

# High gain lateral amorphous selenium (a-Se) detector for medical imaging

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## ABSTRACT

Amorphous selenium (a-Se) is a well known photoconductor and has been used in both indirect and direct conversion x-ray detectors for a variety of medical imaging modalities such as mammography. It goes without saying that interest for having a photodetector with higher gain never ceases. There has been a lot of research on taking advantages of the avalanche multiplication phenomenon inside a vertical a-Se structure to produce high internal gain in the photodetector (e.g. HARP camera for low-light settings). The fast response time and high gain of the a-Se avalanche photodetector makes it a promising candidate to replace photomultiplier tubes (PMT) or silicon avalanche photodiode (APD) based photomultipliers (SiPM) in applications such as positron emission tomography (PET) detectors. Recently, a lateral metal-semiconductor-metal (MSM) a-Se photodetector has been reported as a competitive alternative in terms of ease of fabrication and integration, speed and low dark current. Thus, we believe the lateral structure is also promising for high gain photodetector applications like PET. In this paper, we intend to investigate the effect of increasing electric field on the lateral a-Se structure and compare the results with the modified lucky drift model which presents a good agreement with experimental data on avalanche multiplication in vertical a-Se structures. Our study shows that a gain of  $\sim 100$  can be achieved in a lateral structure under a modest field strength of  $40 \text{ V}/\mu\text{m}$ . Even though the observed dark current of  $\sim 800 \text{ nA}$  is still far beyond the requirement of a practical detector, the achievable high gain allows us to design better detectors for high-end applications such as PET with a unique lateral approach.

**Keywords:** Amorphous selenium, Photodetector, Avalanche gain

## 1 INTRODUCTION

Imaging technology always embraces detectors with higher sensitivity and lower noise. For instance, the early detection of breast cancer is crucial for efficient treatment. To produce a high quality image, either the electronic noise should be kept to a minimum or the x-ray photoconductor's conversion gain should be enhanced. For applications like mammography tomosynthesis where the x-ray dose is low, the quantum noise is quite significant [1]. In this case, increasing the photoconductor's conversion gain is the best solution. Vast attention has been given to the avalanche multiplication phenomenon to achieve internal gain inside the photoconductive material. Avalanche photodiodes have been used in many applications such as optical communication. Recently, IBM scientists utilized nanophotonic avalanche photodetectors on a small silicon circuit to replace the electrical signal that is used to communicate through wires between computer chips [2]. Avalanche multiplication in amorphous selenium was reported for the first time by Juska et al. in 1980 [3]. The device structure used by Juska was a simple structure of a-Se sandwiched between two insulating polyethyleneterephthalate layers. The insulating layers were used to avoid any possible charge injection from the electrodes due to the high applied electric field. The insulating layer however prevents the exit of photogenerated carriers to the external circuit. Some years later, using a-Se with proper blocking contacts lead to the commercial deployment of high-gain avalanche rushing photoconductor (HARP) TV camera tubes [4]. The avalanche multiplication converts a faint optical signal to a significant electrical signal which is suitable for low-light level conditions compared to other competing technologies.

Although the existence of avalanche multiplication in a-Se has been known for a relatively long period, the process of avalanche multiplication in amorphous semiconductors is not yet fully understood according to the different motion of electrons due to the inherent disorder potential inside amorphous materials. Among existing

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models intending to describe avalanche multiplication inside amorphous materials, the modified lucky drift model has been shown to provide a good fit to experimental data [5]. The modified lucky drift model considers the effect of carrier scattering due to the disorder potential in addition to carrier scattering with phonons (which is the subject of the lucky drift model for crystalline material). In this model, primary carriers continuously gain and lose energy based on elastic and inelastic scattering in their paths across the electric field. In order to achieve an avalanche state, the carriers should acquire the ionization threshold energy required to excite secondary carriers. The mean free path of carriers in amorphous material is very small (in the range of a few interatomic spaces) [6]. This means the electric field should be sufficiently high to help carriers reach the ionization threshold energy during their transport along their path. Although there is an advantage to increasing the electric field, there is a limitation due to the breakdown of the material caused by the injection of excess carriers. It has been found that the right choice of electrode and blocking materials can reduce this problem in multilayer vertical a-Se structures.

