2013 International Image Sensor Workshop
June 12-16, Snowbird, UT

The DUV Stability of Superlattice-doped CMOS Detector Arrays

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Abstract

JPL and Alacron have recently developed a high performance, DUV camera with a superlattice doped CMOS imaging detector (Figure 1). Superlattice doped detectors achieve nearly 100% internal quantum efficiency in the deep and far ultraviolet, and a single layer, Al_2O_3 antireflection coating enables 64% external quantum efficiency at 263nm. In lifetime tests performed at Applied Materials using 263nm pulsed, solid state and 193nm pulsed excimer lasers, the quantum efficiency and dark current of the JPL/Alacron camera remained stable to better than 1% precision during long-term exposure to several billion laser pulses, with no measurable degradation, no blooming, and no image memory at 1000 fps.

Superlattice Doped Detectors

The quest for a DUV-stable silicon imaging detector has reached an impasse. DUV radiation inevitably creates high densities of interface and oxide trapped charge in silicon detectors. Radiation-hardened oxides help to limit the damage, and doping the surface helps to mitigate its effects, but the fundamental problem remains. State-of-the-art silicon detectors have repeatedly failed under irradiation by pulsed DUV lasers.[1,2]

A different approach is needed. To paraphrase Lieutenant Lawrence, the trick is not minding the damage. We have used molecular beam epitaxy to embed multiple 2D-doped layers within a few nanometers of the silicon surface (Figure 2).[3] The quantum properties of the superlattice lead to the required DUV stability.

Figure 1: Alacron FC300 back-illuminated DUV camera with JPL superlattice-doped and AR-coated CMOS imaging array.

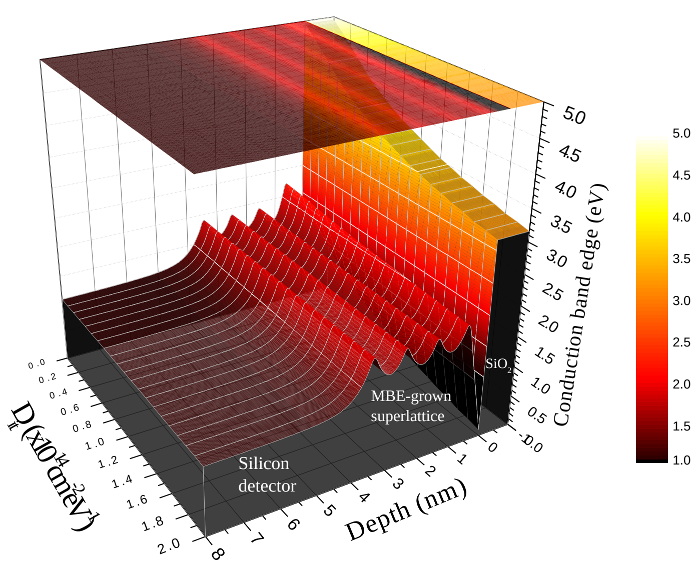

Figure 2: Superlattice doping comprises multiple two-dimensional sheets of dopant atoms within a few nanometers of the detector surface, which screen the detector from DUV-induced damage up to interface trap densities exceeding $10^{14}cm^{-2}eV^{-1}$.

DUV Detector Requirements and Limitations

State-of-the-art wafer and reticle inspection systems use deep ultraviolet (DUV) lasers at 263 nm and 193nm for optical detection of defects down to the range of 32nm to 20 nm and below. Imaging systems require resolutions of approximately 8 megapixels, and frame rates of up to 1000 frames per second. High brightness sources and efficient detectors are required for maximum throughput. While back-illuminated CMOS imaging arrays meet the requirements for resolution, frame rate, and noise, stability and durability under DUV illumination present major technological challenges.

DUV-stable silicon detectors that would meet these requirements have been sought for years.[1] Surface passivation methods used to fabricate UV-sensitive, back-illuminated silicon detectors comprise a variety of field-induced and surface doping passivation technologies. These methods include chemisorption charging, ion implantation, and dopant diffusion, all of which are used in commercially-available silicon detectors. Nevertheless, DUV stability remains elusive due to the excessive damage induced at the Si-SiO_2 interface by DUV photons.

