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Avalanche Multiplication in Amorphous Selenium

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Avalanche multiplication occured in amorphous selenium (a-Se) sandwich cells at electric fields higher than 8×10^5V/cm. Electron and hole ionization rates (α and β), which are obtained from the thickness dependence of the multiplication factor, have single exponential dependence on the reciprocal field. The excess noise factor was estimated to be small because of the large ratio of β to α. An avalanche type image pick up tube which has the a-Se photoconductive target was fabricated, and extremely higily sensitivity (the quantum efficiency greater than 10) was achieved. It also is found that the avalanche multiplication in a-Se occurs uniformly over areas larger than $1cm^2$.

1. Introduction

Avalanche multiplications in various crystalline semiconductors have been studied intensively[1]. This is because these studies are important both in the material science under high electric fields and in electronic device applications such as APDs or IMPATT diodes.

Concerning amorphous materials, Hindley[2] and Mott[3] suggested that the avalanche multiplication process may be included in the threshold switching phenomenon in thin films of amorphous chalcogenide semiconductors[4]. Recently, the avalanche multiplication has been observed in amorphous Se (a-Se) photoconductive targets of image pick up tubes[5] and the ionization rates in the targets were determined[6].

In the present paper, we report the measurements of the avalanche multiplication effect in a-Se sandwich cells with blocking contacts. The ionization rates have been obtained from the thickness dependence of the multiplication factor. The obtained electric field dependence of the electron ionization rate is far stronger than that of Ref.6). Uniform multiplication over areas of $1cm^2$ was observed in the characteristics of the avalanche type image pick up tube.

2. Experimental

The structure of the sample is shown schematically in Fig.1. The semi-transparent Cr electrode is deposited by the sputtering method on a glass substrate. The CeO_2 layer which is a hole blocking layer and the a-Se layer are successively vacuum deposited in the same chamber. The thicknesses of the a-Se layers are changed from 0.5μm to 4μm. A small amount of LiF is doped in the a-Se in the vicinity of the CeO_2 layer. This doped layer, which acts as

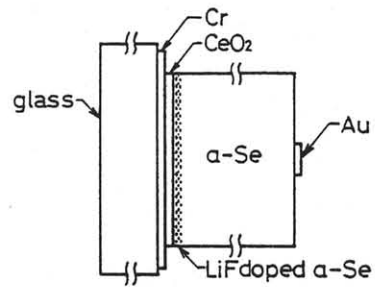

Fig.1 Schematic view of the sandwich cell.

a positive space charge region, weakens the electric field at the boundary with the CeO_2 layer. As a result, injection of holes from the Cr electrode is prevented more effectively. Finally, the sandwich cell structure is completed by the deposition of a semi-transparent Au electrode. The Au/Se junction forms the electron blocking contact. The effective cell area is $3mm^2$.

The a-Se layer is biased so as to the Cr electrode side becomes positive, and the sample is illuminated by the monochromatic light of 400nm. Because of the large absorption coefficient of a-Se at this wave length[7], the light is absorbed in the a-Se layer within a depth of about 500Å from the illuminated side. Therefor, the resulting currents can be treated as hole initiated currents and electron initiated currents under the illumination through the Cr and the Au electrodes, respectively.

3. Results and Discussion

3-1 Current-electric field characteristics

The current - electric field characteristics of a-Se for various film thicknesses are shown in Fig.2(a) and (b). The photocurrents shown in (a) correspond to the hole initiated currents, and those in (b) to the electron initiated currents. The dark currents measured at 5 seconds after removing the illumination at each field are also plotted in Fig.2(a). Since the transparencies of the electrodes slightly differed from each sample, the light intensity was adjusted so as to fit the saturation level of the photocurrent density to 100 nA/cm^2.

Photocurrents increase rapidly with increasing electric field and tend to saturate for a certain field range. In this region, the photoconductive quantum efficiency almost reaches unity for 400nm wavelength light[7]. Then the photocurrents increase again for fields higher than $0.8x10^6$ V/cm and $1.2x10^6$V/cm for the hole and the electron initiated currents, respectively. The photoconductive quantum efficiency is about 40 at the electric field of $1.4x10^6$ V/cm for the a-Se layer which has the thickness of 1μm. The rate of increase of the photocurrent in this region is the more rapid for the thicker a-Se layer. On the other hand, the dark currents don't show such rapid increases in the measured field range. These significant features can't be explained by the space charge limited current, which shows the opposite thickness dependence, or the carrier injection from the electrode. It is clearly indicated that the avalanche multiplication takes place in the a-Se layer.

