A solid-state amorphous selenium avalanche technology for low photon flux imaging applications

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Purpose: The feasibility of a practical solid-state technology for low photon flux imaging applications was investigated. The technology is based on an amorphous selenium photoreceptor with a voltage-controlled avalanche multiplication gain. If this photoreceptor can provide sufficient internal gain, it will be useful for an extensive range of diagnostic imaging systems.

Methods: The avalanche photoreceptor under investigation is referred to as HARP-DRL. This is a novel concept in which a high-gain avalanche rushing photoconductor (HARP) is integrated with a distributed resistance layer (DRL) and sandwiched between two electrodes. The avalanche gain and leakage current characteristics of this photoreceptor were measured.

Results: HARP-DRL has been found to sustain very high electric field strengths without electrical breakdown. It has shown avalanche multiplication gains as high as 10^4 and a very low leakage current (≤ 20 pA/mm²).

Conclusions: This is the first experimental demonstration of a solid-state amorphous photoreceptor which provides sufficient internal avalanche gain for photon counting and photon starved imaging applications. © 2010 American Association of Physicists in Medicine. [DOI: [10.1118/1.3483096](https://doi.org/10.1118/1.3483096)]

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A number of important applications in diagnostic imaging require low-noise imagers with high detection efficiency. For instance, in imaging modalities that rely on photon counting, such as positron emission tomography (PET) or single photon emission computed tomography, each primary gamma ray emitted from the patient should, upon interaction, produce a distinct count in the imager. In photon starved integrating detector applications such as fluoroscopy, the radiography/fluoroscopy (R/F) imager should ideally have sufficiently low noise to be capable of detecting as little as a single x ray at each detecting element (del) in the low-exposure regions of the image.¹ Furthermore, next-generation cone-beam computed tomography and tomosyn-

thesis, which reconstruct three-dimensional volumes from a series of low-exposure two-dimensional radiographs, would benefit from low-noise imagers.

In this article, we introduce a novel solid-state detection technology based on an amorphous selenium (*a*-Se) photoreceptor. As will be seen, this photoreceptor has some unique characteristics which enable it to detect extremely low quantities of light. As such, it provides an efficient means of detecting single x rays or gamma rays when optically coupled to a suitable scintillator or phosphor.

The detection efficiency of an imager based on a solid-state photoreceptor depends on three fundamental noise sources: (1) Quantum noise, (2) photoreceptor noise, and (3)

electronic noise. We shall briefly discuss each of them. (1) The quantum noise associated with the stochastic variation of the detected quanta imposes a fundamental limitation on the image quality. Ideally, the imager should only be limited by the quantum noise. (2) The photoreceptor is a key component of the imager and produces electric charge for each photon interaction. This charge is collected at the attached electrodes by applying a voltage across the photoreceptor. The noise inherent to the photoreceptor, mostly thermal and shot noise, is largely dependent on the bandgap energy of the photoconductor, electrode properties, and the magnitude of the applied voltage. (3) The charge readout lines and amplifiers used in most modern photon counting imagers (PCIs) and flat panel imagers (FPIs) generate an electronic noise in the range $\sim 10^2$ – 10^3 e/del (input-referred) at room temperature for typical digital sampling frequencies in the range 0.1–1 MHz.^{1,2} This source of noise can significantly affect the performance of medical imagers.¹ Hence, for the imager to be quantum-noise limited, the photoreceptor should, for each individual photon interaction, produce a sufficiently large amount of charge to overcome the electronic noise, yet not introduce any appreciable photoreceptor noise. This can be achieved with a photoreceptor which produces $\geq 10^3$ electrons per photon interaction and has negligible thermal noise and shot noise.

Traditional vacuum electro-optical devices such as x-ray image intensifiers and photomultiplier tubes (PMTs) with scintillators used in fluoroscopy and photon counting, respectively, provide high and almost noiseless internal gains. The reason the internal gain is essentially noiseless in these systems is that it follows a large conversion gain (typically $>10^3$). In addition, this internal gain makes the electronic noise in subsequent stages negligible. It is highly desirable to provide the same capability for a solid-state device. Avalanche multiplication in *a*-Se could, in principle, provide the sufficient low-noise internal gain necessary for quantum-noise limited operation in FPIs and PCIs.^{3,4}

