Radiation-hard, Nanosecond-gated CMOS Imaging Detectors

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Sandia National Laboratories and the Jet Propulsion Laboratory are working together to develop radiation-hard CMOS imaging detectors with nanosecond temporal resolution. This work is being carried out by JPL's Advanced Detectors, Systems and Nanoscience program in collaboration with Sandia's Ultrafast X-ray Imager (UXI) program.

In order to study the physics of matter at exceptionally high energy densities, Sandia National Laboratories has developed the world's fastest multi-frame digital X-Ray imaging detectors (Claus *et al.*, 2015 and 2016; Dayton *et al.*, 2016). Figure 1 shows a cross-section of Sandia's UXI detectors. Time-gated imaging with nanosecond temporal resolution is achieved by burst-mode detection using banks of capacitors to locally store multiple image frames. High sensitivity to X-rays and fast response are achieved by integrating the CMOS ROIC with a thick, back-illuminated photodiode array. The UXI detectors currently use an ion-implanted layer with a metal grid electrode to provide a uniform bias to the illuminated side of the photodiode array. In order for the detectors to withstand high-speed, pulsed-power imaging, heavy implant doses are required. One significant problem with this approach is the ion-implanted surface causes significant loss of signal for shallow-penetrating radiation. Improving the sensitivity to soft X-rays and low energy electrons is important for several reasons. Low energy electron detection is critical for pulse-dilation cameras currently under development, which are expected to achieve temporal resolution in the range of 10's of picoseconds using nanosecond-gated detectors (Hilsabeck *et al.*, 2010). Soft X-ray sensitivity is essential for plasma temperature measurements in MagLIF fusion targets (Slutz *et al.*, 2010).

JPL and Sandia are working together to solve this problem by using molecular beam epitaxy (MBE) to achieve stable, high quantum efficiency for soft X-rays and low energy electrons. Ion-implanted detectors are well-known to suffer severe surface damage and performance degradation from exposure to ionizing radiation, including deep ultraviolet and X-ray photons (Defise *et al.*, 1998; Li *et al.*, 2003 and 2005). JPL's delta-doping and superlattice-doping technologies have solved this problem for a variety of imaging

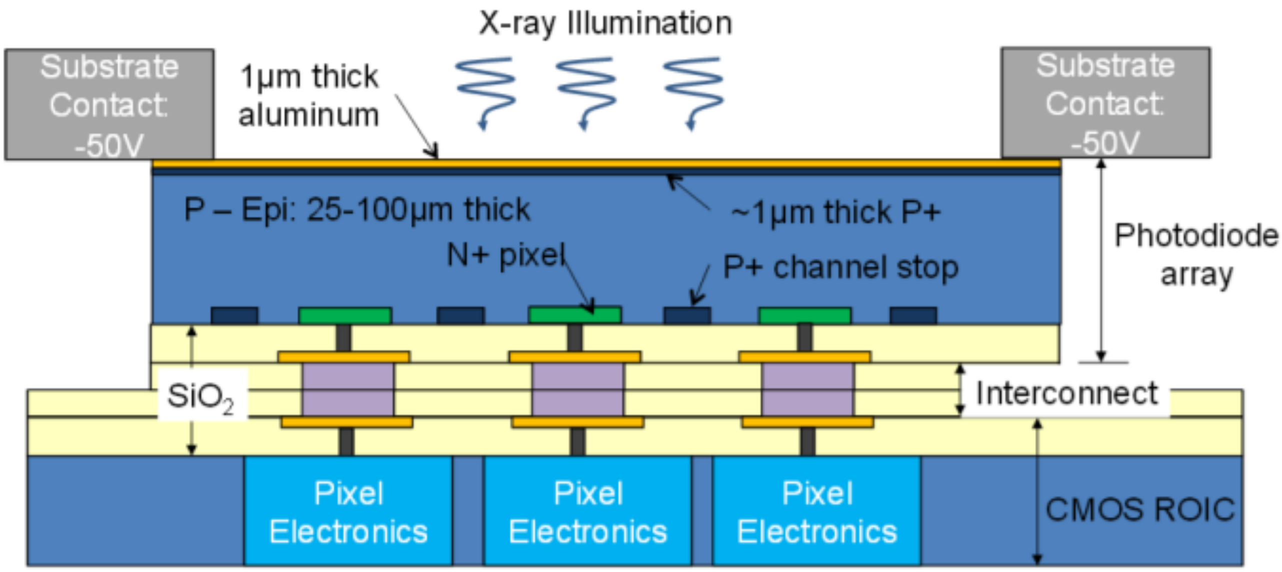

Figure 1: Sandia's ultrafast X-ray imaging detectors comprise a thick photodiode array attached to a CMOS ROIC using direct-bond interconnect technology.

