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Avalanche-Mode a-Se Thin Films for Solid State Image Sensors

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1. Introduction

The first high sensitivity image pick-up tube using a 2 μm-thick a-Se HARP (High-gain Avalanche Rushing amorphous Photoconductor) which has an avalanche multiplication phenomena at a bias voltage of 240 V was developed by K. Tanioka et al. in 1987[1]. Research is now being conducted on a compact solid state image sensor which connects MOSFET readout circuits and an a-Se HARP film using indium (In) microbumps[2].

There is no limit to the applied voltage of an image pick-up tube practically. In the latest HARP image pick-up tube, the thickness of the film and the bias voltage were increased to 25 μm and 2500 V, respectively, in order to obtain much higher sensitivity (multiplication factor : 600)[3].

In the case of the solid state HARP image sensor, however, it is necessary to cause avalanche multiplication at a relatively low bias voltage below the endurance voltage of the readout circuit, which limits a-Se film thickness. Now, a MOSFET with an improved endurance voltage has been developed for the solid state HARP image sensor, which can operate at a bias voltage of 60 V [4].

In this study, the thickness of an a-Se film for a solid state HARP image sensor was decided by calculating the avalanche multiplication factors. The spectral response of the a-Se thin HARP film was also calculated and compared with the measured results using image pick-up tubes.

2. Design of the a-Se thin HARP film

When high voltage is applied to an a-Se film, electron-hole pairs produced by an incident photon are accelerated by a large electric field. These accelerated carriers produce other electron-hole pairs by impact ionization[1,2].

Assuming that a uniform electric field is applied to an a-Se layer and that photogenerated carriers are only produced at the surface of an a-Se film, the multiplication factor M is described as

$$M = \frac{(\beta-\alpha)\exp((\beta-\alpha)L)}{\beta-\alpha\exp((\beta-\alpha)L)} \quad (1)$$

where L is the thickness of the a-Se film, α is the impact ionization factor of the electron, and β is the impact ionization factor of the hole[5]. The ionization factors α and β are

$$\alpha = 3.8\times10^{7}\exp(-1.5\times10^{7}/E)\ (\text{cm}^{-1}) \quad (2)$$
$$\beta = 1.7\times10^{7}\exp(-9.3\times10^{6}/E)\ (\text{cm}^{-1}) \quad (3)$$

where E (V/cm) is the applied electric field[6].

We calculated the dependence of multiplication factors on the a-Se film thickness and bias voltage. The multiplication factors were calculated by using equations (1), (2), and (3) as shown in Fig. 1. As the thickness of an a-Se film decreases, the bias voltage required to cause avalanche multiplication falls. It is known, however, that dark current is higher in thinner films for the same multiplication factor and that it is also higher at a higher bias voltage for the film with the same thickness[7]. The increase of dark current causes the degradation of picture quality. Therefore, in order to achieve the aimed multiplication factor of 4 with a low dark current at the bias voltage of 60 V,

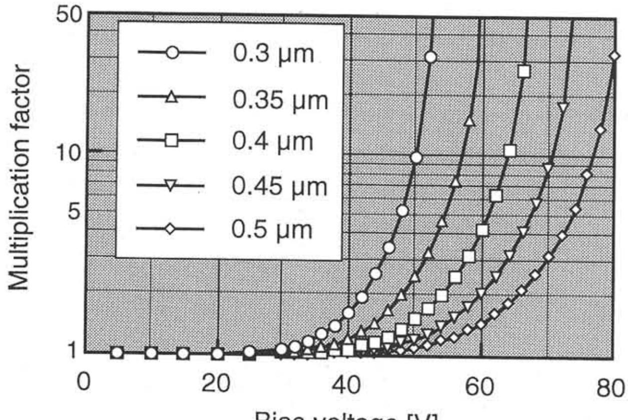

Fig. 1. Dependence of multiplication factors on the a-Se thickness and bias voltage.

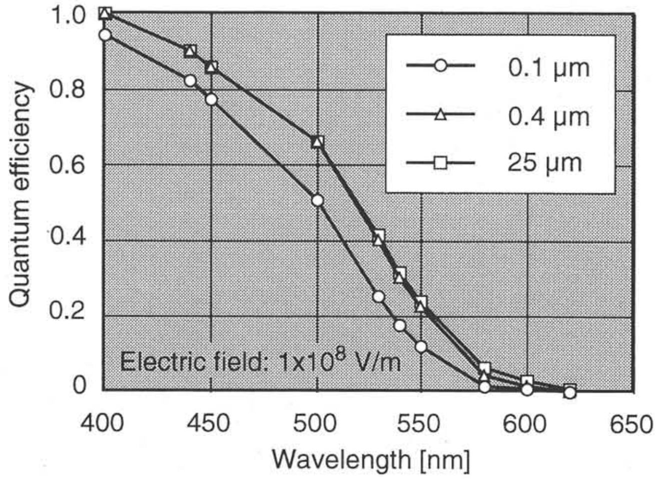

Fig. 2. Dependence of quantum efficiency on the a-Se thickness and wavelength.

