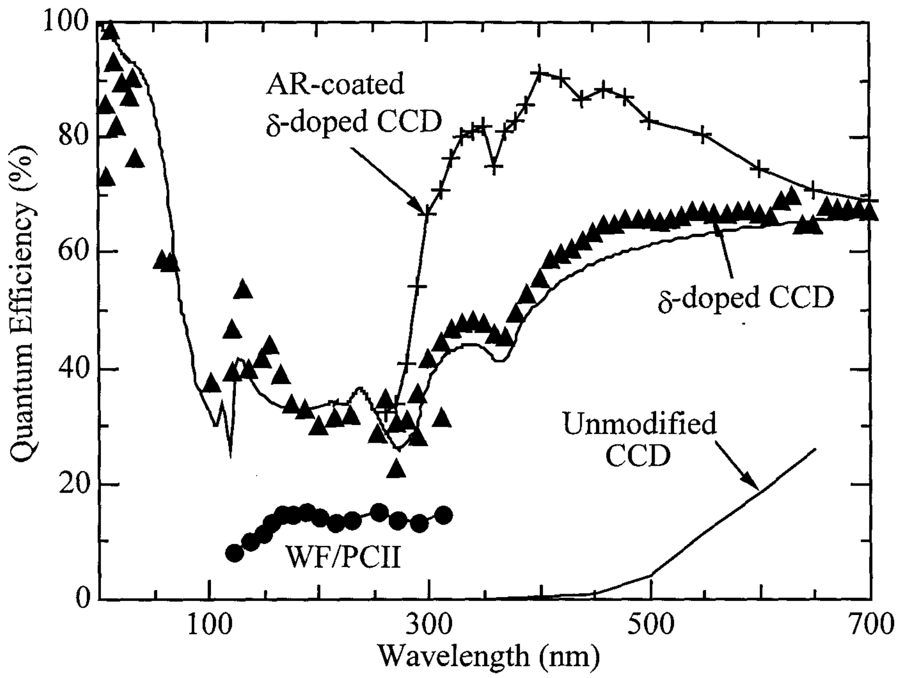

Figure 2. Quantum efficiency of a bare delta-doped CCD (triangles) compared with solid line (Si transmittance) shows 100% internal QE. QE is enhanced by the addition of anti-reflection coatings optimized for the 300-400 nm regions .

The EUV measurements shown in figure 2 were performed at Stanford Synchrotron Radiation Laboratory (SSRL) . A vacuum chamber was attached to a beam line at SSRL through an interlocked gate valve maintaining a ~10^{-8} torr vacuum during the measurements. A cryo-shroud cooled to liquid nitrogen temperature was placed between the camera and the beam line and was cooled prior to the cooling of the CCD. This helped keeping the CCD surface contamination to a minimum as was evidenced by constant results obtained during temperature cycling of the device. A heater was used to keep the device at elevated temeperature during the cooling of the cryo shroud and the device was cooled slowly to –100 °C for duration of the measurements. Figure 3 is a photograph of the chamber equipped with the CCD camera and the croshroud. A NIST-calibrated photodiode was used for flux measurements for quantum efficiency calculations.

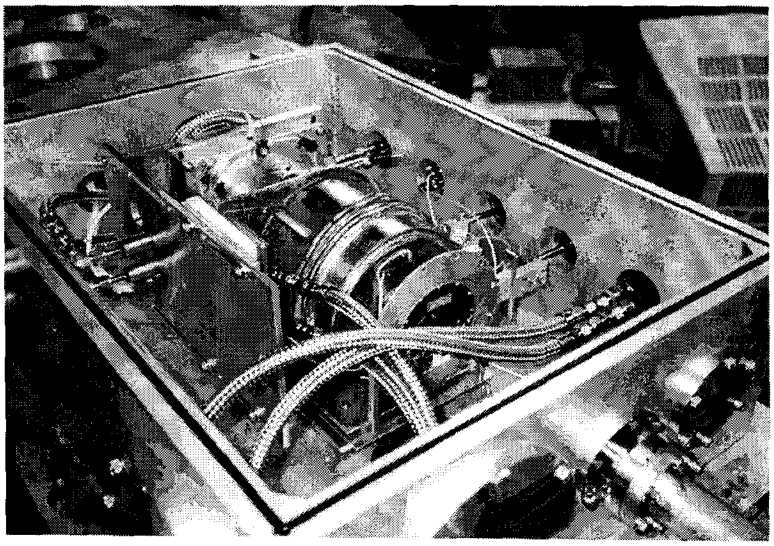

Figure 3. SSRL setup showing the CCD camera, cryoshroud and shutter.

