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High Throughput, High Yield Fabrication of High Quantum Efficiency Back-illuminated Photon Counting, Far UV, UV, and Visible Detector Arrays

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Abstract

In this paper we discuss the high throughput end-to-end post fabrication processing of high performance delta-doped and superlattice-doped silicon imagers for UV, visible, and NIR applications. As an example, we present our results on far ultraviolet and ultraviolet quantum efficiency (QE) in a photon counting, detector array. We have improved the QE by nearly an order of magnitude over microchannel plates (MCPs) that are the state-of-the-art UV detectors for many NASA space missions as well as defense applications. These achievements are made possible by precision interface band engineering of Molecular Beam Epitaxy (MBE) and Atomic Layer Deposition (ALD).

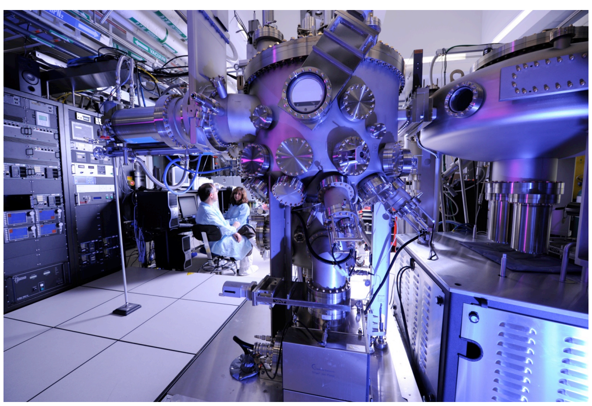

Figure 1. JPL's eight-inch silicon MBE enables high throughput production of delta-doped and superlattice-doped back-illuminated imaging arrays. Using an automated robotic transfer system and computer-controlled growth processes, the system is capable of handling up to sixteen 200 mm wafers at a time.

Introduction

It is well established that back illumination is required to achieve the highest sensitivity, restore 100% fill factor in CMOS imagers, and enable detection of short wavelength photons. To achieve the above performance requires passivation of surface states and defects. The atomic-scale precision and reliability of molecular beam epitaxy (MBE) is ideally suited for surface passivation, due to the precise control of positioning, the low temperature activation of dopant, and the ability to incorporate a large concentration of dopants in single atomic sheets. Low-temperature MBE growth processes are fully compatible with silicon foundry fabrication processes, enabling wafer-scale production of back-illuminated imaging detectors with high yield and high throughput. Since JPL's invention of MBE as a tool for surface passivation of back-illuminated imaging arrays, delta-doped detectors have demonstrated excellent performance and unique capabilities in achieving nearly 100% internal quantum efficiency (QE) over a wide spectral range, and exceptional stability [Hoenk92]. Delta-doping has been demonstrated in back-illuminated CCD, CMOS, PIN diode arrays, and hybrids devices spanning a variety of formats and designs. With the recent acquisition and commissioning of a production-scale silicon MBE system, JPL has greatly expanded its capabilities for producing high-performance delta-doped, back-illuminated imaging arrays with high throughput and high yield (Fig. 1).

While the major driver for this expansion has been meeting NASA's requirements for large focal plane arrays used in astronomy and cosmology, JPL's investment in high yield, high throughput, production of delta-doped and superlattice-doped imaging arrays have benefited research in a great many fields of science and engineering. At JPL, we are developing UV detectors for a variety of applications, including mapping the intergalactic medium in cosmology, detection of UV spectroscopic lines for atmospheric and planetary science, in vivo detection and delineation of skin and brain cancers, and semiconductor wafer and mask inspection and metrology at deep UV wavelengths [Nikzad12, Hamden12, Greer 2013, Hoenk13].

The emphasis on the QE results presented in this paper is on deep and far UV, however, the delta doping and associated back-illumination technologies developed at JPL and presented here are equally relevant and importantly applicable to visible as well as extreme UV and soft x-ray applications. Elsewhere, we present results on unique stability of response [Hoenk13]. The recent focus on the UV is due to both the immediate applications in JPL programs and because of the challenges posed in the UV part of spectrum. UV photons interact with the outermost layers of materials, and therefore are highly sensitive to surface effects, including especially surface/interface defects and traps in back-illuminated detectors. Therefore, surface bandstructure modifications and nano-engineered materials are especially important for UV detectors, optics, and instruments.

Surface Passivation of back illuminated detectors: Delta doping and Superlattice Doping

Delta doping is the growth on the back surface of fully fabricated, foundry-finished devices of an ultrathin (2-3 nm) layer of single crystal silicon, in which an ultrahigh surface density of dopants is embedded in a single atomic sheet. The technique is well established and well documented to achieve near 100% internal QE, and highly stable response in n channel and p channel devices [Hoenk92, Nikzad94, Blacksberg05].

