Direct Detection of 100–5000 eV Electrons With Delta-Doped Silicon CMOS and Electron-Multiplying CCD Imagers

Blake C. Jacquot, *Member, IEEE*, Michael E. Hoenk, Todd J. Jones, T. J. Cunningham, and Shouleh Nikzad, *Member, IEEE*

***Abstract*—We have demonstrated a direct detection of 100–5000 eV electrons with a back-illuminated boron delta-doped hybrid silicon complementary metal–oxide–semiconductor imager operating in full depletion and a silicon electron-multiplying charge-coupled device (CCD) operating in partial depletion. The delta-doping molecular beam epitaxy increases sensitivity to low-energy electrons and improves low-energy electron detection threshold relative to conventional solid-state detectors. We compare the gain measured in these two delta-doped devices with gain measured from control delta-doped CCDs.**

***Index Terms*—Charge-coupled device (CCD) image sensors, complementary metal–oxide–semiconductor (CMOS) image sensors, electron detection, silicon radiation detectors.**

I. Introduction

Detecting low-energy particles has applications in space plasma physics, electron microscopy, vertex detection for particle accelerators, ionizing radiation monitoring, and electron bombarded arrays [1]–[5]. Applications that would benefit from compact tools with fast readout also include miniature mass spectrometers and biomedical instruments. The most common detectors for these measurements are windowless electron multiplier detectors such as microchannel plates [1]. However, they lack energy information on incident particles, require high voltages for normal operation (e.g., 2–3 kV), and suffer from substantial gain and efficiency drift. In contrast, silicon-based image sensors such as charge-coupled devices (CCDs) and CMOS imagers offer information about incident particle energy [by Auger effects or quantum yield (QY)], use low operating voltages (< 100 V), and have stable gain and quantum efficiencies (QEs). The problem with untreated silicon is the lower sensitivity bound for incident electrons. This results from a "dead layer" near the back-side surface where carriers are either trapped in surface interface states or recombine in a field-free region before reaching front-side readout electronics.

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Flash gate and ion implantation applied to thinned back-side-illuminated CCDs have achieved a minimum energy threshold of 100 eV for electrons [6]. Recent work using boron chemical vapor deposition has achieved detection of Extreme Ultraviolet (EUV) light but has not been tested for low-energy particles [7]. In addition, because it is a high-temperature process, this technique cannot be applied to fully fabricated (i.e., metalized) devices. CMOS image sensors used to detect electrons at 20–30 keV with back-side oxide passivation have been reported [2]. CMOS detectors have been used to report a gain of 180 when exposed to 2 keV electron illumination [8].

CMOS imagers and electron-multiplying (EM) CCDs have many desirable traits. CMOS detectors offer high radiation tolerance relative to CCDs, ease of manufacturing, and high spatial resolution. Thin oxides of CMOS imagers give a low cross-sectional volume for storage of troublesome flatband shifting fixed charge from radiation events. CMOS imagers have a large industrial base for both high and low volume production and are the most common ground-based imager comprising a wide assortment of architectures including monolithic and hybridized designs. Pixel sizes range from $\sim$7 μm for scientific imaging down to $\sim$1.2 μm for current high-volume processes. In EMCCDs, electron multiplication enhances signal-to-noise ratio at low signal levels by boosting the measurement above read noise. This happens by passing signal electrons through an avalanche gain register prior to readout [9].

In this brief, we report the first use of delta-doped hybrid CMOS and monolithic EMCCD image sensors for direct detection (i.e., no preacceleration or intermediate conversion) of 100–5000 eV electrons. Delta doping enables improved low-energy detection threshold, and because it is applicable to fully fabricated devices, it allows a choice of silicon-based detector platforms. We compare results from these devices with delta-doped conventional CCDs and delta-doped p-i-n diode arrays. We also use the different devices' readout and collection schemes for QY and backscatter assessment.

II. Experimental Details

To demonstrate applicability to different platforms, to make a comparison of collection efficiency, and to compare effects of gain in measurements, we chose the following delta-doped devices for our measurements: hybrid CMOS imagers, EMCCDs, and conventional CCDs.

We used a hybrid CMOS imager designed at the Jet Propulsion Laboratory initially for an *in situ* planetary camera. The device has 1728 rows × 1728 columns with a 4-μm pixel pitch and a 5-μm epi layer. Each column employs its own on-chip analog-to-digital converter with 8-bit nonlinear Gray code data output [10]. The conversion gain between digital numbers and electrons collected was determined by mean-variance methods with visible light.

