# Delta-doped CCDs with integrated UV coatings

Peter W. Deelman*[a], Shouleh Nikzad[a], and Morley M. Blouke[b]

[a]Center for Space Microelectronics Technology, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109-8099
[b]Scientific Imaging Technologies, Inc., Beaverton OR 97975-0569

## ABSTRACT

Although they are not intrinsically sensitive to ultraviolet light, CCDs can be treated to have UV-enhanced response. JPL has developed a technology for modifying the backside of thinned, commercial CCDs that uses low-temperature molecular-beam epitaxy (MBE) to produce stable, 100% internal quantum efficiency throughout the full ultraviolet waveband. The delta-doping process is reproducible, the response of delta-doped CCDs is stable over several years, and no hysteresis is exhibited. The delta-doping process is compatible with optical filters and antireflection coatings deposited directly on the CCD back surface, because the delta-layer is localized beneath the back surface. Integrated filters eliminate the need for the additional structural support of an external filter; eliminate the need for the lossy substrates on which external filters are constructed and which would introduce loss and cut off the response at short wavelengths; imply fewer optical surfaces and eliminate the 2–3% minimum loss associated with each; and are more robust than the fragile and bulky external filter technologies.

We have established our ability to deposit filters and coatings directly on delta-doped CCDs by constructing a metal/insulator MBE chamber connected via an ultra-high-vacuum transfer line to the silicon MBE chamber, in which delta-doping is performed. We have fabricated preliminary $MgF_2$ AR coatings on delta-doped SITe CCDs.

**Keywords**: Delta-dope, CCD, UV, Detector, AR

## 1. INTRODUCTION

Conventional, back-illuminated silicon CCDs suffer from extremely low quantum efficiency (QE) at wavelengths less than 400 nm due to the conspiracy of two material properties. First, for a typical, back-illuminated CCD, a naturally-occurring sheet of charge (positive, in this case) that forms at the silicon-silicon dioxide interface creates a backside potential well that can trap minority carriers. Second, the absorption length of ultraviolet (UV) photons in silicon is small compared to the width of this potential well. Thus, the minority charge carriers generated near the backside surface by UV photons are trapped in the backside well and are never able to diffuse to the frontside collection well.

UV flooding, chemical charging (NO absorption), electrically floating thin metal layer[1], and active charging with a thin metal gate layer (biased flash gate) are some of the treatments devised to deal with the backside potential well[2].

JPL has developed a technology for modifying the backside of thinned, commercial CCDs that uses molecular beam epitaxy (MBE) to produce stable, 100% internal QE throughout the full UV waveband[3,4]. The MBE-enhanced device is referred to as a delta-doped CCD because MBE is used to place a single atomic plane of boron dopant atoms (known in the MBE literature as "delta-doping") within a 2.5-nm-thick layer of epitaxial silicon grown on the backside surface of a thinned CCD. The delta-doped layer behaves as a sheet of negative charge ~5Å underneath the oxide interface. The delta-doped layer is a permanent structural part of the device and provides reflection-limited QE. The delta-doping process, as implemented at JPL, is a low-temperature, post-fabrication treatment that is compatible with typical CCD fabrication processes.

It has been established that the response of delta-doped CCDs is stable over several years, is reproducible, and exhibits no hysteresis. All measurements show that delta-doped CCDs exhibit quantum efficiencies at the theoretical limit, which we define here to the reflection-limited response of silicon. For example, the QE of a delta-doped Reticon CCD measured immediately after delta-doping, eighteen months afterward, and three years afterward remained at the theoretical limit.[4] Similar behavior was observed in devices which had been exposed to 50–1500 eV electron beams as part of charged-particle detection experiments.

