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Silicon and III-N UV Photon Counting Detectors

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Abstract

In this paper we present results from two approaches to achieving single photon counting detection in the ultraviolet (UV) spectral range. We discuss our results of back-illuminated electron multiplying charge-coupled devices (EMCCDs) with unprecedented high quantum efficiency (QE) in the 200 nm spectral range. We also discuss the results of fabricating avalanche photodiodes (APDs) in III-nitride materials with high QE and intrinsic solar blindness.

Introduction

The UV spectral range is rich with information that can be employed to study stars and galaxies, cosmos, exoplanets, and solar system planets including primitive bodies, Enceladus, and Europa. Hubble Space Telescope (HST), Galaxy Evolution Explorer (GALEX), and the Cassini mission have shown exciting new science findings that will require further observations with more powerful UV instrumentation. The UV region is particularly important for sensing the thin atmospheres produced by outgassing and internal activity, as well as for examining surface composition. Emission lines and bands from H, C, O, N, S, OH and CO; absorption lines by CO_2, H_2O, NH_3, N_2; and surface reflectance spectra in the UV are all essential for detection of ice, iron oxides, organics, and other compounds and are used as diagnostic tools for understanding the nature and habitability of these bodies. In addition to space and defense applications, UV is used in cancer detection, wafer inspection, lithography, and electrical safety inspection.

Because UV instruments are often photon starved, photon-counting detectors are required, and because UV is often detected in presence of visible background, visible-blindness needs to be achieved. Because of these requirements and despite the advances in solid-state imaging, the field of UV instrumentation is still dominated by image-tube technologies such as photomultiplier tubes (PMTs) and microchannel plates (MCPs).

With advances in solid-state imaging technology architecture that possess gain, enhancements at the nanoscale for surface and interface engineering and surface passivation, and progress at large scale for production, have all led to these imagers being highly competitive and even superior in performance and cost to replace image-tube technologies in UV instrumentation.

In this paper we will discuss two different approaches to solid-state photon counting UV imaging and detection. *In the first approach*, we employ back illumination processes developed in our laboratory including Molecular Beam Epitaxy (MBE)-based superlattice and delta doping as well as Atomic Layer Deposition (ALD)-based custom antireflection (AR) coatings and integrated filters on EMCCDs. Our recent results show record high UV quantum efficiency of 60-80%. Integrated ALD filters are used for visible rejection. We have measured dark current and clock-induced charge at low enough levels to make these detectors attractive and competitive for photon counting applications. *In the second approach*, we use gallium nitride and its alloys in a hybrid APD design. III-Nitrides are wide bandgap materials with tailorable cutoff in the visible. We have achieved 50% QE in GaN and AlGaN APDs. Due to lack of native substrates, III-N's suffer from defects and leakage. ALD's nanoscale precision and conformal coating capability were used for sidewall passivation against leakage, resulting in consistent improvement over detectors coated using Plasma Enhanced Chemical Vapor Deposition (PECVD). In both approaches better than 10^4 out of band rejection has been achieved, which is at the same level as the traditional image tube-based UV detectors.

We present results of both of these approaches including their concepts, designs, characterization, and processing techniques. We also provide an update on our high throughput processes that are compatible with large-scale production.

Silicon Single Photon Counting Detectors detectors: Delta doping and Superlattice Doping of Electron Multiplying CCDS

With EMCCDs [Hynecek2001, Jerram2001], APD arrays, and Single Photon Avalanche PhotoDiode (SPAD) arrays [Charbon2008], it is now possible to achieve single photon counting in silicon arrays. Combining delta doping with custom antireflection (AR) coatings allows high and stable QE for single photon counting applications, particularly in the UV. Visible-rejection filters directly deposited on back illuminated silicon arrays render these devices with high in-band efficiency in the UV and near four orders of magnitude out of band rejection. We have thinned, delta doped/superlattice doped and AR-coated EMCCDs in two formats—e2v's 0.5-megapixel CCD97 and 2-megapixel CCD 201—(Figures 1-2). We have demonstrated high QE in the most challenging part of the UV spectrum, i.e., in 100-300 nm [Nikzad2012]. Delta doping is achieved using molecular beam epitaxy (MBE) to grow an ultrathin (2-3 nm) layer of single crystal silicon on the back surface of fully fabricated, foundry-finished and thinned devices, An ultrahigh surface density of dopant is embedded in a single atomic sheet within this silicon layer. [Hoenk1992, Nikzad1994, Blacksberg2005].

