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Excess Noise Characteristics of a-Si:H p-i-n Photodiode Films

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1. Introduction

Hydrogenated amorphous silicon (a-Si:H) films have been widely used, not only as solar cells and thin film transistors, but also as image sensors. There are some advantages in their application. The a-Si:H film can efficiently absorb visible lights, and it is compatible with processes for conventional charge-coupled devices (CCDs) and complimentary metal-oxide-semiconductor (CMOS) devices. Therefore it seems that the a-Si:H photodiode film is suitable for photo-conversion film for stacked-type image sensors. If an avalanche phenomenon can be occurred in a-Si:H p-i-n photodiode film, the high sensitive and small size image sensor can be realized.

Recently we observed the avalanche multiplication phenomenon of photocurrent in an a-Si:H p-i-n photodiode film fabricated on the n-type Si substrate[1]. In this photodiode film, it was confirmed that there was 40-times maximum multiplication gain measured in the photodiode with a 360-nm-thick intrinsic a-Si:H layer, when a voltage of about 100V was applied to the device. The typical photocurrent and dark current characteristics are shown in Fig. 1 as functions of a reverse bias voltage.

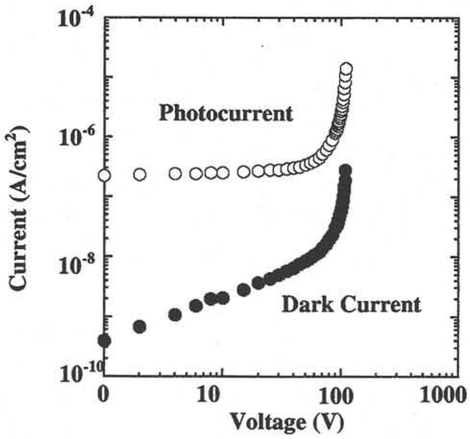

Fig. 1 Photocurrent characteristics of the p-i-n photodiode film

It was confirmed by characteristics of wavelength dependence of photocurrent multiplication rate that the mechanism of the photocurrent multiplication, in an a-Si:H photodiode was avalanche phenomenon[2]. Figure 2 shows the wavelength dependence of photocurrent multiplication rate in the device. It is found that the multiplication rate is higher at shorter wavelengths. Since carrier generation by shorter wavelength lights was occurred nearer to the surface, carriers travel longer distance inside the film, which leads to the higher multiplication rate. This is an evidence that the multiplication is caused by the avalanche multiplication in the a-Si:H film. However, it is not satisfied that the evidence of mechanism.

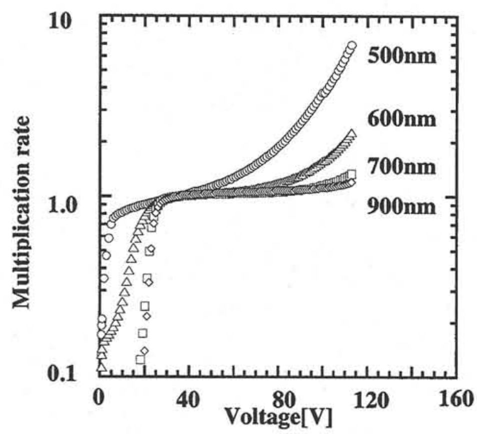

Fig. 2 wavelength dependence of photocurrent multiplication

The avalanche process is intrinsically statistical in nature so that individual carriers have different avalanche gains characterized by a distribution with an average. This causes the excess noise [3]. If it occurred avalanche phenomenon, the device is generated on excess noise. So we investigated excess noise characteristics due to the elucidation of the mechanism of the photocurrent multiplication in the device.

2. Experiments and Results

2.1 Photodiode film

A simple p-i-n photodiode with Pt / a-SiC:H (p-type) / a-Si:H (i-type) / c-Si (n-type) substrate structure. The a-Si:H and p-type a-SiC:H films were deposited using a plasma enhanced chemical vapor deposition (CVD) apparatus at a substrate temperature of 250°C, a RF power density of 20mW/cm^2 and a pressure of 0.12Torr. The thickness of an intrinsic a-Si:H layer (light absorbance layer) and a p-type a-SiC:H layer were 360nm and 140nm, respectively. Dark and photocurrent characteristics were measured under the irradiation of 500nm light. The value of photocurrent is defined as the difference between a value under the light irradiation conditions. and the dark current.