* Correspondence: Email: peter.deelman@jpl.nasa.gov; Telephone: 818 354 9443; Fax: 818 393 4540

## 2. DELTA-DOPED SITE CCDS

Recently, JPL has begun delta-doping CCDs fabricated by Scientific Imaging Technologies, Inc. (SITe) to take advantage of SITe CCDs' capability and performance. We have been working with two formats: the SITe 502A, which is a 512×512 device, and the SITe 001, which has an 1100×330 spectroscopic format. Although JPL has developed its own backside bonding and thinning process (see the paper by Jones *et al.* in this volume), devices obtained for these experiments were bonded to glass ceramic substrates and thinned by SITe, using a proprietary, wafer-level process. The CCDs were delta-doped at die level at JPL, then returned to SITe for packaging and electrical testing. The measured QE for each one of the two formats of CCD is shown in Fig. 1. The two devices exhibit identical, reflection-limited quantum efficiencies.

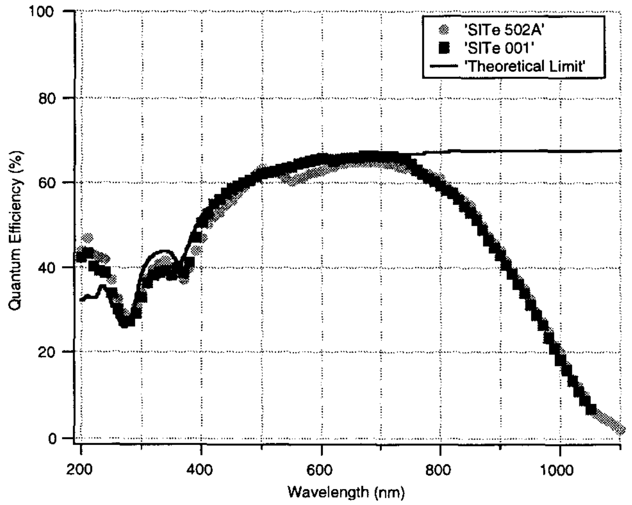



**Figure 1**. Measure QE of two bare, delta-doped SITe CCDs: the 502A, which is a 512×512 device, and the 001, which has a 1100×330 spectroscopic format.

## 3. INTEGRATED COATINGS AND FILTERS

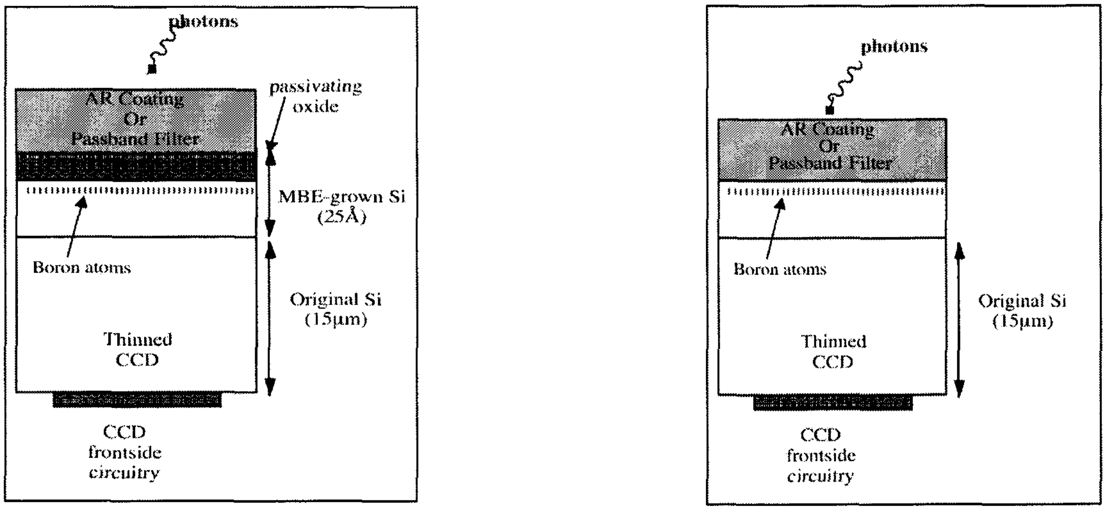
Delta-doped CCDs are compatible with filters deposited directly on the CCD backsurface, because the delta-layer is localized beneath the backsurface. There are numerous advantages to direct deposition of anti-reflection (AR) coatings and passband filters on CCDs: doing so eliminates the need for additional structural supports for external filters; it eliminates the need for the substrates on which external filters are constructed and which would introduce loss and cut off the response at short wavelengths; it implies fewer optical surfaces and eliminates the 2–3% minimum loss associated with each; it is more robust than the fragile and bulky external filter technologies; and the available wavelength regime for which filters can be designed ranges continuously form the near-IR to soft X-rays. Potential applications for delta-doped CCDs with integrated filters include multispectral imaging, solar-blind detection (particularly where signal-to-noise is dominated by scattered light), and passband imaging.