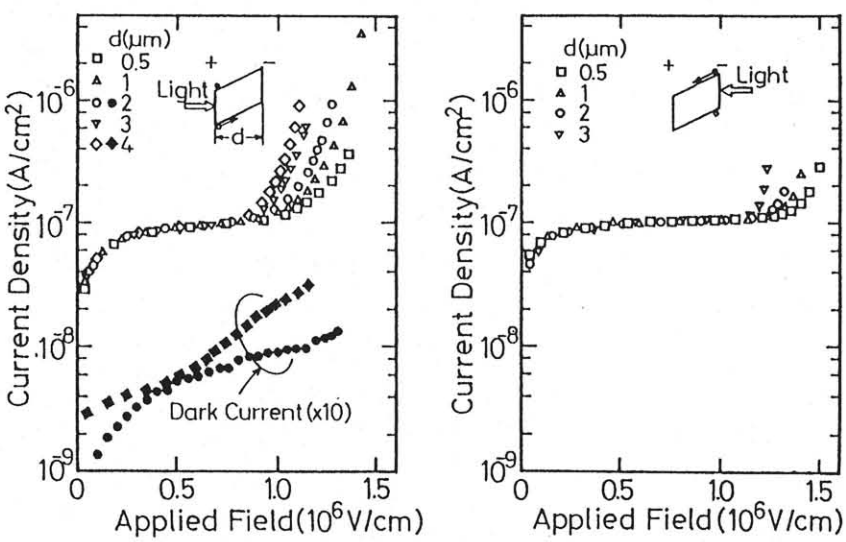

Fig.2 Electric field dependences of (a)hole initiated photo currents, dark currents, and (b)electron initiated photo currents.

3-2 Hole and electron ionization rates

The hole and the electron ionization rates (β and α) have been calculated from the thickness dependence of the multiplication factor. Here, we assumed the position independent ionization

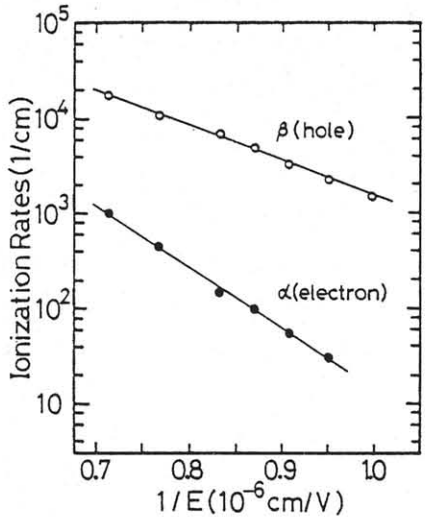

Fig.3 Hole and electron ionization rates for a-Se. The solid lines show the least squares fittings.

rates. The results are shown in Fig.3, in which α and β are plotted in relation to the reciprocal electric field 1/E. Both α and β have single exponential dependence on 1/E over the entire range of the applied electric fields. The solid lines in the figure show the least squares fittings which are expressed as

$$\alpha = 3.8\times10^{7}\exp(-1.5\times10^{7}/E)\ \mathrm{cm}^{-1}$$

and

$$\beta = 8.8\times10^{6}\exp(-8.7\times10^{6}/E)\ \mathrm{cm}^{-1}$$

for $1.0\times10^{6}\mathrm{V/cm} \leq E \leq 1.5\times10^{6}\mathrm{V/cm}$. Taketoshi et al.[6] also obtained the ionization rates from the hole initiated current

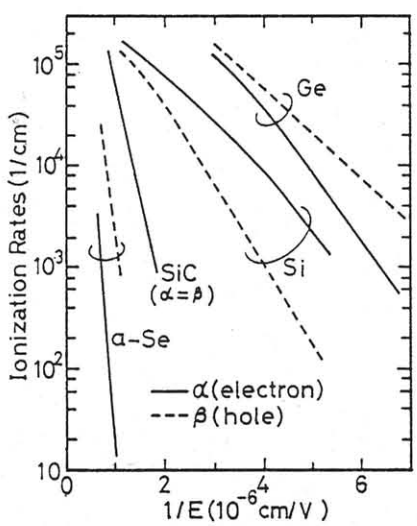

Fig.4 Ionization rates for a-Se (our work) and some crystalline semiconductors (from Ref.1).

characteristics of the image pick up tube. Their result for β is in good agreement with the expression presented here. On the other hand, their result for α has much smaller field dependence than that of this work. One of the reason of the disagreement may be the difference of the sample structure.