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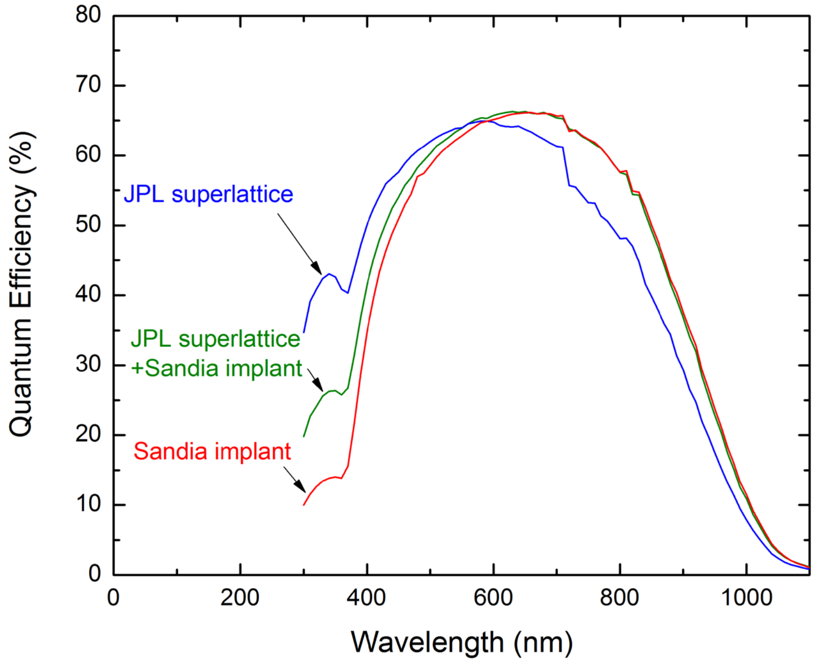

Figure 2: UV-visible quantum efficiency measurements show that superlattice-doping enables significantly higher sensitivity to shallow-penetrating photons than ion-implantation. In the near ultraviolet, where the photon absorption depth is less than 10 nm, superlattice-doped photodiodes exhibit nearly 100% internal quantum efficiency. Ion-implantation, either alone or in combination with superlattice doping, causes significant loss of signal.

detectors, including CCDs and CMOS imaging detectors (Hoenk et al., 1992; Hoenk, 2013; Nikzad *et al.* 2012 and 2015; Hoenk *et al.* 2015). Using MBE to grow a crystalline layer of silicon only a few nanometers thick, JPL can create a surface doping layer that is one to two orders of magnitude thinner than the ion-implanted layers in Sandia's previous generation of detectors. JPL uses nanoscale surface doping based on 2D-doping superlattices, which can achieve surface dopant densities approaching 10^{15}cm^{-2}. Detectors passivated using 2D-doping superlattices achieve nearly 100% internal quantum efficiency because dopants are confined to the MBE-grown surface which is only a few nanometers thick (Nikzad *et al.* 2012 and 2015; Hoenk *et al.* 2015). At the same time, superlattice-doped surface stabilizes the detector against radiation-induced surface damage. Lifetime measurements performed with pulsed, deep ultraviolet excimer lasers demonstrate that superlattice-doped detectors retain high, stable QE despite high levels of radiation-induced surface damage (Hoenk *et al.*, 2013 and 2014).

JPL and Sandia recently completed a proof-of-concept demonstration of pulsed-power X-ray photodiodes modified at JPL using superlattice doping for surface passivation. Sandia's front-illuminated, single-element photodiodes use a similar design to the photodiodes arrays in their UXI detectors to meet the requirements for pulsed-power applications. For this proof-of-concept demonstration, Sandia used a split-lot design to produce photodiodes with three different surface doping profiles. Wafers were sent to JPL to be modified using superlattice doping, and were then returned to Sandia for final processing, packaging and characterization. Initial tests showed that superlattice-doped photodiodes are compatible with Sandia's design and fabrication processes, and they exhibit good forward and reverse I-V behavior up to the full 50 V reverse bias required for high carrier velocity throughout the detector. Figure 2 shows measurements of quantum efficiency comparing superlattice-doped and ion-implanted photodiodes. Superlattice-doping has already enabled the highest quantum efficiency that Sandia has measured. Superlattice-doped photodiodes exhibited nearly 100% internal quantum efficiency in the near ultraviolet, where the 1/e absorption depth is less than 10 nm. Electron sensitivity measurements showed similar trends, as superlattice-doped detectors exhibit five times higher sensitivity to 1 keV electrons than ion-implanted detectors (Figure 3). Pulsed-power X-ray measurements show that superlattice-doped photodiodes function well at high X-ray fluence (Figure 4). Experiments are currently underway to further optimize the performance of superlattice-doped photodiodes for pulsed-power applications and to develop n-type superlattice-doped photodiodes.

