P5 An a-Se HARP Layer for a Solid-state Image Sensor

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1. Introduction

The image pickup tubes with amorphous selenium (a-Se) High-gain Avalanche Rushing amorphous Photoconductor (HARP)[1] realizes both high sensitivity and good picture quality. The color camera using this tube is now widely used under poor lighting conditions, such as for shooting nocturnal animals and underwater, for medical X-ray imaging and for astronomical observation.

Recently, new high sensitivity solid state image sensor which connects CMOS readout circuits with HARP layer using indium (In) microbump electrodes was proposed[2]. This image sensor is expected to realize a compact high sensitivity color camera.

In this solid state image sensor, it is necessary to cause avalanche multiplication at a relatively lower bias voltage than in a tube considering the endurance voltage of the readout circuit.

We optimized the thickness of a HARP layer for the image sensor and, furthermore, investigated the improvement of the sensitivity by increasing the quantum efficiency with tellurium (Te)-doping.

2. Design of the a-Se thin HARP layer

When high voltage is applied to an a-Se layer, 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].

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

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

where L is the thickness of the a-Se layer, α is the impact ionization factor of the electron, and β is the impact ionization factor of the hole[3].

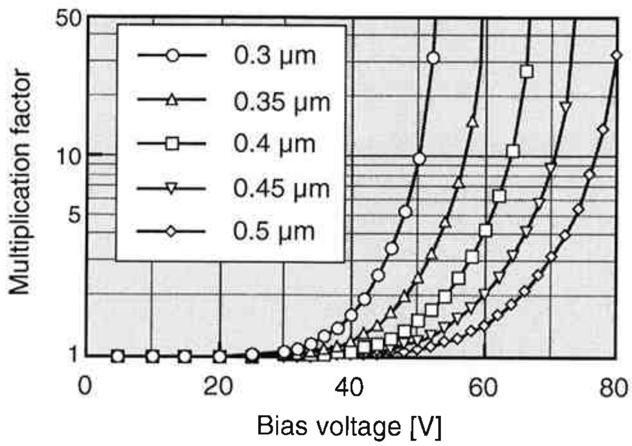
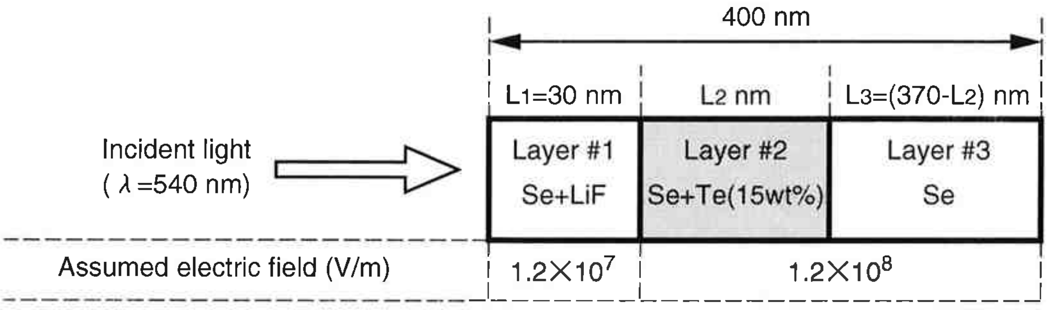


Fig. 1. Dependence of multiplication factors on a-Se thickness and bias voltage.



$$\eta = (1 - e^{-\alpha_1 L_1})\,\eta_1 + e^{-\alpha_1 L_1}(1 - e^{-\alpha_2 L_2})\,\eta_2 + e^{-(\alpha_1 L_1 + \alpha_2 L_2)}(1 - e^{-\alpha_3 L_3})\,\eta_3 \quad (4)$$

η : Quantum efficiency

α_n : Absorption coefficient [6]

L_n : Layer thickness

η_n : Photodetection efficiency [7]

Fig. 2. Calculation model of quantum efficiency for Te-doped a-Se.

The ionization factors α and β are

$$\alpha = 3.8 \times 10^7 \exp(-1.5 \times 10^7 / E) \quad (2)$$

$$\beta = 1.7 \times 10^7 \exp(-9.3 \times 10^6 / E) \quad (3)$$

where E (V/cm) is the applied electric field[4].

The multiplication factors were calculated by using equations (1), (2) and (3) as shown in Fig. 1. As the thickness of an a-Se layer decreases, the bias voltage required to cause avalanche multiplication falls. It is known, however, that dark current is higher in thinner layers with the same multiplication factor and that it is also higher at a higher bias voltage for the layer with the same thickness[5]. The increase of dark current degrades 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, we decided that the suitable thickness of a-Se layer for a solid state image sensor should be 0.4 μm.

3. Increasing quantum efficiency with Te-doping

As mentioned above, the multiplication factor obtained in the solid state HARP image sensor is less than that in the tube, such as 10 in the earliest HARP tube[1], due to the endurance voltage of the readout circuit. We investigated the improvement of the sensitivity by increasing the quantum efficiency with Te-doping.

To estimate the improvement of the quantum efficiency of a-Se HARP layer with Te-doping, we assumed the model consisted of three layers as shown in Fig. 2 and calculated the quantum efficiency for a wavelength of 540 nm at an electric field of 1.2×10^8 V/m. In this model, it is assumed that the electric field of the first layer is reduced by doping lithium fluoride (LiF) by tenth and the doping concentration of Te is 15 %.

Here, L2 = 0 nm means the conventional HARP layer for solid state image sensor. Also L2 = 60 nm is equivalent to the extended red HARP layer of image pickup tube[8].

The calculation results are shown in Table 1. The quantum efficiency is increased as thickening the Te-doped region. For example, the quantum efficiency in the case of L2 = 120 nm is twice higher than that in L2 = 0 nm, also 20 % higher than that in L2 = 60 nm.

