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Superlattice-doped detectors for UV through gamma-ray imaging and spectroscopy

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Stable, high performance detectors for the far ultraviolet through x-ray regions of the spectrum are needed for a variety of instruments and applications in NASA, the U.S. Departments of Energy and Defense, medicine, and the semiconductor industry. Whereas state-of-the-art silicon detectors have many advantages in these applications, radiation-induced degradation of surfaces and interfaces remains a challenging problem. In particular, silicon detectors can achieve high quantum efficiency and low noise performance in low light level environments, but this performance depends on the stability of the illuminated back surface. State-of-the-art surface passivation processes entail a tradeoff between performance and stability. For example, the SOHO Extreme Ultraviolet Instrument used back-illuminated CCDs that were fabricated using state-of-the-art ion implantation and anneal technologies for surface passivation. Whereas the SOHO CCDs initially exhibited high quantum efficiency and low noise, they suffered severe degradation when they were operated in space. Detector quantum efficiency fell by as much as 80%, and the devices became permanently unstable (Figure 1).[1] An in-depth study concluded that SOHO's ion-implanted CCDs had suffered irreversible surface damage caused by exposure to solar EUV radiation. Here we show that JPL's unique surface passivation technologies solve this problem by using molecular beam epitaxy (MBE) and atomic layer deposition to engineer a highly stable Si-SiO_2 interface.

In the 2013 IISW workshop, we reported on the DUV stability of CMOS imaging detectors passivated using JPL-developed MBE passivation technologies.[2] Back-illuminated, superlattice-doped CMOS detectors were exposed to DUV lasers at 193nm and 263nm. Superlattice-doped detectors did not suffer any measurable degradation even after exposure to >2 billion laser pulses at full saturation. Internal QE was nearly100% (excluding Quantum Yield) with no blooming and no image memory at 1000 fps. At 263nm, a single layer Al_2O_3 coating enabled an external QE of 64%. High modulation transfer function was achieved, with no blooming and no image memory at 1000 fps. In this paper, we report advances in this technology with new detectors and new coatings, including significant progress on the development of multilayer and solar blind coatings.

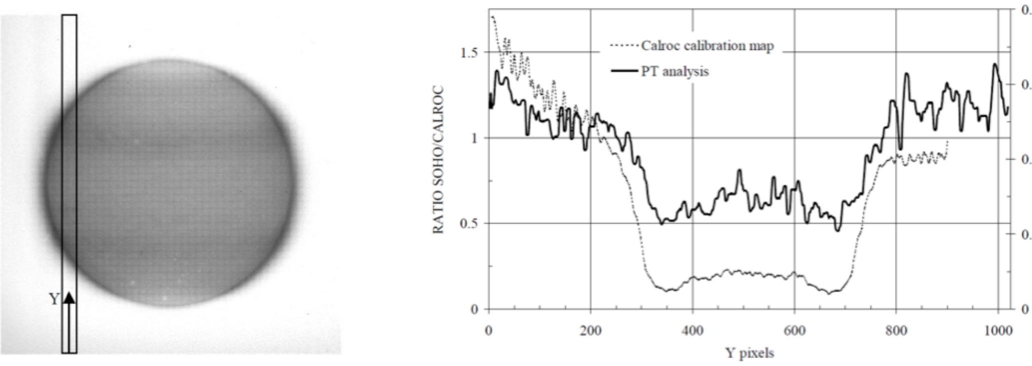

Figure 1: Comparison of back-illuminated, ion-implanted CCD response before and after exposure to solar extreme ultraviolet radiation demonstrates severe, permanent damage caused by traps formed at the Si-SiO_2 interface. (Source: Defise et al., 1998)