The feasibility of direct deposition of AR coatings on delta-doped CCDs was previously demonstrated by depositing $HfO_2$ films to enhance the quantum efficiency in two different regions of the spectrum (the region around 270 nm and the 300–400 nm region)[4]. Hafnium dioxide layers were deposited in collaboration with Prof. M. Lesser at the CCD laboratory of the University of Arizona, using resistive heating to evaporate the $HfO_2$. This approach avoids the X-ray exposure encountered in e-beam evaporation. Using a shadow-masking technique, two separate $3 \times 5$ mm$^2$ areas were used for the deposition of the two films on the same CCD. Because these were single-layer coatings, the AR-coated response qualitatively followed the characteristic peaks in the Si reflection response. The response of the AR-coated regions showed the expected enhancement in the quantum efficiency, indicating that the additional AR coating processes did not disrupt the delta-doped layer.

## 4. ADVANTAGES OF IN SITU DEPOSITION

One of the major technological hurdles for UV-sensitive CCDs is the need for some type of filter to reject visible wavelengths. UV observations can be severely compromised by light leaks in the visible waveband because the visible intensity from many astronomical sources is orders of magnitude stronger than the UV intensity. For example, astronomical objects often emit $10^4$ to $10^8$ visible photons for every UV photon in the 100 to 200 nm wavelength region[5]. The problem is exacerbated because the maximum sensitivity of the CCD is also in the visible wavelength regime.

We have already pointed out that delta-doped CCDs are compatible with having filters deposited directly on the CCD backsurface, and that there are numerous advantages for doing so. For imaging applications at wavelengths less than approximately 140nm (for example, the 121 nm Lyman-α line of great importance in astronomy), it becomes desirable not only for the filter to be integrated with the CCD, but also for the filter to be deposited *in situ*, because the native $SiO_2$ surface layer becomes strongly absorbing at these wavelengths.

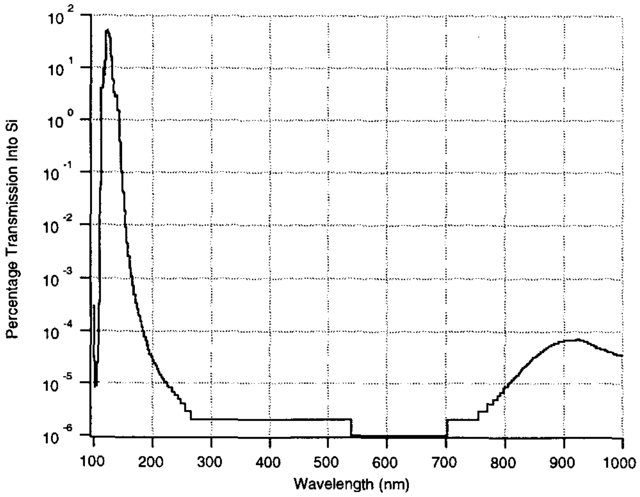



(a) (b)