It should be noted that the avalanche multiplication phenomenon is not the only mechanism responsible for achieving photocurrent multiplication. Space charge limited or internal field modification limited processes can lead to photocurrent multiplication. For instance, a gain of up to 70 has been reported in hydrogenated amorphous silicon-based p-i-n junction with an a-SiN:H layer arising from the tunneling of electrons across the band gap through localized states in the a-SiN:H layer [7]. To get photocurrent multiplication by this mechanism, the right choice of layers with proper band gaps and density of localized states is crucial. After illumination, the field redistribution should be in favor of tunneling.

In this work we have fabricated a lateral a-Se photodetector structure and have studied its photoconductive response at 468 nm wavelength illumination. In comparison with different detector technologies, a lateral selenium detector has some advantages which are summarized in Table 1. In particular, advantages include the ease of fabrication and integration, low voltage of operation, speed of operation, and feasibility in a variety of imaging modalities. In addition, a lateral structure appears to easily achieve high gain compared to a vertical avalanche structure in which high field must be applied.

## 2 Experimental

In this section, we demonstrate experimental results on the investigation of photocurrent characteristics and quantum yield in the lateral a-Se photodetector structure. The cross-sectional diagram of the lateral a-Se photodetector with aluminum electrodes is shown in Fig. 1. This structure was fabricated by conventional microelectronic processes by using two photolithography masks. The details of the fabrication can be found in reference [8]. This design has an electrode spacing of 1  $\mu\text{m}$ , electrode length of 60  $\mu\text{m}$  and electrode width of 2  $\mu\text{m}$ . The thickness of the a-Se layer is 2  $\mu\text{m}$ .

**Table 1.** Comparison of different technologies.

<b>Detector Factor</b>	<b>Lateral Selenium</b>	<b>Vertical Selenium</b>	<b>P-I-N</b>
<b>Ease of Fabrication</b>	Very Good no blocking contacts	Good	Good
<b>Detection Mode (Spatial Resolution)</b>	Indirect	Direct (best)	Indirect
<b>Voltage of Operation</b>	Low (30-60 V)	High (>2500 V)	Lowest (5-10V)
<b>Ease of Integration</b>	Simple	Simple	Challenging (additional masks )
<b>Speed of Operation</b>	1000 Hz	1-3 Hz	30 – 60 Hz
<b>External Quantum Efficiency</b>	> 1 potentially	< 1	< 1
<b>Avalanche Gain</b>	Possible	Possible	No
<b>Medical Imaging Applications</b>	Fluoroscopy, flat panel CT, Dental Imaging, SPECT & PET	Mammography	Fluoroscopy, flat panel CT, Dental Imaging, SPECT & PET

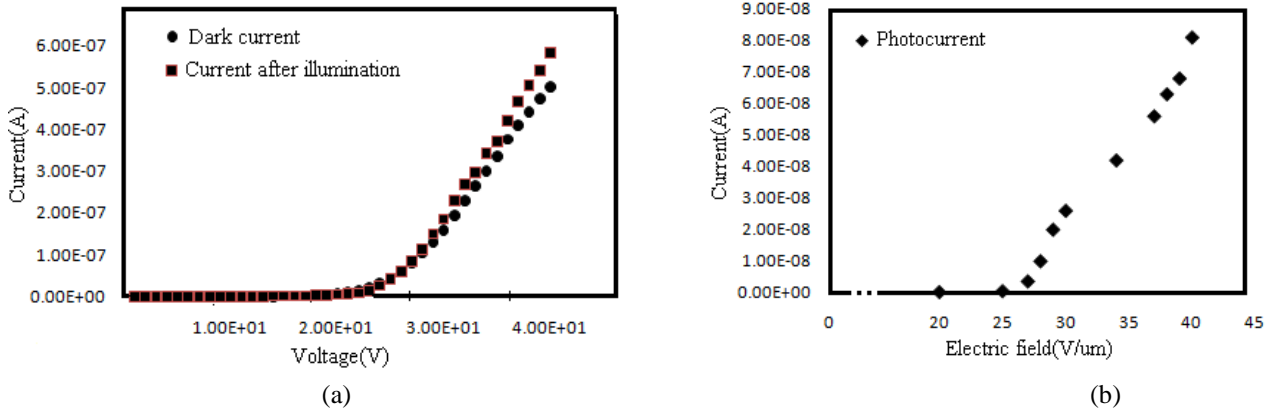


**Figure 1.** Cross-sectional diagram of fabricated lateral detector (left) and micrograph of the fabricated detector (right).