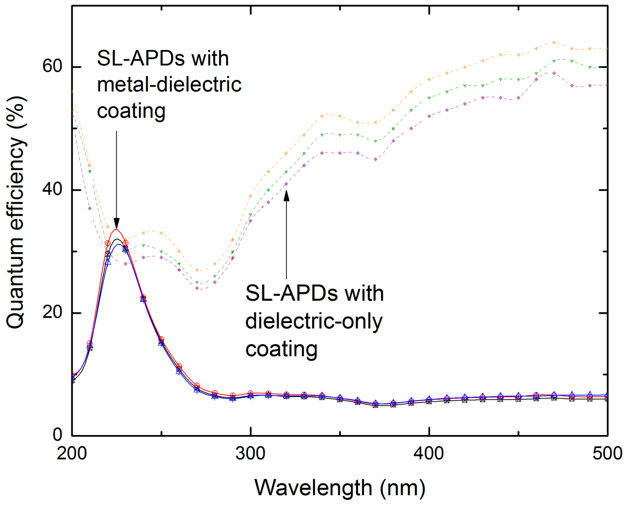

Figure 2: Superlattice doped avalanche photodiodes with integrated 3-layer metal-dielectric filter demonstrate the potential for DUV detectors with integrated solar-blind filters. The QE at full depletion could not be directly measured because of gain; extrapolations of QE vs. bias voltage estimate in-band QE >50% at full depletion. (Source: Nikzad *et al.*, 2014.)

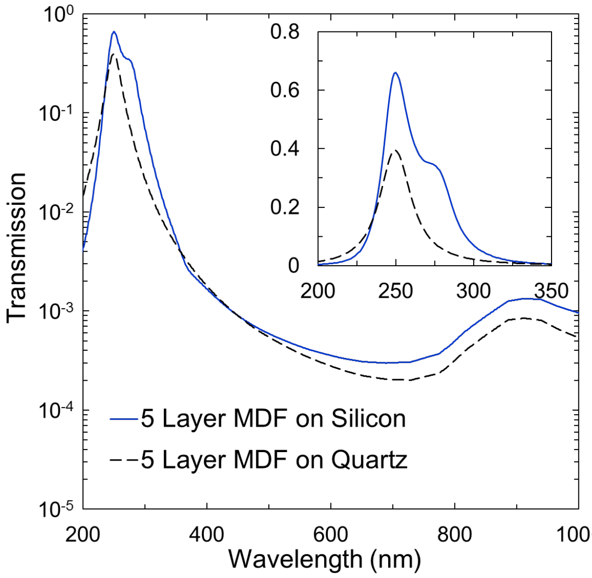

Figure 3: The calculated performance of a five layer metal-dielectric filter on silicon or quartz substrates, showing in-band QE>60% and out-of-band rejection approaching 10^{-4}. (Source: Hennessy *et al.*, 2014.)

Superlattice doping does not prevent surface damage, but rather protects the device from its effects.[3-5] In extreme cases, surface damage from UV photons can exceed 10^{14} traps/cm^2. The growth of a 2D-doping superlattice by molecular beam epitaxy can place up to 10^{15} dopants/cm^2 within a few nanometers of these surface traps. Lifetime tests performed on superlattice-doped detectors by Applied Materials Inc. demonstrated that detector performance remains stable despite high levels of UV-induced surface damage. The unique stability of superlattice-doped detectors can be explained in terms of the physics of superlattice-doped surfaces. Radiation-induced surface defects form interface states that can trap a high density of charge at the Si-SiO_2 interface. In the case of superlattice-doped surfaces, charge is transferred from the superlattice to the interface traps, thus forming a nanometer-scale charge dipole layer at the Si-SiO_2 interface. This surface dipole layer stabilizes the surface band structure in the detector, effectively creating a surface passivation layer that remains stable despite high levels of radiation-induced surface damage.[5]

Superlattice doping has enabled the production of stable, high efficiency CMOS and CCD imaging detectors, fully-depleted silicon photodiodes, and linear mode avalanche photodiodes. The stability of superlattice-doped surfaces makes these devices compatible with a wide variety of antireflection (AR) coatings formed by atomic layer deposition (ALD). We have demonstrated superlattice-doped detectors with integrated multilayer AR coatings that achieve >80% quantum efficiency in the visible (broadband) and deep ultraviolet (narrow band).[6-9] In a breakthrough for silicon detectors, we have developed metal-dielectric multilayer coatings for solar blind silicon detectors with >50% in-band quantum efficiency and up to four orders of magnitude out-of-band rejection (Figures 2 and 3).[10] Future work is needed to characterize and qualify the stability of these coatings for demanding environments and applications.