Applications in astronomy require stable device performance. Figure 4 shows quantum efficiency data over a three-year period. No degradation of the device quantum efficiency was observed. The device stability with respect to history of illumination has also been examined. Increasing the exposure time by a factor of 100 and returning to the original exposure time yielded identical quantum efficiency for the delta-doped CCD, demonstrating that no quantum efficiency hysteresis exists in the device.

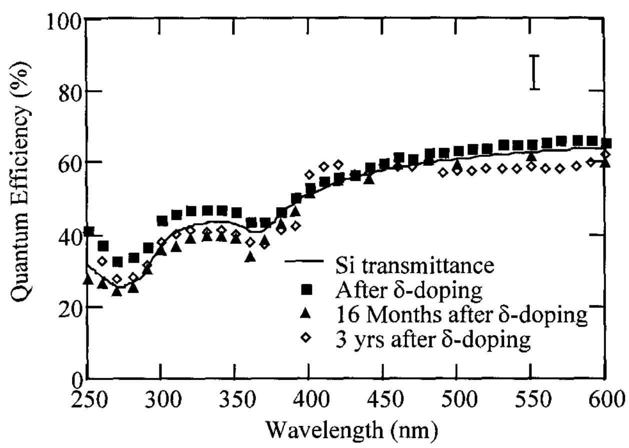

Figure 4. QE measured over a three-year period on the same delta-doped 512-by-512-pixel Reticon CCD. The CCD was stored unprotected in a laboratory environment. The error bars represent the accuracy (±5%) of the measurement systems used.

Delta-doped CCDs for 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. Quantum efficiency measurements in the UV indicate that electrons generated near the surface of delta-doped CCDs are detected efficiently and delta-doped CCDs are promising as imaging detectors of 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 a scanning electron microscope.[3,4] All devices were fully-characterized using UV illumination prior to the electron measurements.

Figure 5 shows the electron quantum efficiency of a delta-doped CCD plotted as a function of incident energy. Quantum efficiency was calculated by dividing the measured current from the CCD configured in photodiode mode to the measured electron beam current (measured by a Faraday cup), which is equivalent to the number of electron-hole pairs detected divided by the number of incident electrons. The measured quantum efficiency of the delta-doped CCD increases with increasing energy of the incident beam. The dependence of quantum efficiency on incident energy is due to the complicated interaction of electrons with silicon which results in the generation of multiple electron-hole pairs in the cascade initiated by each incident electron. A significant fraction of the incident energy is undetected, due to backscattering of incident electrons and other energy dissipation mechanisms (e.g., secondary and Auger electron emission). Multiple electron-hole pair production, also known in the literature as quantum yield, is also observed in the measured UV and x-ray response of delta-doped CCDs and other devices. Quantum yield greater than unity has been previously observed in backside-illuminated CCDs modified using the flashgate[5] and ion implantation[6] at electron energies greater than 1 keV. We have also used delta doped CCDs to image electrons in the 200-500 eV range[3].