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 [Hoenk2013a,b, Hoenk 2014]. 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 QE. The superlattice-doped devices were first demonstrated in CMOS for industrial applications, and have now been demonstrated in CCD and CMOS designs for scientific applications.

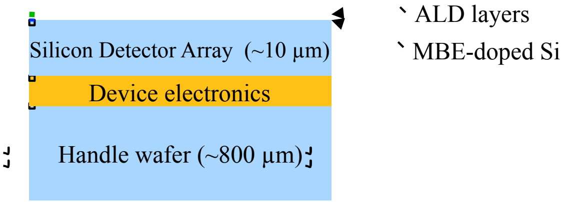

Figure 1: Schematic diagram of a superlattice doped or delta doped arrays (summarized as MBE-doped layers), ALD coated back illuminated Si detector array.

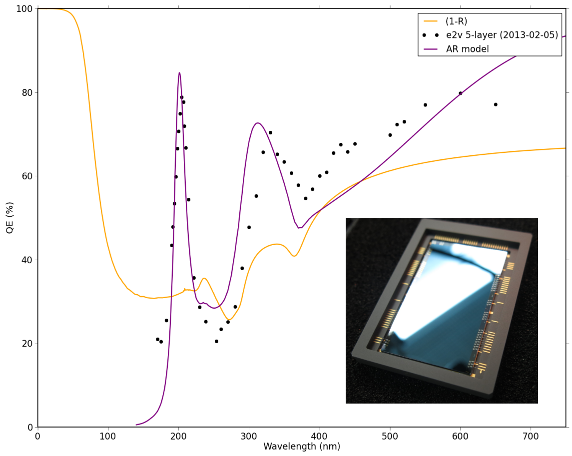

Figure 2: FUV response in EMCCD array. This device is optimized for a balloon experiment where the atmospheric window is centered at 200 nm. Inset: Photograph of superlattice doped and ALD-coated two-megapixel EMCCD.

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 creates devices with nearly 100% internal QE where dominant loss is due to the reflection of photons. Antireflection coatings have been used to further enhance the external QE. While AR coatings can enhance the QE, 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 UV range, where absorption of photons takes place in the first few nanometers.

ALD is a variation of CVD 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. We have used ALD in conjunction with MBE to achieve higher than 50% QE in the very challenging part of the spectrum, namely 100-200 nm range [Nikzad2012, Hamden2012, Greer2013]. Due to its precision control, ALD is ideal for multilayer stacks to achieve high QE in the challenging range of FUV [Hamden12]. Other custom bands for example shown in figure 2 can further increase QE to unprecedented values. All these results surpass any other UV device performance to date. Using the thickness and stoichiometric control of ALD, we have also shown integrated filters with better than four orders of magnitude out-of-band rejection [Nikzad 2014, Hoenk 2014].

Solar Blind, UV Photon Counting with III-N: AlGaN Avalanche Photodiode (APD) Arrays

Photon-counting solar-blind UV APDs can be made possible by using the wide bandgap materials of GaN and its alloys [Verghese 2001]. These materials have intrinsic merits for the development of APDs. The III-nitrides are physically and chemically robust, can be doped both n and p type, and have been shown to achieve high QE as photodetectors, detector arrays, and photocathodes. These are among the attributes that make III-nitride materials nearly ideal for detectors with gain such as APDs.

Our work has focused mainly on p-i-n structures in which the absorption and multiplication take place in the same region, with some preliminary research into back-illuminated vertically separate absorption and multiplication (SAM) APD structure [Suvarna 2013, 2015]. We have shown better than 50% QE in these APDs (Figure 3).

