DUV Optimized CCD with Oxide Micro-lenses

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Abstract

This paper presents the fabrication and characterization of an image sensor with sensitivity from UV-C (200nm) to NIR (1000nm). Deep ultraviolet (DUV) sensitivity in the 200 to 268nm range is achieved by replacing organic micro-lenses with oxide equivalents and removing silicon nitride from the optical path. Both EMCCD, with <1e- noise, and conventional CCD variants will be discussed. Quantum efficiencies in excess of 45% were measured at 250nm and >25% at 200nm.

Methods to produce gapless inorganic lenses will be presented with associated process sensitivities and performance tradeoffs. Challenges of DUV operation and testing will be reviewed including light sources, UV reliability, and quantum efficiency measurements.

Introduction

Existing sensors typically employ organic micro-lenses to optimize quantum efficiency. Although effective for visible light, the transmission of these materials drops abruptly below 300nm. Oxide lenses have excellent transmission in the UV, but increase process complexity. A simplified and economical oxide lens process can allow applications below 300nm including spectroscopy, machine vision, power line inspection, and lithographic inspection.

High intensity UV radiation has been shown [1] to cause point defects, decreased response, and/or increased dark current in silicon image sensors. The electron-hole pairs generated near the surface by UV photons are much more susceptible to electric fields and lattice defects at the silicon-oxide interface than lower energy photons absorbed deeper into the bulk. The interface itself can be damaged by UV light causing a shallow well at the surface that holds UV generated photons at the surface where they recombine with holes and are lost [1]. Nanoscale interface engineering using Atomic Layer Deposition (ALD) and Molecular Beam Epitaxy (MBE)[4,5] have been demonstrated as tools to address these surface issues. This work characterizes the performance of a UV optimized optical stack in an interline CCD with traditional pinned photodiode and a hydrogen passivated silicon/oxide interface.

Two processes were initially evaluated for the fabrication of TEOS oxide lens structures; pattern transfer and dep-etch. Pattern transfer involves creating the lens structure in one layer and transferring it into a second material using an etch process at or around 1:1 selectivity. [2] The dep-etch approach [3] begins with a “seed” pillar feature that is subjected to a series of over-coat and etch back processes to form the desired shape. The dep/etch process described in this work was selected due to superior process control and photo-response non-uniformity (PRNU) performance.

Fabrication Process

The process sequence illustrated in Figure 1 is based on a interline CCD process developed to deliver low dark current (3e-/s at 40C, <0.1e/-s at -10C) for conventional visible light applications. This is achieved with a pinned photodiode and a hydrogen passivated silicon/oxide interface. The oxynitride acts both as an environmental barrier and a nearby source of hydrogen to passivate the surface. The photodiode nitride film in the stack can be tuned as an antireflection coating or removed completely depending on the application.

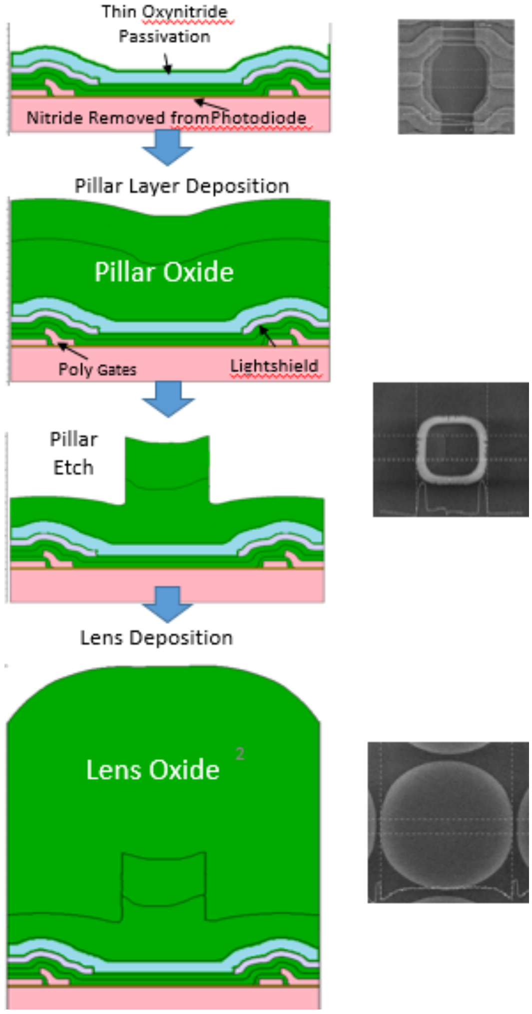


Figure 1: Dep-etch lens process sequence

The lens formation process begins with the deposition of a TEOS oxide with a typical thickness of between 2 and 3 microns. This layer is then patterned and etched to produce a pillar that serves as a “seed” for the subsequent lens dep/etch process steps to form the desired shape.

Process Challenges

Since a lens acts as an optical concentrator, subtle differences in lens size, shape, and surface topography are also amplified and can cause local or global PRNU across the sensor. Although many processes can produce lens shaped features, it is challenging to create extremely uniform arrays across large areas.