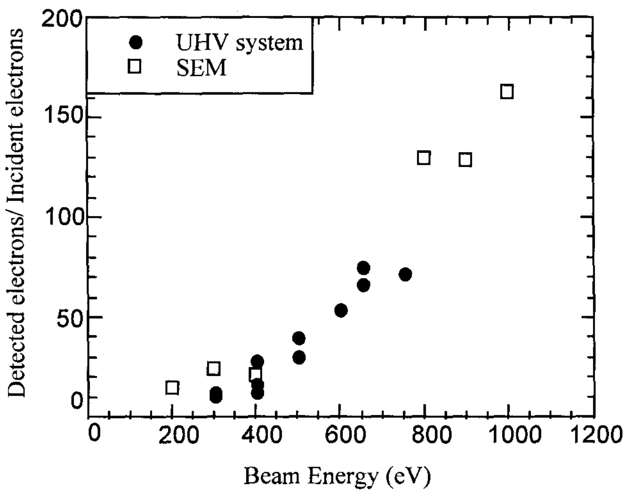

Figure 5 Ratio of detected electrons to incident electrons as a function of energy. The response of the CCD increases with increasing energy as result of multiple electron-hole pair generation.

Thinning and bonding at JPL

We have developed an end-to-end post fabrication processing for back-illuminated devices with UV enhancement and additional antireflection coatings [Jones2000, Deelman2000]. Thinning process at JPL has been developed to be versatile and applicable to both die and wafer level [Jones2000].

To achieve flat focal plane arrays, the CCD can be bonded to a flat substrate prior to the thinning. We have developed a bonding approach that is compatible with temperature and ultrahigh vacuum requirements of delta doping using gold-gold diffusion via thermocompression. This method has been described in detail in the paper by Jones et al [Jones2000]. The result of bonding a silicon substrate to the frontside of the CCD and thinning the CCD to 10 μm has rendered flatness within 200 Å.

Another approach for obtaining flat membrane is to attach the membrane to a flat substrate after the UV enhancement process such as delta doping has been performed. This way epoxy can be used as a bonding agent since the restrictions imposed by temperature and ultrahigh vacuum requirements have been removed. We have demonstrated flat focal plane arrays by creating a pressure differential across the membrane and the substrate. Figures 5 and 6 show two implementations of this approach. The small bumps on the flat array is the result of trapped particulates that can be removed by careful inspection and preparation of the surfaces.

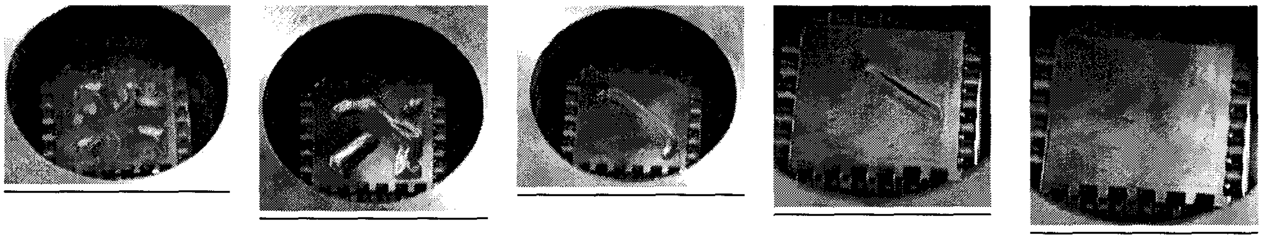

Figure 5. Freestanding membranes wrinkles are removed as a result of pulling the membrane down to the substrate.

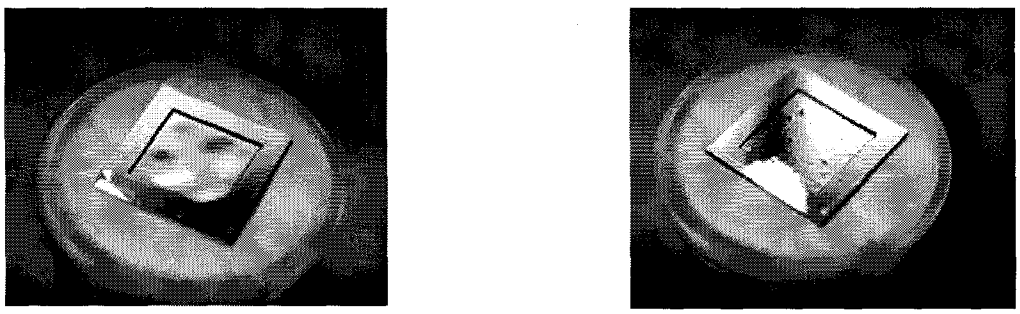

Figure 6 . Substrate is attached post accumulation processing. Sintered glass substrate is used to allow suction of excess boding epoxy. Substrates can be polished to optical flatness and membrane mimics the surface quality of the substrate