More recently, superlattice-doped devices have exhibited unprecedented stability in response to high flux, high-energy deep ultraviolet photons. This process has been described elsewhere [Hoenk13]. Briefly, growth of multilayers of structures similar to delta layers greatly enhances the stability of the device when exposed to ionizing radiation while exhibiting 100% internal quantum efficiency. The superlattice-doped devices were first demonstrated in CMOS arrays, and have now been demonstrated in CCD formats for scientific applications.

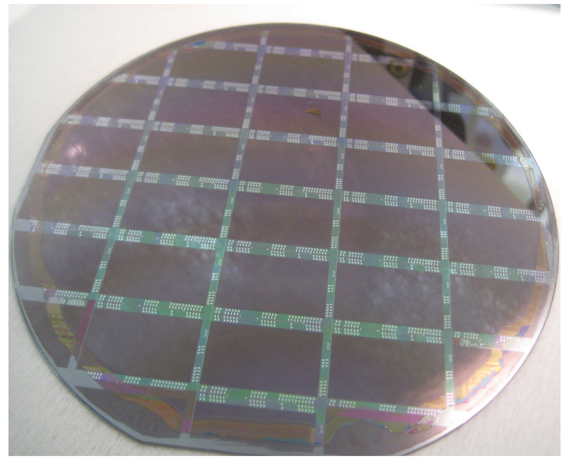

Figure 2 Photograph of the back surface (illumination side) of a frontside-supported, thinned, and delta-doped wafer with exposed bond pads.

Atomically Precise antireflection coatings and bandpass filters using atomic layer deposition

By growing delta-doped and superlattice-doped layers on back-illuminated devices, we take control of the silicon-silicon oxide interface in order to allow the collection of photogenerated carriers. This endows the devices with nearly 100% internal QE, i.e., the dominant loss is due to the reflection of photons. Clearly, antireflection coatings can be used and have been used to further enhance the external QE. While antireflection coatings can enhance the quantum efficiency, these additional layers introduce new surfaces and interfaces. In order to reliably and repeatedly produce films with close to ideal materials properties and achieve the highest QE, these interfaces have to be controlled at atomic level. This is especially true in the ultraviolet range, where absorption of photons takes place in the first few nanometers.

Atomic Layer Deposition (ALD) is a variation of chemical vapor deposition where self-limiting, atomic layer by atomic layer growth is used to deposit ultrathin, multilayer coatings that are conformal, smooth, pinhole free, dense, and stoichiometric. The precision control afforded by ALD is ideal for multilayer stacks which enable 80-100% QE in the challenging range of FUV [Hamden12]. We have used atomic layer deposition in conjunction with MBE to achieve highest QE to date of any type of device in the ultraviolet [Nikzad12] [Hamden12][Greer13].

High throughput delta doping and end-to-end post fabrication processing

In the past three years, we have established high throughput back illumination processes including MBE-based passivation. JPL collaborated with Veeco to design a first-of-its kind 8-inch wafer silicon molecular beam epitaxy (MBE) system, so that fully fabricated silicon imagers of various designs can be delta doped at wafer level. Prior to the MBE, wafers containing single large format or multiple smaller format devices are bonded to handle wafers and are thinned to specific target thickness according to their epi thickness, pixel size, full depletion, and point spread function requirements. Thinned, supported wafers are prepared for loading into 8-wafer cassettes in the MBE's intro and storage chambers. Automated loading and computer-controlled growth processes allow batch processing of multiple wafers using our MBE growth and passivation processes (figure 2).

Antireflection coatings are modeled and designed using standard calculations as well as TFCalc™. ALD layer deposition takes place directly after the MBE process in one of the two ALD machines at JPL's Microdevices Laboratory (MDL): 1) JPL's Oxford ALD system has a growth chamber capable of handling wafer sizes up to 8 inches in diameter. The system is equipped with up to three precursor compounds and six reactive gases such as ammonia and hydrogen, 2) The Beneq ALD system is a high throughput, load locked instrument that has been recently installed at JPL's MDL. The growth chamber of this ALD system is equipped with up to six metal precursors, four reactive process gases and two thermal reactive sources. The small volume of the growth chamber allows for highly precise temperature control, and the plasma source is fully configurable, offering capabilities for implementing both direct and remote plasma growth processes. Device wafers up to 200 mm in diameter can be AR-coated in one deposition run; alternatively, wafers can be diced into sections or individual devices prior to AR coating (figure 3).

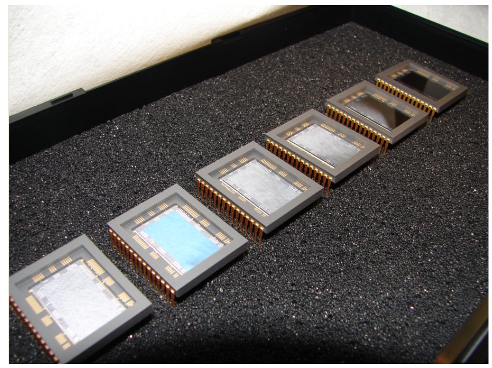

Figure 3. Photograph of several simultaneously delta doped electron-multiplied CCDs in one wafer. Two have multilayer ALD far UV AR coatings and one has a two-layer design to enhance the near UV response.