The pillar etch process itself posed the most challenges. It was desirable to have a single oxide film over the oxynitride to maximize UV transmission and minimize reflections at layer interfaces. A timed oxide etch was designed to end within the pillar layer deposition. The depth of this etch and the changing properties of the exposed photoresist requires careful management of the carbon ratio. Too much polymer deposition results in non-uniform buildup on horizontal surfaces that produces a rough surface between the pillars. Too little polymer deposition causes the resist sidewall to erode and partially or fully expose the top of the pillar during the etch. This erosion rate and subsequent breakthrough can have significant local and global variation leading to visible image artifacts.

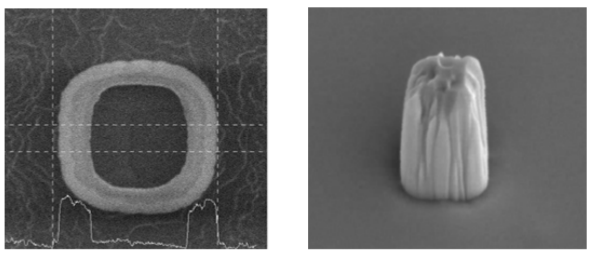


Figure 2: Pillar etch process issues

Process conditions have been optimized to balance these effects and PRNU values are comparable to visible light organic lens performance.

DUV Performance and Optimization

The impact of different materials and photodiode AR layers on quantum efficiency (QE) were evaluated. Above 500nm, oxide lenses with visible light optimized AR coatings performed well through the IR range. Below 250nm, UV optimized ONO layers and no-nitride samples outperformed the visible optimized stack. Results are shown in Figure 3.

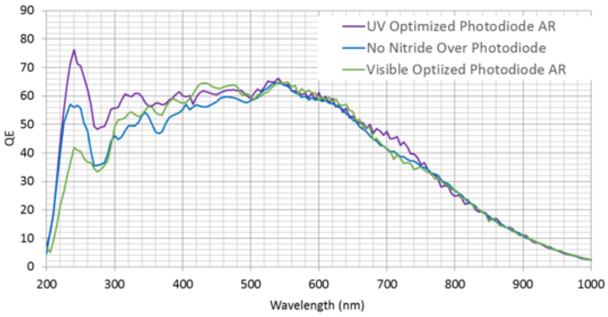


Figure 3: QE w/ UV optimized AR layers

The sharp decline in QE below 220nm is caused by the oxynitride as shown in Figure 4 where the quantum efficiency improved by a factor of three when the layer was removed from the photodiode. Dark current increased when the oxynitride was removed.

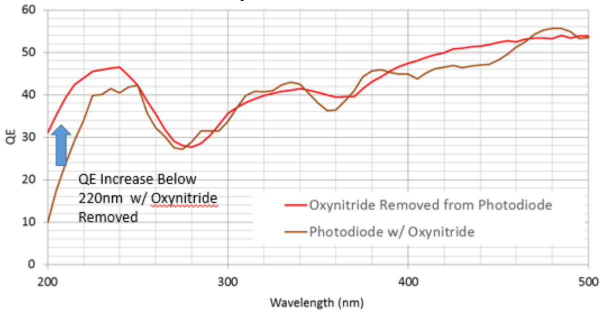


Figure 4: Impact of oxynitride film at 200nm

UV Stability

In a pinned photodiode, a high concentration of holes at the surface suppresses thermal generation of electrons at interface states by providing a lower energy alternative (recombination). Photo electrons generated by the UV signal are also subject to recombination, but are quickly pulled into the photodiode by the strong electric fields present in the device. The impact of prolonged UV exposure on dark current and photo-response was characterized by placing a 268nm UV diode on the surface of the sensor. Emission rates were approximately 300 times the exposure level needed to create a saturated image within the normal frame time.

No ghost (latent) images were observed in either dark or bright field images. Photo-response and dark current were not impacted. Further evaluation revealed decreased margin in the photodiode transfer gate voltage necessary for lag free operation. More pulling potential was needed in the exposed regions to completely empty the photodiodes.

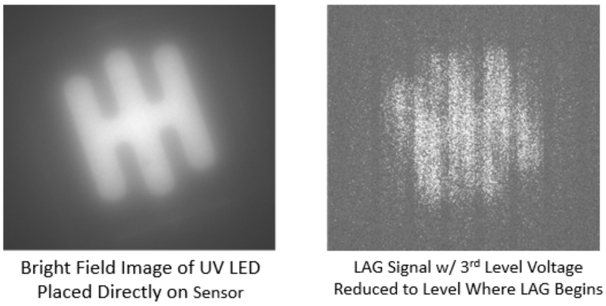


Figure 5: Latent UV LED pattern seen in reduced transfer gate voltage lag image

In figure 5, the left image is a normal bright field image showing the shape of the LED emission when placed directly on the sensor. The right image shown the remaining signal in the photodiode when the device is operated at a marginal transfer gate (V3rd level) voltage.