The ionization rates of a-Se obtained here are re-plotted with those of typical crystalline semiconductors[1] in Fig.4. Note that the ionization rates of a-Se have the strongest 1/E dependence, and large ionizations in a-Se arise only at higher electric field, even though the band gap E_g of a-Se is smaller than that of crystalline SiC. The field dependence of the ionization rate can be written approximately as $\exp(-E_i/eEl)$ where E_i is the threshold energy for ionization, and l is the optical phonon mean free path[8]. In amorphous semiconductors E_i may not be so larger than E_g, since there is no requirement for momentum conservation. Therefore, it is suggested that the strong 1/E dependence of the ionization rate in a-Se is caused by the short mean free path of carriers.

It can be also seen from Fig.4 that the ratio of the hole ionization rate to the electron ionization rate, $K=\beta/\alpha$, is very large in case of a-Se. It reaches about 100 in the field of 1×10^{6}V/cm. These are

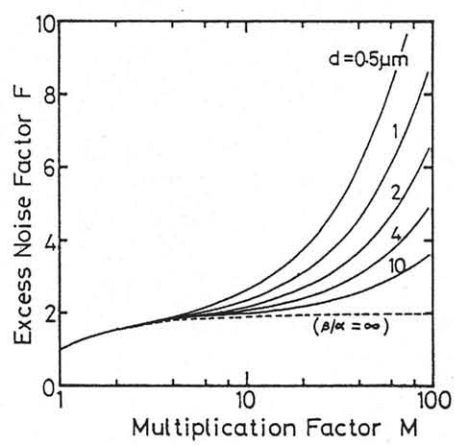

Fig.5 Plots of excess noise factor vs. avalanche multiplication factor in a-Se layer with different thicknesses.

essential to the low excess noise feature of avalanche photo diodes[9]. Figure.5 shows the excess noise factor F vs. the multiplication factor M for various a-Se layer thicknesses calculated from the obtained expression for the ionization rates. Here, F is defined as

$$\overline{I_n}^2 = 2eI_sM^2FB,$$

where $\overline{I_n}^2$ is the mean square shot noise current, I_s is the input current, and B is the bandwidth. The broken line shows the ideal excess noise factor, i.e. for $K=\infty$. If the thickness of the avalanche layer is 2μm and the multiplication factor is 10, then F=2.2 for a-Se while F=2.7 for crystalline Si (calculated from the expression in Ref.10). This indicates the low excess noise feature of the a-Se.

3-3 Application to image pick up tube

We applied the a-Se photoconductive target with 1 inch in diameter to an avalanche type image pick up tube[5]. Typical images on a monitor which were reproduced by the avalanche type image pick up tube and a conventional one are shown in Fig.6. From the figure, much higher sensitivity compared with the conventional image pick up tube and the low excess noise feature can be understood. It was also found that the avalanche multiplication in a-Se occurs uniformly over the scanning area which is larger than $1cm^2$.

(a) (b)

Fig.6 Images on a monitor reproduced by (a) the avalanche type image pick up tube and (b) a conventional image pick tube. The illumination was 200(lx) and the iris was F4 for both images.

4.Conclusion

Avalanche multiplication was achieved for the first time in an a-Se sandwich cell. The electric field dependences of hole and electron ionization rates were obtained. At the electric field of $1.2x10^6$ V/cm, the ionization rates are about $1.4x10^2$ /cm and $6.3x10^3$ /cm for electron and hole, respectively. Because of the large ratio of the hole ionization rate to the electron ionization rate, the excess noise by the avalanche multiplication in a-Se is rather small compared to that of typical crystalline semiconductors. The a-Se target was applied to the photoconductive target of an image pick up tube and extremely high sensitivity with good uniformity over the scanning area was obtained.

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