Single photon counting platform application

In the UV, and especially in UV spectroscopy, single photon counting detection is required. That is why image-tube based MCPs, despite their low QE of 10%, have remained the dominant detectors in UV scientific instruments. Image-tube detectors have also remained dominant in night vision and other DoD applications. With electron multiplied CCDs (EMCCDs) [Hynecek01, Jerram01], Avalanche Photodiode arrays, and Single Photon Avalanche PhotoDiode (SPAD) arrays [Charbon08], it is now possible to achieve single photon counting in solid-state arrays. Combining delta doping with custom AR Coatings allows high and stable QE for single photon counting applications, particularly in the UV. We have thinned, delta doped and AR-coated EMCCDs (e2v's CCD97) and have demonstrated high QE in the most challenging part of the UV spectrum, i.e., in 100- 300 nm. Figure 4 shows individual films deposited on various CCDs while figure 5 shows the composite of the response with comparison to MCPs flown on GALEX, showing a factor of 5-10 improvement in the QE.

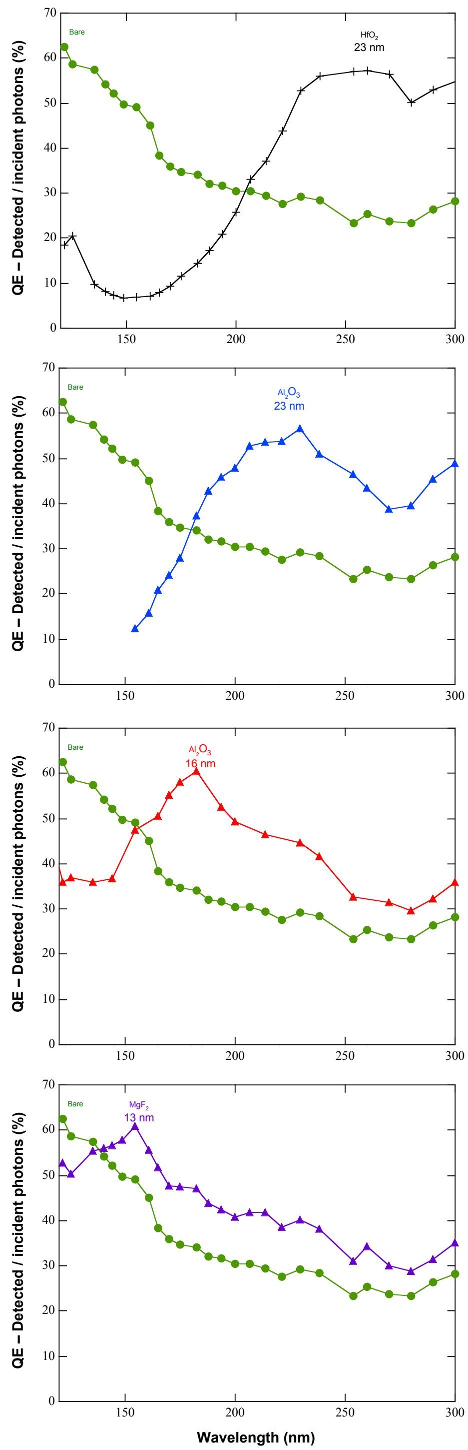

Figure 4 QE of ALD AR-coated, and delta doped CCDs achieving > 50% in the region of interest, from top: HfO_2 in region of 340-270 nm, Al_2O_3 in 173-230 nm, MgF_2 (thermal), 130-160 nm, and finally a bare delta doped array in 121.6-132 nm. Note that a 1-nm layer of Al_2O_3 as a diffusion barrier between device and HfO_2.

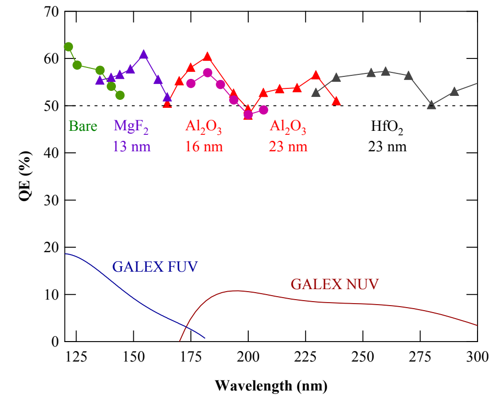

Figure 5 Quantum efficiency of multiple delta-doped CCD devices with AR coatings designed to achieve at >50% in each region.

A larger device optimized for atmospheric window of 195-205 nm is being developed for a balloon experiment with Caltech and Columbia University.

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