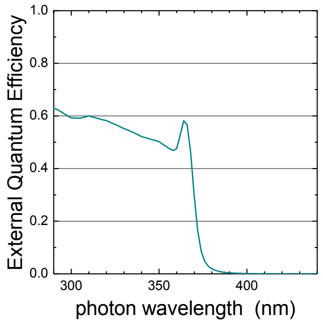

Figure 3: External QE as a function of photon wavelength for an Al_2O_3 –passivated GaN p-i-n APD with zero applied voltage. With no applied voltage, there is unity internal gain.

Sidewall-related defects in GaN APDs have often been observed to contribute to undesirable current components such as those produced by defect-related microplasmas. SiO_2 is most commonly used for passivation, due to its availability and simplicity of growth. However, it is not the optimized passivation for AlGaN materials. We have explored other materials prepared by ALD for passivation for superior dielectric quality. ALD is capable of depositing conformal coatings with monolayer uniformity, even for complex geometries, and therefore is particularly suitable for passivation layer depositions.

The use of ALD Al_2O_3 as a sidewall passivation layer was observed to result in the reduced occurrence of premature breakdown in mesa p-i-n GaN APDs when compared to devices fabricated with a more common PECVD SiO_2 passivation [Hennessy 2013]. Mesa APDs with diameters ranging from 25 to 100 µm show a significant reduction in median dark current for the ALD-passivated devices (Figure 4). The reduction in median dark current was most significant for the smallest devices, showing an order of magnitude improvement at reverse biases near avalanche. The interfacial effect of ALD Al_2O_3 was investigated by fabricating MOS capacitors which show a large reduction in both slow trapping and faster interface states compared to SiO_2 devices (Figure 4).

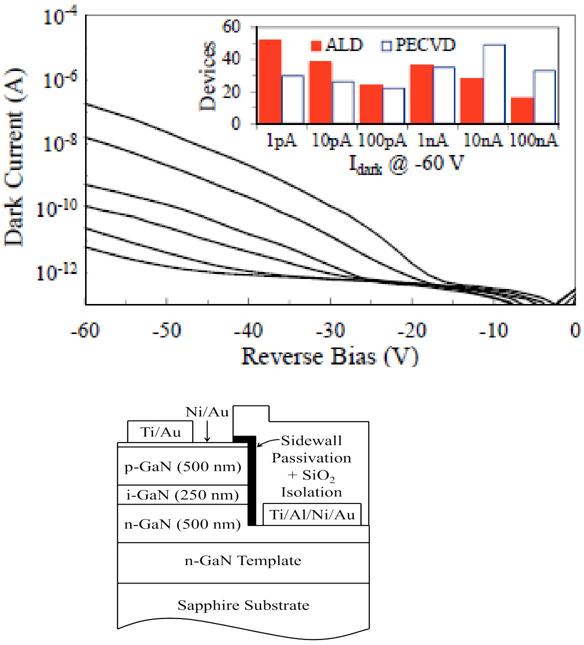

Figure 4: (Top) Example of the variation in reverse bias behavior observed for ALD-passivated GaN APDs. Inset: histogram of ~200 devices with 25 µm dia on co-processed samples receiving a sidewall passivation layer of ALD Al_2O_3 or PECVD SiO_2. (Below) Schematic of device geometry showing PECVD passivation.

Summary and Discussion

Results of two approaches to single photon counting ultraviolet detectors were presented. In silicon photon counting is achieved using EMCCD architecture but the techniques presented here are applicable to CMOS arrays and other architectures possessing gain such as SPADs. Out-of-band rejection in silicon is achieved through visible rejection filters designed as an integrated part of the back illuminated silicon detector and is deposited (in part) using ALD. This approach takes advantage of the maturity and mass production of silicon imaging. In III-Nitride materials, we use an APD approach for the detection and gain and the readout is achieved by hybridization through a CMOS readout integrated circuit (not discussed here). Due to their wide bandgap, III-N materials are inherently visible blind and their high pass cutoff can be tailored using varying Al fraction in the $Ga_{1-x}Al_xN$ alloy. Excellent results have been achieved in both approaches. Silicon-based devices are ready for deployment and III-N arrays will have longer-term applications.

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