Figure 3 illustrates the damage wrought by DUV radiation on an ion-implanted, back-illuminated silicon device. In the figure, surface damage is quantified in terms of the density of interface traps, D_{it}. High quality, hydrogen-passivated silicon surfaces can have defect densities as low as 10^{10} $cm^{-2}eV^{-1}$. Exposure to DUV radiation catalyzes various “depassivation” processes that, in effect, convert latent defects into electrically active traps. In extreme cases, DUV radiation causes virtual disintegration of the oxide lattice structure, resulting in defect densities exceeding 10^{14} $cm^{-2}eV^{-1}$.[4] As shown in the figure, charge trapped at the Si-SiO_2 interface creates a potential well for electrons, which is often referred to as the “surface dead layer.” Whereas low defect densities correspond to a thin dead layer, higher trap densities cause the width and depth of the dead layer to increase dramatically. DUV-damaged, ion-implanted detectors exhibit low, unstable quantum efficiencies and marked degradation of dark current due to dynamic charging and discharging of interface traps under illumination. Comparing the length scales in Figures 3 and 4 graphically illustrates the built-in stability of superlattice doped detectors.

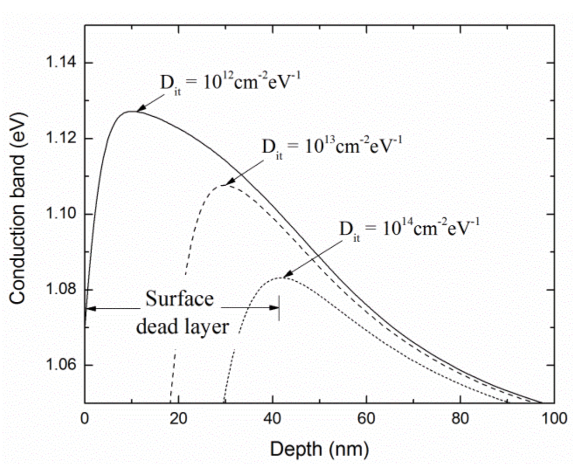

Figure 3: Ion-implanted detectors damaged by DUV radiation exhibit a “surface dead layer” that traps photogenerated charge and causes low, unstable DUV quantum efficiency.

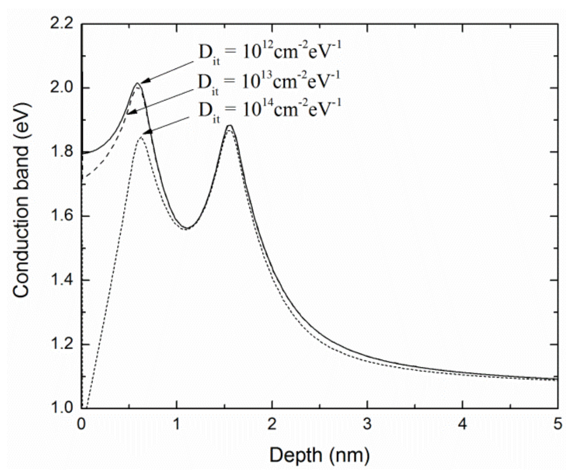

Figure 4: Superlattice doping creates a nanometer-scale, near surface quantum well. Quantum confinement effectively prevents electron trapping at the interface, resulting in high, stable DUV quantum efficiency.

Superlattice Doping and AR-coating of 200mm CMOS Detector Wafers

DUV-stable surface passivation was implemented using JPL's newly-developed superlattice doping technology. Detector wafers comprising 64 CMOS arrays were bonded to a silicon wafer for mechanical support and back-thinned at JPL to expose the 5 μm epilayer (Figure 5). JPL grew a two layer doping superlattice on the thinned detectors at full 200 mm wafer scale using a Veeco Gen 200 molecular beam epitaxy system (MBE) and Oxford atomic layer deposition (ALD) systems. Each of the layers contained a sheet of boron atoms with a surface density of 2×10^{14} cm^{-2}, with an interlayer spacing of 1 nm. A 2.5 nm silicon cap layer was grown on the superlattice to stabilize and protect the superlattice. Devices used in 263 nm experiments included an antireflection coating grown by ALD, comprising 28 nm Al_2O_3. Devices used in 193 nm experiments were not AR-coated.