Detectors under Development using High Resistivity Silicon Technology

Hybrid and monolithic approaches are being developed to combine the delta doping technology to the new high resistivity silicon detectors. High resistivity silicon detectors can be depleted for the entire wafer thickness with modest fields (~100 V). Combining these detectors with delta doping allows detection of photons that have shallow absorption paths in silicon such as UV photons as well as higher energy photons with long absorption length into silicon such as low energy x rays. 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 shown that the detector is effectively delta doped. Further work in quantifying these results and development of the n-type detector is underway.

Field observations and feedback from scientific community

Delta-doped CCDs have been used in collaborations with several scientists in a number of field observations. In collaboration with Caltech, a delta-doped CCD was used to image galaxies in the near UV at Caltech's Palomar observatory. In a sounding rocket experiment in collaboration with the University of Colorado, a delta-doped CCD was used as the detector in the spectrograph for ozone concentration measurements in the upper atmosphere.

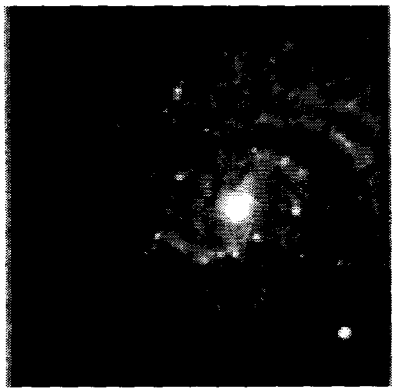

Figure 7 . Image of a spiral galaxy taken at the Palomar observatory. For comparison the same image in the visible is shown in 5b.

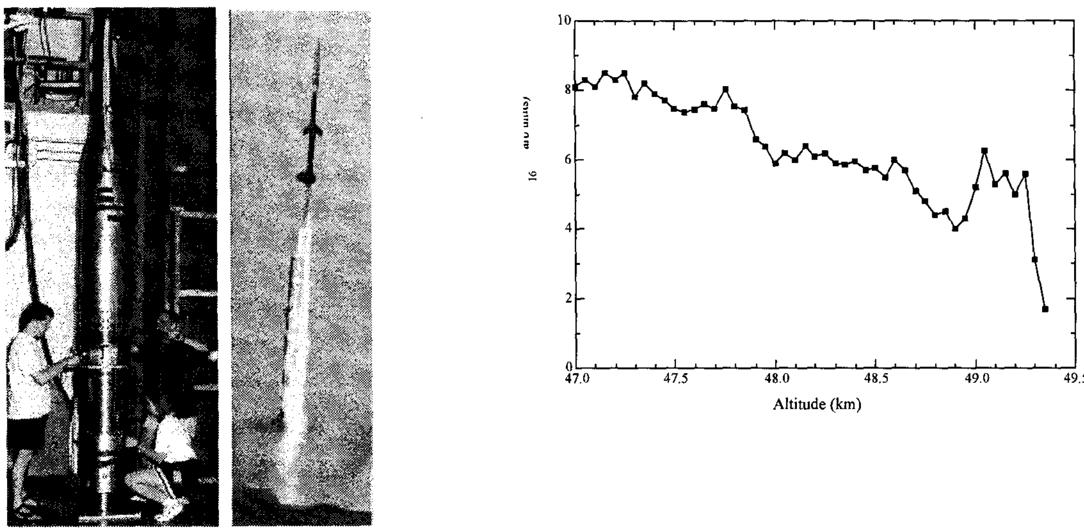

Figure 8 . Picture of HOMER sounding rocket and b) a sample of data that was taken during the rocket flight.

Use of delta-doped CCDs in very high precision photometry in collaboration with NASA Ames has been carried out showing that delta-doped CCDs have the dynamic range and stability necessary for high precision photometry [Barouki97].

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