We used a commercial EMCCD with a 1024 × 512 format, 16-μm pixel L3CCDs (e2v CCD97s), and a 20-μm epilayer [9]. Processing is similar to the given CMOS imager [11]. We thinned to 8 μm by removing the p^+ substrate and approximately 12 μm of the epilayer using a multistep process starting with the chemical mechanical polishing (CMP) process followed by chemical thinning to achieve a smooth and highly specular silicon surface. Following the thinning, a series of solvent cleaning steps were used to eliminate the residual organic material used in processing steps such as photoresist and waxes. The devices were then delta doped.

Delta-doped 1000 × 1000 format CCDs acted as control devices relating new imagers to prior tests. We used two control imagers: one with a 12-μm free-standing thin membrane and one with a 20-μm back-supported thin membrane.

All devices were modified with delta-doping technology to enable low-energy electron detection with techniques described previously [11]–[14]. Unlike ion implantation that requires postannealing or a "pure Boron" technique that needs very high temperature [7], delta doping is a gentle technique that can be applied to fully fabricated silicon arrays (e.g., CCD or CMOS). Delta-doping technology uses molecular beam epitaxy to grow, at low temperature (i.e., less than 450 °C), a 2.5 nm single-crystal silicon layer with a high concentration of charge (dopant), which is embedded nominally in a single atomic sheet, at a depth of a nanometer from the native oxide/silicon interface. This delta layer eliminates the "dead layer" by altering the near-surface bandstructure and lowers the detection threshold for low-energy particles. The delta-doped layer acts as the back-surface electrode making the device sensitive to any particle able to penetrate more than a nanometer.

All devices in this brief are back-illuminated (illuminated from the nonmetalized side) and thus have a 100% fill factor. This contrasts with the pixel area available for collection, which depends on electrostatics of pixel design.

III. Results and Discussion

Silicon response for incident electrons is a convolution of QY, internal QE, and collection efficiency (e.g., backscatter). Our first studies focused on detection threshold and QY by using partially depleted back-side-illuminated delta-doped CCDs and fully depleted p-i-n diode arrays [12], [13]. In this brief, we are exploring the use of CMOS detectors and EMCCDs. CMOS detectors offer advantages of low power, compactness, and faster and more versatile readout (e.g., windowing). EMCCDs when operated in high-gain mode provide additional advantages for single particle detection. Studying devices with a different readout schemes also could offer further insight in the detection of low-energy electrons.

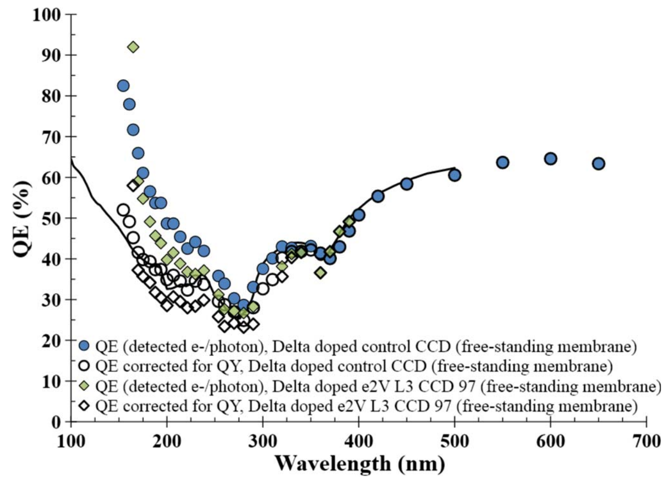

Fig. 1. Quantum efficiency for delta-doped CCDs used in this brief. The reflection-limited response verifies the integrity of the delta layer. The imagers were characterized in both imaging and photodiode mode. QE data from the CMOS imager were not collected. All imagers are back illuminated.

We have evidence that the CMOS image sensor is fully (or near-fully) depleted, which may enable more accurate determination of gain and collection efficiency by allowing collection through the entire photodiode volume. Evidence of full depletion is gathered empirically by monitoring dark current before and after delta doping. Dark current after delta doping was measured as 695 pA/cm^2 at room temperature. Full depletion presents high dark current prior to delta doping, indicating the depletion region has reached the sites producing surface-generated dark current. Delta doping passivates the back side and prevents it from delivering surface-generated carriers to the imaging array. A partially depleted EMCCD was also used to demonstrate the technology for applications with faint signals or faint objects that may benefit from the avalanche gain register. We compare the two in order to investigate QY and collection efficiency.