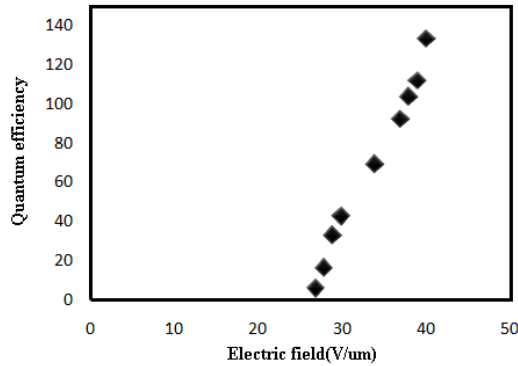
The Current-Voltage characteristics of the device with and without illumination were measured (Fig. 2-a). The measurements were carried out using a Keithley S2600 low-noise microprobe station. In order to measure photocurrent, the device was illuminated by a fixed (continuous) incident monochromatic light of wavelength 468 nm. The light intensity was  $180 \mu\text{W}/\text{cm}^2$ . Fig. 2-b shows the photocurrent at different electric field strengths ranging from  $20 \text{ V}/\mu\text{m}$  to  $40 \text{ V}/\mu\text{m}$ . The photocurrent  $I_{\text{ph}}$  is given by the subtraction of dark current from the measured current under illumination. The quantum yield of photogeneration was calculated using the measured photocurrent by the following expression:

$$\eta = \frac{I_{\text{ph}}e}{I_{\text{hv}}} \quad (1)$$

where  $e$  is the elementary charge, and  $h\nu$  is the energy of incident photon.



**Figure 2.** a. Signal current and dark current versus voltage, b. photocurrent-field characteristic.



**Figure 3.** The dependence of quantum yield on applied electric field.

Fig. 3 shows the calculated quantum yield as function of electric field. The quantum yield for an electric field of  $25 \text{ V}/\mu\text{m}$  was close to unity. We calculated the gain ( $G$ ) by the following relation:

$$G = \eta(E)/\eta(25\text{V}/\mu\text{m}) \quad (2)$$

where  $\eta(25\text{V}/\mu\text{m})$  is approximately equal to unity. Therefore, the gain and quantum yield for electric field above  $25\text{V}/\mu\text{m}$  are the same. The lucky drift model predicts an avalanche gain for electric field larger than  $70\text{-}80 \text{ V}/\mu\text{m}$  in

vertical structure. This result suggests that the avalanche multiplication is not the responsible mechanism for creating gain in this structure. One of the possible mechanisms responsible for the excess photocurrent and resulting gain might be due to the injection of more holes from the electrode [9]. The hole mobility ( $\sim 0.12\text{cm}^2/\text{Vs}$ ) in a-Se is generally two orders of magnitude higher than the electron mobility ( $\sim 0.003\text{cm}^2/\text{Vs}$ ) [10]. After generation of electron-hole pairs due to incident light, while the faster holes are collected by the cathode, the electrons are still proceeding towards the anode. The process creates an absence of holes and hence a net negative charge in the region that is compensated for by injection of holes from the anode into this region. This process leads to the generation of more holes upon absorption of a single photon. We are working to better understand the existence of gain in this type of device structure, including exploring other possible mechanisms responsible for the observed gain.

### 3 Conclusion

A photocurrent multiplication phenomenon is observed in a lateral a-Se based photodetector. A quantum yield of 136 is obtained in the presence of an applied electric field of  $40\text{ V}/\mu\text{m}$  which eliminates the need of applying a very high bias potential across the photodetector. The results suggest that the gain is not due to avalanche multiplication, which is the responsible mechanism for carrier multiplication in vertical structures. Currently, the main drawback of the device is high dark current. This point needs to be improved before the device can be used for PET detector.

### ACKNOWLEDGMENTS

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