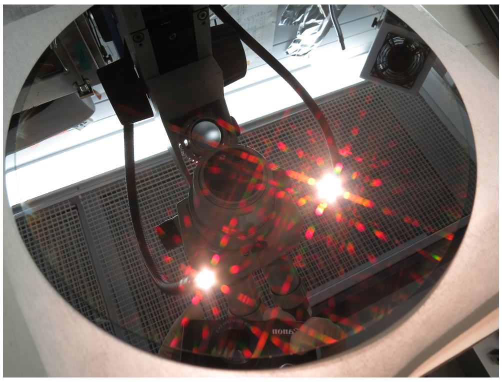

Figure 4: CMOS wafer with CMV12K devices after bonding, thinning, and MBE/ALD passivation. These 3kx4k super HD CMOS detectors were designed by CMOSIS nv and fabricated by TowerJazz on 200mm wafers using a 0.18µm CIS process. Novati bonded the wafers to a 200mm silicon wafer for mechanical support. JPL performed final thinning and surface passivation at full wafer scale using an MBE-grown 2-layer superlattice. Finally, JPL used atomic layer deposition to grow a 2nm Al_2O_3 layer on the back-illuminated surface. Metrological measurements indicate final device thickness between 2 and 3 µm.

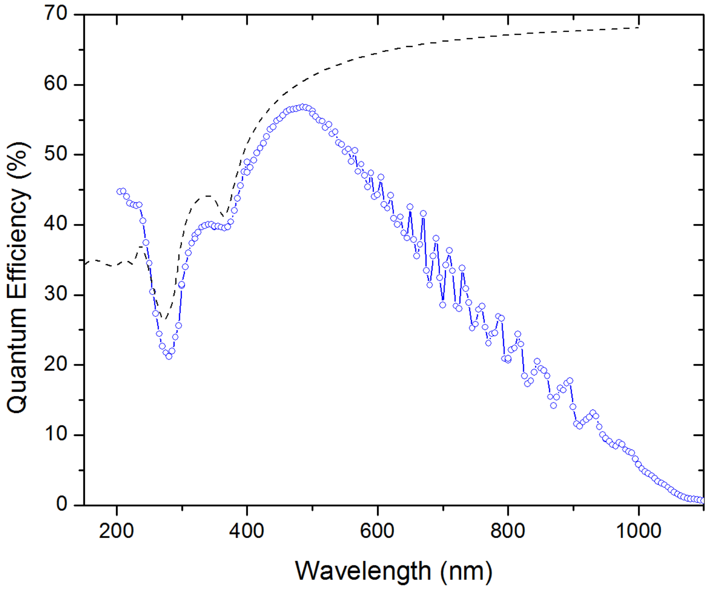

Figure 5: Measured quantum efficiency of back-illuminated, superlattice-doped CMV12000 device. For reference, the optical transmission of a 2nm Al_2O_3 coating on a silicon substrate is plotted as a dashed line. The observed falloff in quantum efficiency at wavelengths longer than 500nm is consistent with the measured 2 to 3 µm thickness of devices after thinning when considering a possible wavelength-dependent fill factor under back illumination. The difference between the coating transmission and the measured QE at short wavelengths suggests that about 90% of UV photons are detected, which is also consistent with a fill factor slightly less than unity. At short wavelengths (below ~300nm), the QE exceeds the optical transmission of the coating, which is consistent with multiple electron-hole pair production by high energy photons (see references on quantum yield).