The result of measured QE for two CCDs with free-standing membranes used in this brief, i.e., the control CCD and the EMCCD, are presented in Fig. 1. The silicon reflection-limited response validates the performance of the delta-doping layer. These imagers were characterized in both imaging and photodiode modes [15]. Photodiode mode is a two-terminal measurement where system-level conversion gain is irrelevant since generated charge is immediately read out rather than converted to voltage by on-chip amplifiers. This eases testing requirements and reduces uncertainty. We have verified independently that operating devices in photodiode mode gives identical results to operating in imaging mode. To further simplify measurement, we do not use the gain register of the EMCCD. We have verified that delta doping does not impact the gain register functionality of the EMCCDs [11].

For low-energy electron tests, imager responses were measured in a scanning electron microscope (SEM) (Supra 50VP by Carl Zeiss) operated in spot mode with independent verification of the electron-beam flux by a Faraday cup. During testing, we first illuminate the Faraday cup with the electron beam and record current by the electrometer (GW Type 31). The beam then illuminates the center of the silicon detector with

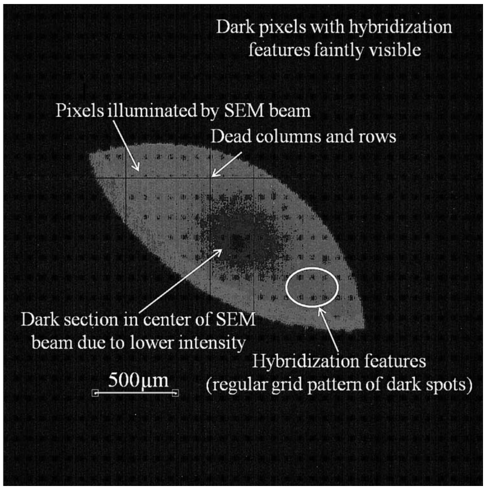

Fig. 2. Single raw frame with ROI of 600 × 600 pixels and 1.1-s integration time from the CMOS imager with an incident 100-eV electron beam. The 4-μm pixel pitch gives excellent spatial resolution of the arc-shaped SEM beam. Dark regions of depressed signal from a regular grid pattern create periodic low measured response. These features likely arise from damage during the hybridization process.

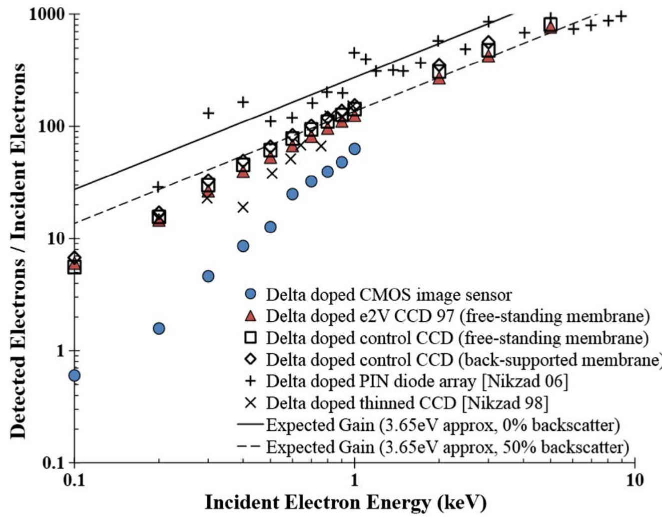

Fig. 3. Response of delta-doped back-illuminated imagers as a function of incident electron energy. Response is a convolution of three terms: transmission of electrons into the device, internal quantum efficiency of the device, and the electron QY in silicon. Not all electrons incident upon the surface will interact with the substrate. All CCDs were run in photodiode mode. The CMOS imager was run in imaging mode with bad columns and rows filtered out and a full two-point correction applied to each pixel. Depressed CMOS response likely stems from extended exposure to hot lift-off solution.

the signal read out by a Labview interface with low-voltage differential signaling for the CMOS detector or an electrometer (Keithley 6514) for the CCDs. The two electrometers gave equal responses when their positions were swapped. Following the silicon detector reading, the beam again illuminates the Faraday cup. Initial and final readings never differed by more than 1% and often did not measurably deviate at all. The incident electron energy was varied from 100 to 5000 eV which resulted in a current of 400–800 pA as measured by Faraday cup. Vacuum levels were approximately 10^{-5} Torr. Detectors were operated at room temperature.