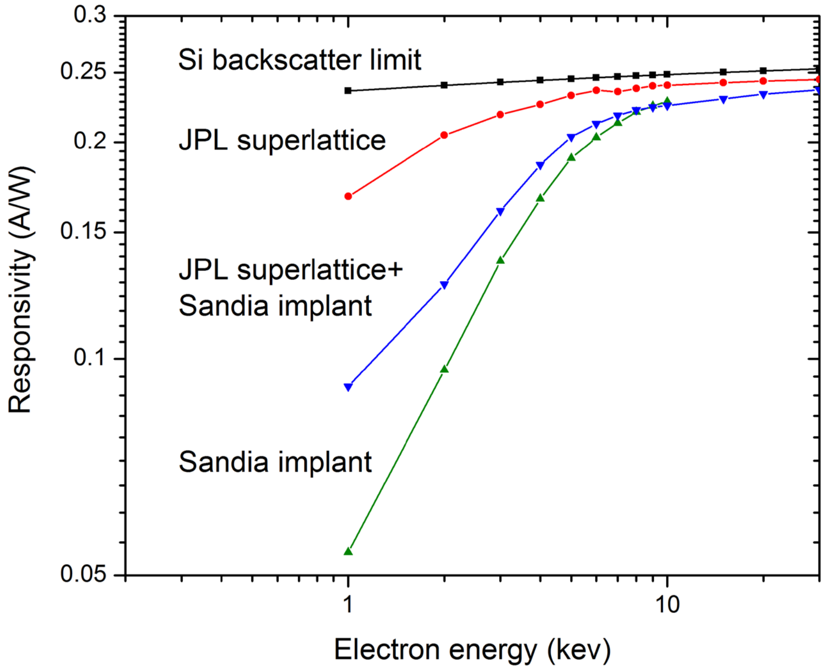

Figure 3: Low energy electron measurements show that superlattice-doping enables significantly higher sensitivity to shallow-penetrating electrons.

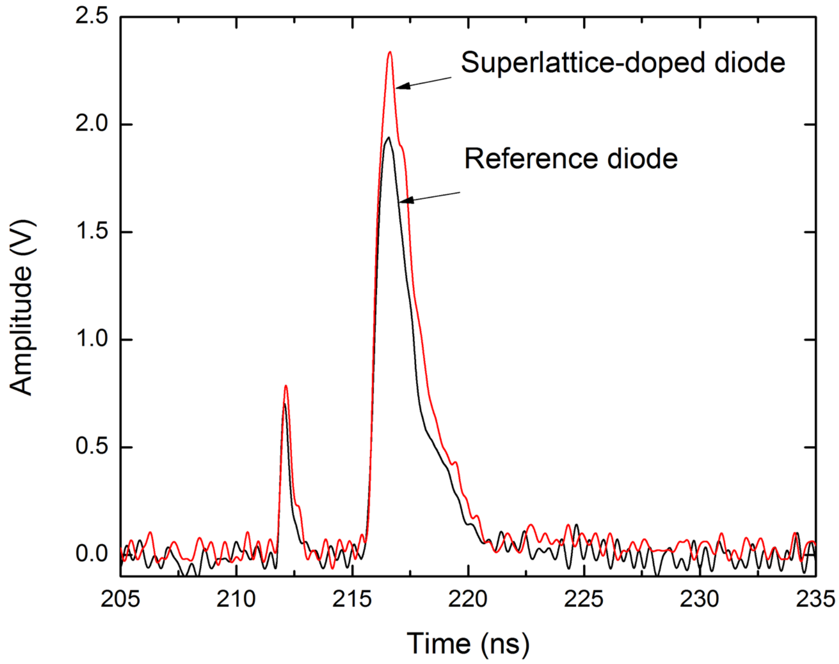

Figure 4: Pulsed-power X-ray measurements comparing the response of superlattice-doped photodiodes with a reference detector demonstrate that superlattice-doped photodiodes exhibit the required high-speed, high-sensitivity response. For this measurement, the X-ray energy was approximately 3 keV, and the integrated signal in the main pulse was approximately 6×10^8 electron/hole pairs.

The long-term goal of this work is to develop high-performance, nanosecond-gated imaging detectors that combine JPL's superlattice-doping processes with Sandia's designs and processes for 3D-integrated UXI detectors. Successful completion of this development will produce new detectors for time-gated imaging and spectroscopy on timescales from nanoseconds to 10's of picoseconds. Sandia will use these detectors in camera systems designed to study the physics of matter at high temperatures and pressures. NASA will benefit from this work by collaborating with Sandia to develop detectors for imaging and spectroscopy in space and planetary exploration. High-speed, time-gated imaging is already enabling new science in biomedicine, nanotechnology and space research (Berrah *et al.*, 2014). The methods and processes that we are developing can ultimately be applied to next generation imaging arrays that use 3D integration to enable unique capabilities and science.

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