a-Se has many properties that make it particularly useful for a wide range of diagnostic imaging applications. Owing to its amorphous state, it can be used to fabricate large integrated monolithic imaging arrays as has already been demonstrated practically in *a*-Se FPIs.⁵ Due to its relatively large bandgap energy ($E_{a-Se}=2.3$ eV compared to $E_{c-Si}=1.1$ eV for a crystalline silicon semiconductor), *a*-Se has essentially no free carriers at room temperature. Hence the thermal component of the photoreceptor noise is negligible. Furthermore, in comparison with other large-bandgap photoreceptors (e.g., CdZnTe, HgI₂, PbI₂, or PbO), *a*-Se has sufficiently large carrier lifetimes so that both positive charge (holes) and negative charge (electrons) can be efficiently collected by the electrodes (i.e., no significant charge trapping occurs). In the avalanche regime, *a*-Se can provide much larger gains than the abovementioned photoreceptors through the avalanche multiplication process, which relies on impact ionization of holes.³ For example, a single 511 keV gamma ray can produce $\sim 10^7$ electrons in an *a*-Se layer having an avalanche gain $g_{av} \sim 10^3$ and coupled to a LYSO scintillator as compared to $\sim 10^4$ electrons for a CdZnTe photoreceptor.^{1,2,4} It

FIG. 1. (a) Diagram illustrating the principle of operation of electroded HARP. Photon-generated holes avalanche and are collected at del electrodes. The dashed horizontal lines are electric field lines. The electric field distribution within a single del (shaded region) is also shown (b). Avalanche multiplication occurs when the electric field strength in the HARP E_{HARP} exceeds the critical field strength E_c . The large field near the electrode edges causes charge injection and precipitates discharges leading to breakdown. In HARP-DRL, (c) a DRL between the electrodes and the HARP reduces the excessive field strength (d) and quenches discharge currents (I_{dis}) while maintaining the same voltage bias V_{HARP} across the HARP.

should be noted that light spreads in thick gamma ray scintillators such as LYSO and that this can reduce the energy resolution and spatial resolution of the detector. However, avalanche *a*-Se need not be used as an indirect-conversion detector (requiring a scintillator), but can also be used to *directly* convert ionizing radiation into electrical charge by dividing the *a*-Se into a conversion region and an avalanche region.⁵ As such, *a*-Se can provide quantum-noise limited detection with the advantage of the high spatial and energy resolution of a direct-conversion photoconductor. Furthermore, since the avalanche gain in *a*-Se strongly depends on the applied voltage, it may easily be adjusted for a specific application. This is critical for FPI applications as it can provide linear operation for a very wide range of mean radiation exposures.³ Currently, *a*-Se is being used in commercial FPI systems;⁶ however, no imaging system yet takes advantage of its avalanche multiplication gain.

The principal challenge with realizing avalanche multiplication in *a*-Se is that it requires a very large electric field ($E \sim 100$ V/μm). To reduce charge injection and maintain a low leakage current at this field (and a low associated shot noise), a layered structure has been developed known as high-gain avalanche rushing photoconductor (HARP). This structure has been described in detail previously.^{3,7} Briefly, HARP is a surprisingly simple structure and consists of an *a*-Se layer sandwiched in between hole and electron blocking contacts. Optical photons produce electron-hole pairs in the *a*-Se. The holes undergo avalanche multiplication as they are swept toward a negatively charged surface. In the HARP tube, this surface is scanned by an electron beam inside a

vacuum to produce an image. The HARP tube can produce $g_{av} \sim 10^3$. Previously, when electrodes have been directly connected to the HARP to realize a solid-state detector [Fig. 1(a)], it has been limited to a practical maximum avalanche gain $g_{av} \sim 10$ due to premature failure at higher gains.⁸ Our expectation is that much higher gains could be achieved in this *electroded* HARP by (1) eliminating the electric field enhancement near the sharp edges of conductive electrodes and (2) quenching incipient electrical discharges which can cause the breakdown of the *a*-Se. In principle, these two problems may be overcome by introducing a distributed resistance layer (DRL) which can be deposited on top of the HARP structure.

The protective mechanism of the DRL can be understood by considering the electric field distribution and charge flow across the HARP and DRL. In the electroded HARP [Fig. 1(a)], the field lines bend near the electrode edges resulting in localized regions of very high field strength ($E > 105 \text{ V}/\mu\text{m}$), which causes injection of electrons into the HARP despite the electron blocking contact [Fig. 1(b)]. If a discharge occurs, the discharge current can escalate, leading to Joule heating, irreversible crystallization, and ultimately break down the *a*-Se. In the HARP-DRL [Fig. 1(c)], on the other hand, the electric field inside the DRL (a weakly conductive material) is very low ($\sim 1 \text{ V}/\mu\text{m}$), thus greatly reducing electron injection [Fig. 1(d)]. Furthermore, any excess discharge current will generate a potential drop across the DRL leading to a reduction of the electric field in the HARP and its associated avalanche gain, ultimately quenching the discharge current. Since the DRL is distributed and provides a series resistance for the charge traversing each del, it functions irrespectively of the del geometry and the photoreceptor scale. It should be noted that a resistive electrode approach based on this same principle has been used recently at CERN to dramatically improve avalanche gain and stability of gas electron multipliers.⁹