The DUV Stability of Superlattice Doped Detectors

Figures 2 and 4 illustrate the stability of superlattice doped detectors by plotting the conduction band edge of superlattice-doped silicon surfaces over a wide range of interface trap densities, D_{it}. The calculated bandstructures represented in these figures were generated using the nextnano3 software package to self-consistently solve the Poisson and Schrödinger equations for a variety of dopant profiles and interface trap densities.[5] These calculations show that the near surface bandstructure of superlattice doped detectors is stable over a wide range of interface trap densities relevant to intense DUV irradiation. Additional details are presented in the patent.[3]

193 nm Experimental Lifetime Setup

The sensor was illuminated with a 193nm excimer pulsed DUV laser that emitted collimated 10 ns pulses at 1000 Hz, at a duty factor (DF) of 67% (2 sec ON, 1 sec OFF). A set of 2 optical diffusers in tandem comprised the beam-shaping optics that provided a Flat-Field (FF) illumination of the surface of the sensor at an energy density of 80 nJ/cm^2, which corresponds

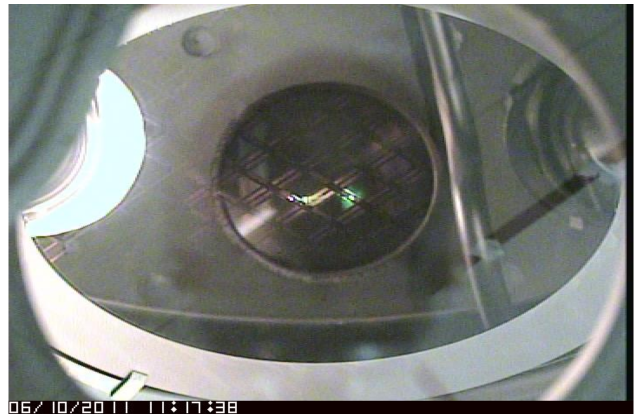

Figure 5: Photograph of a 200 mm wafer in silicon molecular beam epitaxy system taken during superlattice doping process. Specular reflections from the flat silicon surface are visible in the image. The pattern of CMOS devices on the wafer is faintly visible through the 5 μm epilayer due to the partial transparency of thinned, back-illuminated silicon devices. Each wafer comprises ~64 CMOS imaging arrays, each having 1500x2000 resolution.

to the saturation exposure of this detector. A slit of controlled size and position in front of the camera, served to illuminate a distinct area inside the FOV of the sensor while the rest of the sensor was covered for reference (Figures 6 and 7). When the response of the sensor was monitored, the slit was moved out of the line-of-sight and the sensor was exposed to a FF illumination. Following a short monitoring session, the slit replaced the FF in front of the sensor (with a repetition of ~1 pixel) for further accumulation of DUV exposure pulses. The sensor received ~60 MP of 1 saturation exposure per each 24h, and its degradation was monitored on a daily basis.

