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# Electroded avalanche amorphous selenium (a-Se) photosensor

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ABSTRACT

Although avalanche amorphous selenium (a-Se) is a very promising photoconductor for a variety of imaging applications, it is currently restricted to applications with electron beam readout in vacuum pick-up tube called a High-gain Avalanche Rushing Photoconductor (HARP). The electron beam readout is compatible with high definition television (HDTV) applications, but for use in solid-state medical imaging devices it should be replaced by an electronic readout with a two-dimensional array of metal pixel electrodes. However, due to the high electric field required for avalanche multiplication, it is a technological challenge to avoid possible dielectric breakdown at the edges, where electric field experiences local enhancement. It has been shown recently that this problem can be overcome by the use of a Resistive Interface Layer (RIL) deposited between a-Se and the metal electrode, however, at that time, at a sacrifice in transport properties.

Here we show that optimization of RIL deposition technique allows for electroded avalanche a-Se with transport properties and time performance previously not achievable with any other a-Se structures. We have demonstrated this by detailed analysis of transport properties performed by Time-of-Flight (TOF) technique. Our results showed that a stable gain of 200 is reached at 104 V/μm for a 15-μm thick a-Se layer, which is the maximum theoretical gain for this thickness. We conclude that RIL is an enabling technology for practical implementation of solid-state avalanche a-Se image sensors.



## 1. Introduction

The avalanche gain capability of a-Se is of high significance to the development of medical image sensors, where gain is often achieved by bulky, low quantum efficiency vacuum electro-optical devices. To date a-Se remains the only amorphous photoconductor where charge (holes), while drifting in high electric field, can avoid energy dissipation and hence can acquire enough energy to initiate impact ionization and secondary charge creation [1,2]. The avalanche multiplication gain $g_{AV}$ depends exponentially on the a-Se layer thickness $d$ [3,4].. Hole impact ionization in a-Se is triggered at electric fields $F$ exceeding an avalanche multiplication threshold $F_{AV}$. $F_{AV}$ depends slightly on a-Se thickness and is equal to 70 V/μm for 15–30 μm thick a-Se layers.

Practical a-Se avalanche image sensors called High-gain Avalanche Rushing Photoconductors (HARP) have been developed for broadcasting devices and exhibit a high multiplication gain ($g_{AV} > 200$ for $d = 15$ μm and $g_{AV} > 10^3$ for $d = 30$ μm) which provides ultra-high sensitivity and allows for functionality in extremely low light conditions [5–7]. Furthermore, HARP has two other remarkable features, high quantum efficiency (~95% for blue light) and low dark current [4,8]. The latter was made possible by the development of a special blocking structure that effectively suppresses charge injection from electrodes, even at the high electric field needed for avalanche [8,9]. The combination of high multiplication gain with high optical quantum efficiency and low dark current makes avalanche a-Se photosensors an alternative to photomultiplier tubes for a variety of optical and medical imaging applications, e.g. Positron Emission Tomography (PET) [10–12].

Although promising for many imaging applications, practical a-Se HARP photosensors had previously been restricted to signal readout using a scanning electron beam, which requires a vacuum

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operation [5–7]. For use in medical imaging systems, electron beam has to be replaced by a two-dimensional array of pixel electrodes [10]. However, implementation of electronic readout to HARP structure has several technological challenges. First, metal contacts may degrade. Previous attempts to fabricate pixelated electrodes using gold (Au) have been unsuccessful, with the higher noise observed compared to electron beam readout [13]. This excess noise can be attributed to the gradual diffusion of Au into a-Se. Secondly, sporadic dielectric breakdown at the edges of metal electrodes may occur. This can happen because the high electric fields required for avalanche is further increased at the contact edge. An incipient breakdown causes a high current flow that can induce a phase transition due to Joule heating. This may result in irreversible crystallization of an area adjacent to contact [14].

The above challenges have hindered the development of electronic readout methods for avalanche a-Se photoconductors. Enabling stable operation of pixelated a-Se avalanche photosensors without contact degradation, sudden breakdown and associated structural transformations is an important issue in avalanche a-Se technology. We have shown previously that incipient breakdown can be prevented by coating the HARP free surface with a Resistive Interface Layer (RIL) made of a semi-insulating polymer, namely cellulose acetate (CA) [15]. CA has been chosen as RIL for the modified a-Se HARP structure as it bonds well to a-Se and is compatible with a-Se technology: CA has been used as a protective coating in a-Se xeroradiographic plates and in this application extended the plate life by a factor of approximately 10 [16]. Although an improvement of stability against breakdown was evident with our results [15], concern remained regarding possible degradation of transport properties. This issue is addressed here. By analysis of transport properties we show that while improving HARP blocking characteristics, thin ($\sim$1 μm) RIL does not degrade its transport properties: no charge trapping at HARP/RIL interface layer was observed and no deterioration of transient response was found. Furthermore, RIL prevents gold diffusion into a-Se structure. The above features make RIL a practical approach for the development of a-Se solid-state avalanche photosensor with extremely low dark current for a variety of applications in optical imaging and PET.