In contrast to the CCDs, the CMOS imager was run in imaging mode. Fig. 2 shows A single raw image from the CMOS imager with constrained region of interest (ROI) of 600 × 600 pixels operating at a 1.1-s integration time under 100 eV illumination, which gives about 2000 net electrons for an illuminated pixel. Data were collected with varying integration times, with the shortest as 110 μs for 1000 eV. At each energy level, 25 images were collected, converted from microvolts to electrons with measured conversion gain (45 μV/e-), and processed with dark integrations of identical exposure times. Conversion gain was measured from mean-variance curves (also known as photon transfer curves) with visible light. The net signal of a constrained ROI was averaged across the 25 images and differenced with the identically processed 25 dark images to find the net detected signal in electrons. Above 1 keV, the detector saturated for the minimum-allowed integration time, giving an upper bound for the experiment. The CMOS detector was run in imaging mode, and the results are processed by correcting for bad pixels and by performing a full two-point correction (gain and offset) for all pixels prior to further calculation.

In Fig. 3, detector responses as a function of incident electron energy for the CCDs and CMOS detectors used in this brief are shown. The responses are normalized to incident electron flux by dividing the measured signal from the silicon detector by incident electron-beam current measured by the Faraday cup, after unit analysis. This ratio (i.e., gain) is generally much greater than one due to QY from Auger effects. Our measured yield, which is the ratio of measured signal to beam current, of 83.5 at 600 eV for a CCD, translates into an efficiency of 8350%. The same CCD measured a ratio of 353 at 2 000 eV. This ratio should approach incident energy (eV)/3.65 (eV) at high energies due to Auger effects [13]. It can be seen that the data generally follows the linear trend at high energies. The conversion gain measured for the CMOS image sensor had roughly a 10% error due to nonlinearities in the mean-variance curve. However, error bars due to this are too small to be visible in Fig. 3.

The calculated QY using the incident energy (eV)/3.65 (eV) assumption is plotted in the figure along with the same curve assuming 50% backscatter in order to show how the imagers under study compare with theoretical limits. Incident electrons can backscatter either elastically or inelastically from the detector surface, with only a portion of them reaching silicon where they can generate detectable electron–hole pairs.

The backscattering coefficient for 2–20-keV electrons in silicon has been measured as ∼20%–25% [13]. The backscattering coefficient of electrons from solid surfaces has been generally shown to increase for lower energy values [16], [17].

All delta-doped CCDs used in this brief show response similar to prior results, indicating that delta doping has successfully allowed the EMCCD to detect low-energy electrons. The trend reaches expected values at higher energy values and falls below this at lower energy values. For instance, in Fig. 4, the CCDs under study match well with the ∼20%–25% backscatter assumption for energy values between 2 and 5 keV, with a control CCD measuring 26.5% at 5 keV.

As noted, it is possible that the 3.65-eV approximation, which holds at high energy values, may depart from linearity

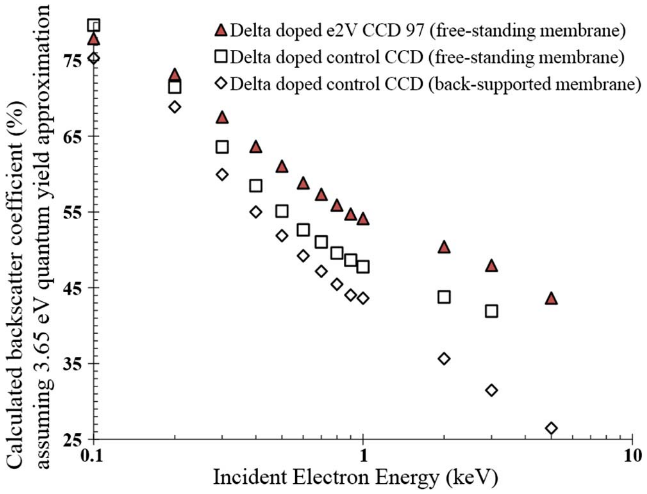

Fig. 4. Calculated backscatter assuming 3.65-eV approximation for QY. Notably, the delta-doped control CCD with back-supported membrane shows an expected response at 5 keV of 26.5%. Backscatter is known to increase at lower energy.

at low energy values. Without the ability to measure backscattered electrons, we could not deconvolve the contributions of backscatter and QY.

We anticipated that the fully depleted CMOS detector would give useful yield and collection efficiency information relative to CCDs; however, we observed a depressed response. This likely results from extended exposure to a hot lift-off solution in order to remove a glass piece from the device. This may affect surface behavior, which complicates the measurement. In the future, glass attachment can be avoided so that removal is not needed.

IV. Conclusion

In conclusion, we have demonstrated direct detection of electrons in the range of 100–5000 eV by a delta-doped hybridized CMOS imager, a delta-doped EMCCD, and delta-doped control CCDs. The response from the EMCCD and control samples are consistent with prior experiments and theoretical expectations. The results extend the range of detector platforms available for monitoring low-energy particles. Future studies will explore the use of other fully depleted delta-doped imagers to further understand yield and collection efficiency at the back-side surface.

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