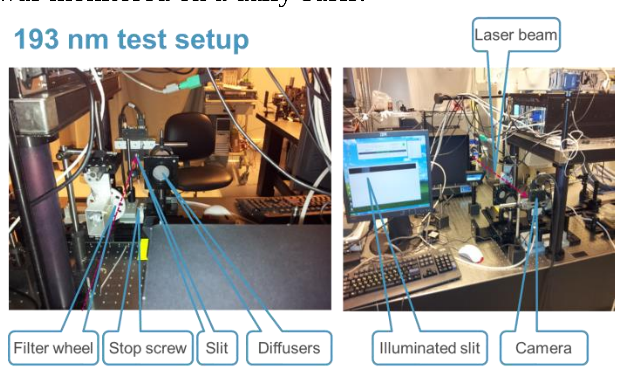

Figure 6: Experimental setup

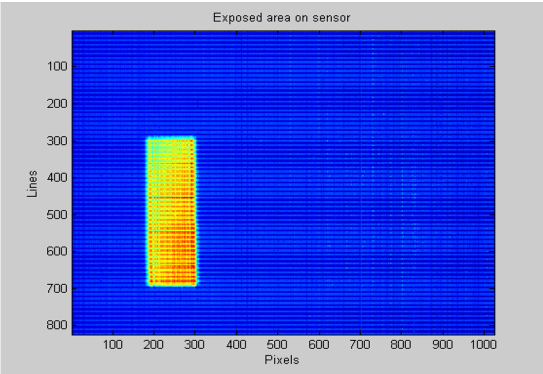

Figure 7: Exposure slit position on sensor

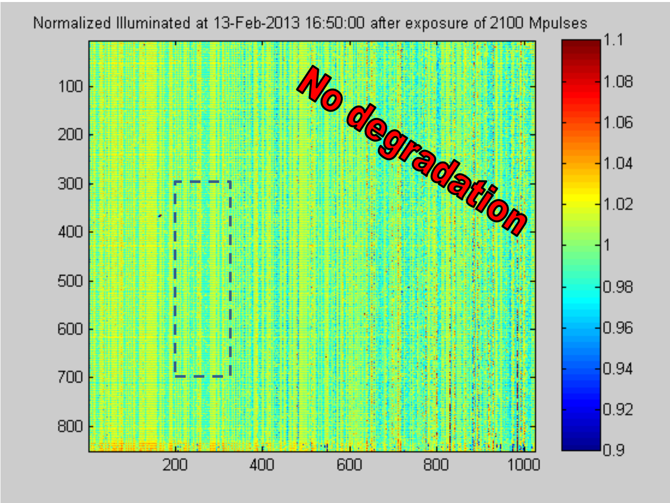

Figure 8: Normalized Spatial Response following 2.1 B pulses

Analysis

Cameras' electronic noises are subtracted to accurately measure the physical stability of the photo response mechanism. Fig. 8 shows an analysis of a 100 consecutive images following 2.1 Billions of 193 nm laser pulses with no evidence of any degradation of the illuminated area.

Following >2 Billion laser pulses at full saturation, there is no measureable change (within +1%) in the local response of the sensor (Figure 7). Current estimation are that actual lifetime exceeds 10B laser pulses. Technology was also verified to meet inspection requirements by measurement of the internal QE to be ~100% (excluding Quantum Yield), with no blooming and no image memory to be present at 1000 fps.

263 nm Results

A similar test setup with a pulsed 263 nm laser on an AR coated sensor, at up to x257 camera saturations, showed no measurable degradation following an accumulated illumination dose of 3100 J/cm^2. No blooming and no image memory were present even at the high saturation levels. The sensor also demonstrated a high MTF (Figure 9).

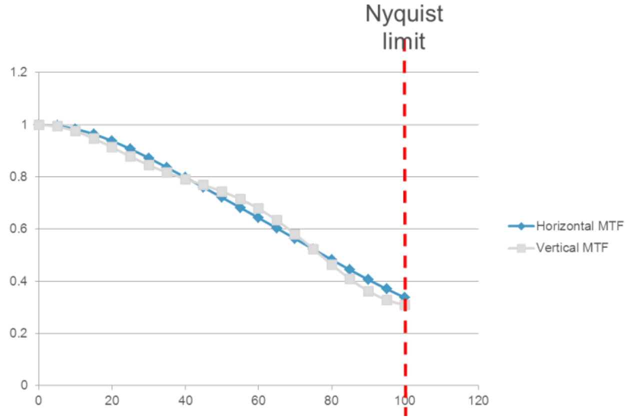

Figure 9: Horizontal and vertical MTF of the sensor

Acknowledgements

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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