## 2. Methods

### 2.1. Sample preparation

Two different types of solid-state a-Se detector structures were prepared based on the HARP target used in a vacuum tube device: *standard* pixelated HARP structure (Type 1), in which 0.8 mm$^2$ gold contacts have been deposited by sputtering directly on a-Se blocking layer (Fig. 1 a), and *modified* pixelated HARP photosensor (Type 2) in which a 1 μm thick RIL (using CA) was spin-coated (in clean room environment, under controlled deposition parameters like: accelerating, decelerating, rotation speed and temperature) prior to the deposition of a 0.8 mm$^2$ gold contact (Fig. 1 b). The HARP structure consists of a 15 μm a-Se photoconductor, sandwiched between 10 nm thick $CeO_2$ layer and 0.5 μm thick $Sb_2S_3$ layer (hole and electron blocking layers, respectively), deposited on an ITO-coated glass substrate (Fig. 1). The details of this structure design can be found in Refs. [5–7].

### 2.2. Time-of-flight measurement

Time-Of-Flight (TOF) technique [17] was used to investigate transport and charge collection in both types of a-Se photosensors. For TOF measurements photosensors were exposed from the ITO side to a short (35 ps) laser pulses with the wavelength of 420 nm

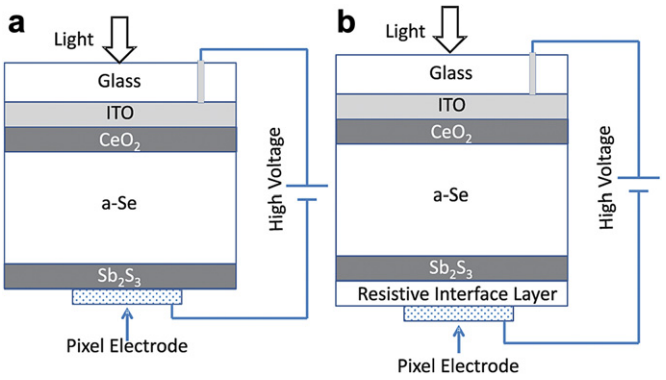


**Fig. 1.** Schematic picture of a-Se structures under investigation: (a) a-Se pixelated HARP blocking structure; (b) a-Se pixelated HARP blocking structure with Resistive interface layer between a-Se and metal electrode.

(which corresponds to the peak emission from scintillation crystals used in PET) and the current transients were monitored at various applied electric fields $F$ by a 6 GHz bandwidth digital oscilloscope (Fig. 2). In both types of a-Se photosensors the electric field across the a-Se layer was created by connecting a positive voltage supply to an ITO layer (Fig. 2). The range of applied electric field was 10–104 V/μm for Type 2 samples (with RIL) and 10–80 V/μm for Type 1 (w/out RIL). Fields applied to Type 1 samples were restricted to prevent the dielectric breakdown which was found to occur above 80 V/μm after a few seconds of operation. It should be noted that in a signal mode (i.e. when a photosensor is exposed to a very short light pulse) the presence of CA layer does not affect either the photocurrent or charge collection from the structure since the capacitance of CA layer is 30 times larger than that of a-Se layer.

Due to the short absorption depth in a-Se at 420 nm, electron-hole pairs (EHP) are generated close to the ITO/a-Se interface. The photogenerated holes traverse a distance equal $d$ whereas the photogenerated electrons travel only a very short distance to the ITO contact. The duration of the laser pulse was negligible in comparison with both the RC constant of a-Se layer and the transit time for holes under all experimental conditions. All measurements were made at room temperature. Current transients for holes allowed us to calculate hole transient time and mobility while the integration of transient photocurrents allowed us to obtain the kinetics of charge collection at different electric field regimes. This in turn permits to derive the ratio between total collected electrons and holes ($n_e/n_h$). The importance of this ratio is that it allows an accurate calculation of the avalanche gain at different fields.

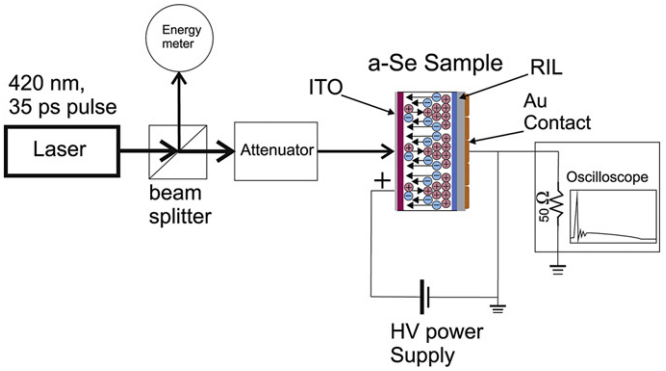


**Fig. 2.** Schematic representation of Time-Of-Flight experimental apparatus which is used for measurement of electron-hole pair generation in a-Se.