The magnitude of this degradation was then characterized over time for each optical configuration (see Figure 6)

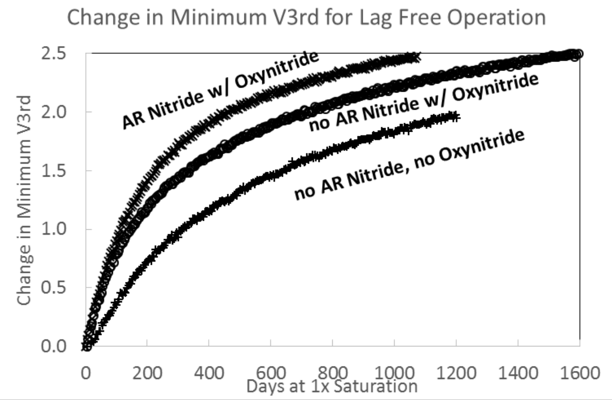


Figure 6: Minimum transfer gate voltage after UV exposure

The more nitride layer interfaces present, the more rapid the degradation. Trapped charge at these interfaces is the likely explanation.

Furthermore, the degradation only occurs if the vertical adjacent gate clocks are running and the sensor is exposed to UV as shown in figure 7. Charge trapped at a gate edge apparently requires both an electric field and the energy from a UV photon to obtain the necessary condition.

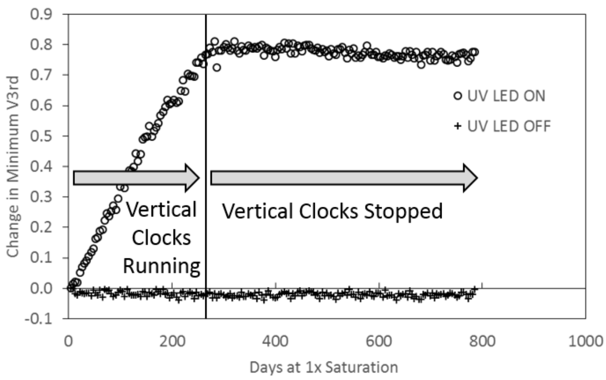


Figure 7: Minimum transfer gate voltage with vertical clocks stopped

Additional Issues

Availability of uniform UV sources with sufficient power posed a significant challenge for device test, characterization, and reliability. QE Measurements in the vacuum UV (<200um) regime were also explored.

Fluorescence of materials under UV light poses additional challenges when operating in this regime. Components, reflectors, epoxy, and even the parts of the commercial UV LEDs themselves can produce secondary emissions at longer wavelengths.

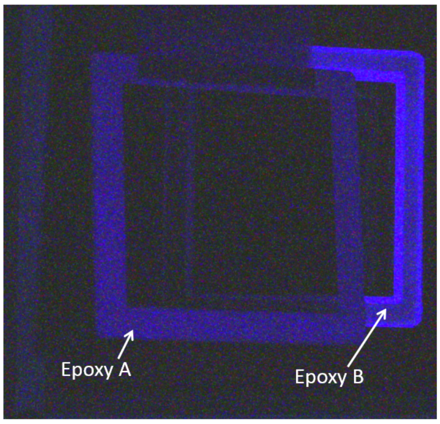
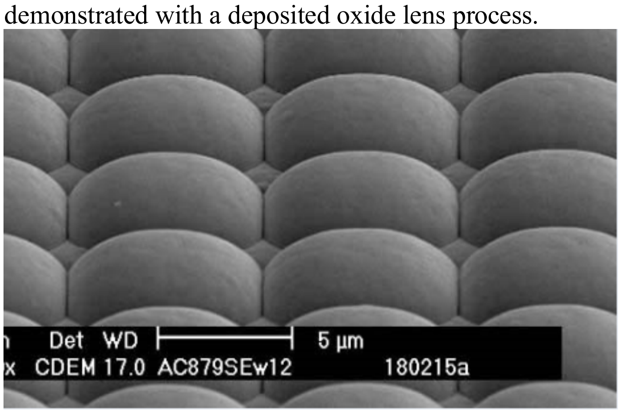


Figure 8: Fluorescence of epoxy under UV illumination

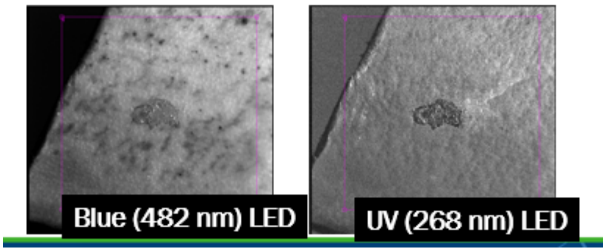
Conclusions

Uniform and efficient micro-lens structures have been demonstrated with a deposited oxide lens process.



Although all results shown are from CCDs, the same techniques are applicable to CMOS devices.

High resolution imaging results obtained in the UV show high levels of surface detail due to the short absorption depth adding a new dimension to UV enabled inspection systems.



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