In order to test the functionality of HARP-DRL, we measured the HARP gain first without and then with the DRL. This was done by illuminating a 1 cm^2 HARP with a pulsed blue light emitting diode with a maximum emission wavelength of 480 nm which is relatively close to the emission wavelengths of LYSO (420 nm) and CsI (550 nm) scintillators commonly used in PET and R/F imagers.^{3,4} Cellulose acetate was chosen as the material for the DRL, since it is known to bond well with *a*-Se and it produces a distributed series resistance of $\sim 10^{12} \Omega \text{ cm}$ which has demonstrated stable operation in avalanche *a*-Se.¹⁰ The acetate was cast on the surface of the HARP. The signal was read out by connecting an oscilloscope to a single 1 mm^2 del electrode made from a conductive polymer (PEDOT) deposited on top of the DRL. As shown in Fig. 2(a), HARP alone could only sustain an electric field strength $E \leq 83 \text{ V}/\mu\text{m}$ (corresponding to an avalanche gain of 2) before exhibiting breakdown (observable as a sudden irreversible onset of leakage current). In contrast, HARP-DRL supported considerably higher fields ($E \leq 105 \text{ V}/\mu\text{m}$) resulting in linear avalanche gains as high as 10^4 [Fig. 2(b)]. This is the first time that gains higher

FIG. 2. Measured signal current I_s for electroded (a) HARP and (b) HARP-DRL. The leakage current I_l is also shown. The *a*-Se thickness in the HARP layer was $15 \mu\text{m}$. The DRL used was a $2 \mu\text{m}$ thick layer of cellulose acetate polymer which was cast onto the HARP layer.

than 2×10^3 have been reported in *a*-Se and is an increase in three orders of magnitude compared to electroded HARP. Furthermore, the reproducibility of the gain measurements suggests that the DRL is a stable and practical means of extending and maintaining the HARP avalanche gain.

The measured leakage current I_l in HARP-DRL (Fig. 2) is very low ($I_l \leq 20 \text{ pA}/\text{mm}^2$) for $E \leq 105 \text{ V}/\mu\text{m}$. Thus, even for imaging applications that require relatively long integration times (i.e., $\sim 100 \text{ ms}$ for FPI), this leakage current produces a charge equivalent to $\sim 10^6 \text{ e}/\text{del}$ (assuming a del size of $300 \times 300 \mu\text{m}$), which corresponds to a shot noise of $\sqrt{10^6} = 10^3 \text{ e}/\text{del}$. As a single x-ray or gamma ray interaction can produce at least 10^6 e in HARP-DRL coupled to an appropriate scintillator,¹⁰ this shot noise is negligible. We have previously shown experimentally that avalanche noise following the detection of high energy photons (x rays) is insignificant in HARP.¹¹ Hence, HARP-DRL can produce very large internal gains with negligible added noise which is crucial for quantum-noise limited detection of x rays and gamma rays.

HARP technology has successfully been used in commercial ultrahigh sensitivity broadcasting cameras for a number of years.⁷ Hence, it is reasonable to expect that a solid-state alternative such as that proposed here will provide reliable operation. Further work, however, is necessary to examine the stability of the HARP-DRL over time and as a function

of radiation exposure. Further investigation is also necessary into development of suitable manufacturing processes for the production of large-area ($>1\text{ cm}^2$) HARP-DRL photoreceptors. Some preliminary research demonstrates that HARP-DRL rise time is $<1\text{ ns}$, suggesting a suitable timing resolution for PCI applications.^{4,10} Although cellulose acetate has been used in this work, it is important to note that other resistive materials may be used to potentially improve the gain and/or other characteristics such as temporal response of HARP-DRL.¹²

In conclusion, we have demonstrated a breakthrough in the practical implementation of a solid-state avalanche photoreceptor technology based on *a*-Se. The deceptively simple addition of a single layer of weakly conductive material (DRL) permits the application of very high electric fields which in turn achieves very high multiplication gains without significantly increasing leakage current and simultaneously protecting the device from breakdown. These gains are the highest reported in a solid-state amorphous photoreceptor. This promises to enable a practical solid-state alternative to bulky PMTs and image intensifiers.

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