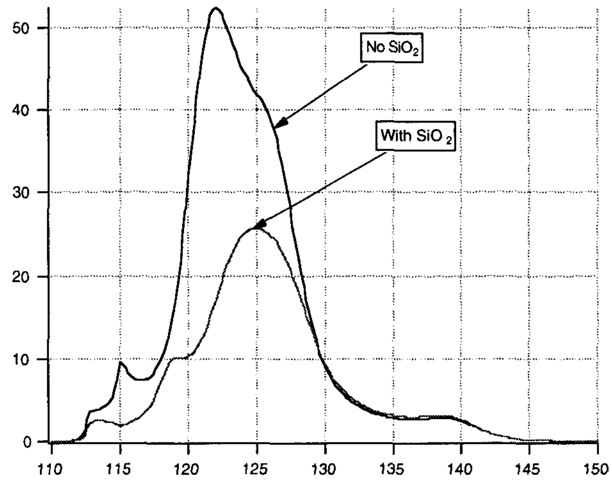
**Figure 2.** (a) Schematic of a typical, delta-doped CCD with an integrated filter or coating. Delta-doped CCDs are compatible with filters deposited directly on the CCD backsurface, because the delta-layer is localized <u>beneath</u> it. (b) By depositing the coating or filter *in situ*, formation of silicon oxide can be avoided.

CCDs are delta-doped in a silicon molecular beam epitaxy (MBE) chamber under ultrahigh vacuum (UHV) conditions. Removing the CCD from UHV chamber in order to perform the deposition of the direct filter in an external chamber would allow the growth of a native $SiO_2$ surface layer during the transfer. For example, the peak transmission for a three-cavity, $MgF_2$/Al Fabry Perot filter optimized for Lyman α (see Fig. 3) is reduced from approximately 50% to approximately 25% in the presence of a 20Å thick oxide (even after optimizing the filter design to accommodate the oxide).

We have established our ability to deposit filters and coatings directly on delta-doped CCDs by constructing a metal/insulator (M/I) MBE chamber. The M/I MBE is a modified Riber 1002 MBE system with a base pressure less than $\sim 2\times10^{-10}$ Torr, thus with an extremely low background of $H_2O$, $O_2$, etc. *In vacuo* transfer of delta-doped CCDs from the Si MBE, in which delta-doping is performed, to the M/I MBE is effected via a UHV track and cassette. The M/I MBE contains four water-cooled effusion cells, three of which are specialized for the high-temperature (up to 2000°C) evaporation required by most high-index materials. The importance of thermal evaporation sources, rather than the conventional, electron-beam sources typically used by coating houses, is that CCD performance is degraded by x-rays generated by electron beams.




(a)




(b)

**Figure 3.** Computed transmission into silicon through an integrated, 3-cavity, Fabry-Perot passband filter fabricated with Al and $MgF_2$. The calculation was implemented in TFCalc and took into account absorption and dispersion of the filter materials. The filter is optimized for the Lyman-α wavelength, 121 nm. In (a), the transmission is plotted on a logarithmic scale, highlighting that transmission in the visible is nearly seven orders down from transmission at Lyman-α. In (b), the effect of a 20Å $SiO_2$ layer is shown to decrease peak transmittance by nearly a factor of two.

## 5. PRELIMINARY RESULTS

We have begun deposition of Al and $MgF_2$ in the M/I MBE. Growth rates have been calibrated from SEM images of the films (an example is shown in Fig. 4), which show the low-temperature $MgF_2$ to have a columnar structure with a relatively smooth surface morphology. The dielectric constant of a thick (2600Å) film grown at room temperature was 1.381± 0.009, as determined by spectroscopic ellipsometry.

Single-layer $MgF_2$ AR coatings optimized for the 200–300 nm region of the spectrum were deposited on delta-doped SITe 502A and 001 CCDs. There was a modest improvement in the QE compared to the uncoated CCDs (e.g., 37% QE at 180nm, compared to 28%), but less than anticipated. A possible explanation is that the $MgF_2$ film thickness was much less than anticipated; however, these results are still under examination. Studies of single-cavity $MgF_2$/Al Fabry-Perot filters have been initiated, as have single-layer $HfO_2$ AR coatings.


**Figure 4.** Scanning electron microscope image of a silicon wafer coated with 3000Å $MgF_2$ and 2000Å Al.

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