We are currently working on developing and qualifying superlattice-doped, AR-coated CMOS and CCD detectors for commercial and NASA applications, including EUV detectors in future ESA and NASA heliophysics instruments and missions. Figures 4 and 5 show quantum efficiency data measured by CMOSIS nv on back-illuminated, superlattice-doped CMV12000 detectors for commercial super HD imaging.[11] For the latest results in our work on high performance, superlattice-doped CCD detectors, see Nikzad *et al.,* this workshop.[12]

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References

[1] Defise, J.M.; Moses, J.D.; Clettec, F; EIT Consortium, "In-orbit performances of the EIT instrument on-board SOHO and intercalibration with the EIT Calroc Sounding rocket program," *Proc. SPIE 3442*, Missions to the Sun II, 126 (November 2, 1998).

[2] Hoenk, M. E.; Carver, A. G.; Jones, T. J.; Dickie, M.; Cheng, P.; Greer, F.; Nikzad, S.; Sgro, J.; Tsur, S.; "The DUV Stability of Superlattice-doped CMOS Detector Arrays," Proceedings of the 2013 International Image Sensor Workshop, Snowbird, UT, June 12-16, 2013.

[3] Hoenk, M.E., "Surface Passivation by Quantum Exclusion Using Multiple Layers," U.S. Patent 8,395,243.

[4] Hoenk, M.E.; Carver, A.G.; Jones, T.J.; Dickie, M; Nikzad, S.; Sgro, J.; Tsur, S.; "Superlattice-doped Imaging Detectors: Structure, Physics, and Performance," Proceedings of the Scientific Detectors Workshop, Florence, Italy, October 7-11, 2013.

[5] Hoenk, M.E.; Nikzad, S; Carver, A.G.; Jones, T.J.; Hennessy, J.J.; Jewell, A.D.; Sgro, J.; Tsur, S.; McClish, M.; Farrell, R.; "Superlattice-doped imaging detectors: progress and prospects," *Proc. SPIE*. 9154, High Energy, Optical, and Infrared Detectors for Astronomy VI, 915413. (July 30, 2014) Montreal, Canada, June 24, 2014.

[6] Nikzad, S.; Hoenk, M. E.; Greer, F.; Jacquot, B.C.; Monacos, S.; Jones, T.J.; Blacksberg, J.; Hamden, E.; Schiminovich, D.; Martin, C.; Morrissey, P., "Delta doped Electron Multiplied CCD with Absolute Quantum Efficiency over 50% in the near to far Ultraviolet Range for Single Photon Counting Applications," *Applied Optics*, Vol. 51, Issue 3, pp. 365-369 (2012).

[7] Greer, F.; Hamden, E.; Jacquot, B.C.; Hoenk, M.E.; Jones, T.J.; Dickie, M.; Monacos, S.P.; Nikzad, S., "Atomically Precise Surface Engineering of Silicon CCDs for Enhanced UV Quantum Efficiency", *Journal of Vacuum Science and Technology A*, 01A103-1 (2013).

[8] Jewell, A.D.; Hennessy, J.J.; Hoenk, M.E.; Nikzad, S., "Wide band antireflection coatings deposited by atomic layer deposition," Proc. SPIE 8820, Nanoepitaxy: Materials and Devices V, (2013).

[9] Nikzad, S.; Hoenk, M.E.; Hennessy, J.J.; Jewell, A.D.; Carver, A.G.; Jones, T.J.; Cheng, S.L.; Goodsall, T.M.; Shapiro, C., "High Performance Silicon Imaging Arrays for Cosmology, Planetary Sciences, & Other Applications," IEDM Proceedings, Invited paper, San Francisco, CA, 2014.

[10] Hennessy, J.J.; Jewell, A.D.; Hoenk, M.E.; Nikzad, S., "Silicon Integrated Metal Dielectric Filters for the Ultraviolet," submitted (2014).

[11] CMV12000 Area Scan Sensors, product sheet available from CMOSIS nv, http://www.cmosis.com/assets/generate-single-pdfs.php?products=cmv12000

[12] Nikzad, S.; Hennessy, J.J.; Hoenk, M.E.; Jewell, A.D.; Carver, A.G.; Goodsall, T.M.; Jones, T.J.; Hamden, E.; Bell, L.D., "Silicon and III-N UV Photon Counting Detectors," International Image Sensors Workshop, Vaals, the Netherlands, June 8-11, 2015.