4. Characteristics of Te-doped thin HARP layer

Based on the calculated results of quantum efficiency, we investigated the characteristics of 0.4 μm-thick HARP layer with four kinds of Te-doped layer thickness shown in Fig. 3.

The current-voltage characteristics is shown in Fig. 4. The signal current with the Te-doped thickness of 120 nm

Table 1. Quantum efficiency.

Thickness of Te-doped layer	Calculated	Measured (with correction)
0 nm	0.30	0.31
30 nm	0.41	
60 nm	0.50	0.47
90 nm	0.56	0.57
120 nm	0.60	0.63
150 nm	0.63	

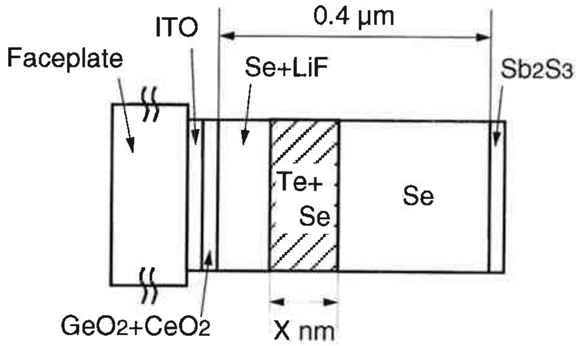


Fig. 3. Experimental HARP layer structure.

using HS-G1 filter was 3 times larger than that of non-doped and was twice larger even than that with the 60 nm-thick Te-doped layer.

The bias voltage is supposed to be almost applied to the third layer, because the resistivity of Te-doped layer is lower than that of pure a-Se layer. As thickening the Te-doped layer, the thickness of third layer decreases in this film structure and then the electric field of the layer increases. This causes the shifts of both signal and dark current curves to low bias voltage region with thicker Te-doped layer.

The avalanche multiplication in HARP layer occurred at an electric field of 1.2×10^8 V/m which the calculation was conducted. It is difficult to measure the quantum efficiency directly at this electric field. Therefore the quantum efficiency at a electric field of 1.2×10^8 V/m is estimated by using the current-voltage characteristics and the quantum efficiency measured at an electric field of 1.0×10^8 V/m (Fig. 5). In addition, the estimated quantum efficiency was corrected considering the transmittance of faceplate glass, Indium-Tin-Oxide (ITO) transparent electrode and hole injection blocking layer (GeO_2+CeO_2). The results agree with the calculated values as shown in Table 1.

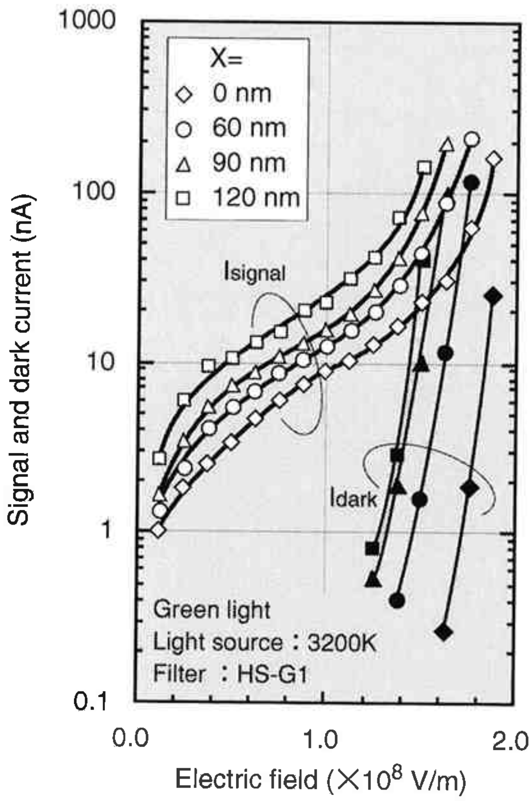


Fig. 4. Current - voltage characteristics.

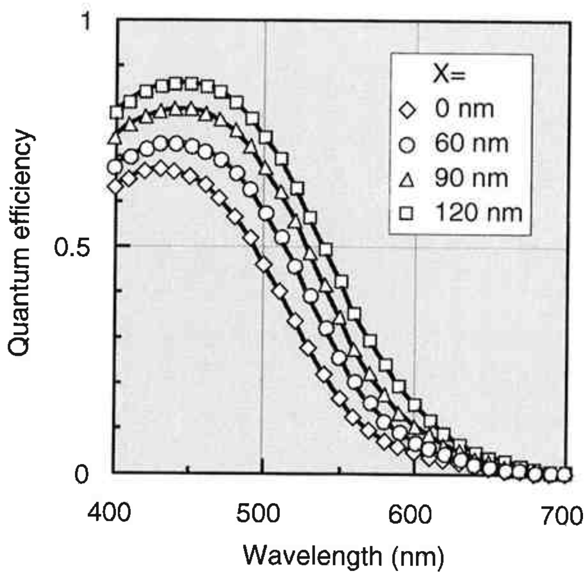


Fig. 5. Measured quantum efficiency at an applied electric field of 1.0×10^8 V/m.

5. Conclusion

We decided the thickness of a-Se HARP layer for solid state image sensor as 0.4 μm considering the endurance voltage of the readout circuit. With this thickness, the avalanche multiplication factor of 4 was obtained with a low dark current at the bias voltage of 60 V.

Furthermore, we investigated the improvement of the sensitivity of the thin HARP film by increasing the quantum efficiency with Te-doping. The quantum efficiency at a wavelength of 540 nm of a-Se HARP layer with 120 nm-thick Te-doped layer is proved to be about twice higher than the non Te-doped layer by both the simulation and the experiment.

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