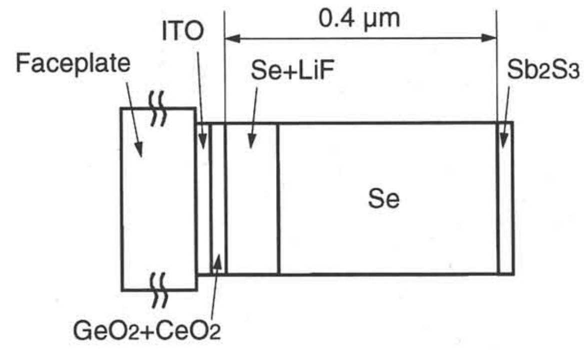

Fig. 3. Cross section of the a-Se HARP film.

we decided that the suitable thickness of a-Se film for a solid state image sensor should be 0.4 μm. This thickness is much thinner than that of the HARP film for an image pick-up tube.

3. Spectral response of the a-Se thin HARP film

Because the optical absorption is highly dependent on the wavelength in a-Se film, the optical absorption coefficients of the a-Se film are $2x10^5$ cm^{-1} at a wavelength of 440 nm, $8.5x10^4$ cm^{-1} at a wavelength of 540 nm, and $7x10^3$ cm^{-1} at a wavelength of 620 nm. Therefore, the difference of the spectral response between the thin and thick HARP film is expected to be large. We calculated the quantum efficiency of a-Se films with different thickness to study this problem[8,9].

The dependence of the quantum efficiency on a-Se thickness and the wavelength of incident light is shown in Fig. 2. Here, the electric field of the a-Se film is $1x10^8$ V/m. There is almost no dependence of the quantum efficiency on a-Se thickness when the thickness is over 0.4 μm. This is due to the following two reasons.

(1) The optical absorption of the green light is about 97% at a thickness of 0.4 μm, which is almost the same at a thickness of 25 μm.

(2) There is a large difference in the optical absorption of the red light. The values of the optical absorption are 24% at a thickness of 0.4 μm and 100% at a thickness of 25 μm. But both the 0.4 μm and the 25 μm thick a-Se films have very low sensitivity for red light due to a small photogeneration efficiency of about 1%.

Concerning the spectral response, it is needed to consider an another factor. In the a-Se HARP film, the mean transit distance of carriers produced by a long wavelength incident light is shorter than that of a short wavelength incident light. This reduces multiplication factors for a long wavelength light and can affect the spectral response.

The a-Se thin HARP film shown in Fig. 3 was fabricated and combined with an electron gun to investigate the spectral response. The spectral response measured at a bias voltage of 40 V (non-avalanche mode) and 60 V (avalanche mode) is shown in Fig. 4. In spite of the dependence of the multiplication factor on wavelengths as mentioned above, the spectral response at a bias voltage of 60 V is almost same as that at 40 V in the green and red wavelength regions. This results is due to the increase of photogeneration efficiency in long wavelength

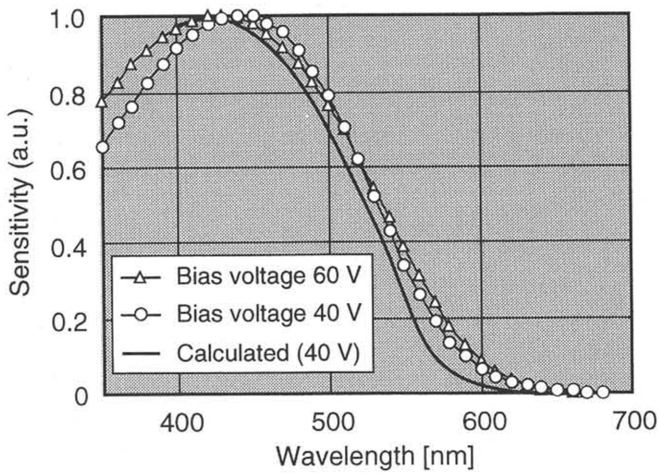

Fig. 4. Spectral response of the a-Se HARP film.

regions which have large dependence on the electric field.

An image sensor for a color camera needs a red response of up to 700 nm[10]. Therefore, an extended-red thin HARP film for the solid state image sensor is being developed by doping the a-Se layer with tellurium (Te)[11].

4. Conclusion

In this paper, the fundamental characteristics of the a-Se thin film for use in solid state HARP image sensors have been studied. From our calculations on the avalanche multiplication factor, we decided that the thickness of a-Se HARP film should be 0.4μm. The spectral response of the 0.4 μm-thick film has been investigated by calculation and measurement, and these very nealy agree.

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