2.2 Noise measurement

The shot noise characteristics of the p-i-n photodiode films were analyzed. A shot noise characteristic of an avalanche photodiode was studied by McIntyer[3]. A shot noise per unit bandwidth during an avalanche multiplication is generally described by the formula

$$i_n^2 = 2qI_{p0}M^2F \qquad (1)$$

where q is the electron charge, I_{p0} is the photocurrent corresponding to the unit quantum efficiency, M is the multiplication gain and F is the excess noise factor. This formula indicates that during avalanche multiplication the increment of the shot noise is larger than the increment of the signal current. If F equals 1 during an avalanche multiplication, the photo signal is multiplied without extra noise.

A noise spectrum from the photocurrent of the a-Si:H photodiode films consisted of low frequency 1/f noise and white noise components. The 1/f noise component seems to be originated from the generation-recombination process in the photodiode film. The level of the white noise component with M=1 is approximately equal to the shot noise calculated by equation(1).

Fig.3 shows incident light intensity dependence of the signal (photocurrent) and noise measured at M=1.

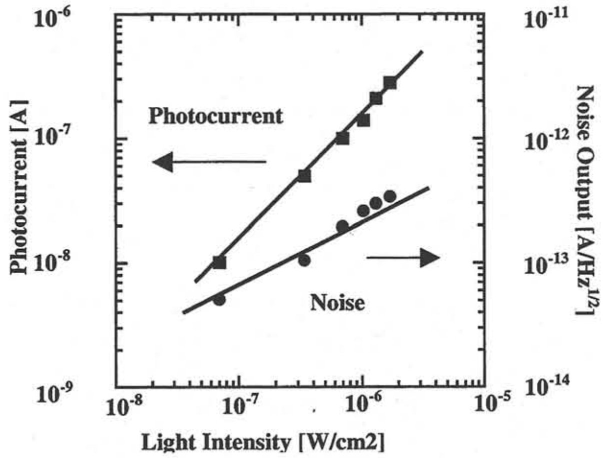

Fig. 3 Dependence of signal and noise outputs on incident light intensity.

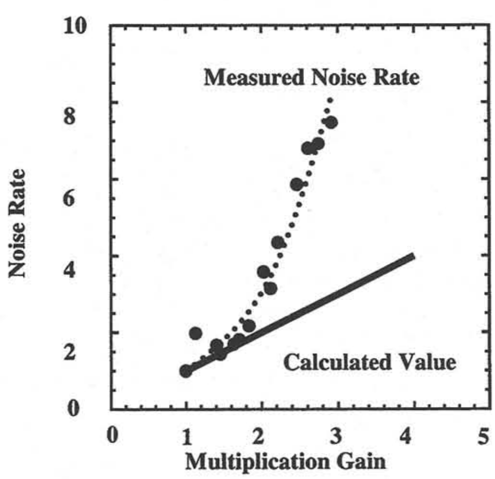

Fig. 4 Comprison between multiplication noise rate of the calculated value as a free excess noise (F=1) and the measured noise.

The signal is proportional to the light intensity, and the slope of the signal versus light intensity is 1.0. The noise spectral density measured on the flat region of the spectral profile is approximately proportional to a square root of the incident light intensity. This characteristics also indicates that the white noise is corresponded to the shot noise.

To clarify the excess noise characteristic of the a-Si:H photodiode film, shot noise characteristics of the photodiode film was investigated. The measurement was carried out at multiplication regions, as a function of the multiplication gain.

The characteristics of multiplication rate of noise increase of the a-Si:H photodiode film is shown in Fig.4. The solid circles indicate the measured noise rate. The solid line shows a calculated value when an excess noise is free (F=1). It can be found that the measured data is larger than calculated value (F=1). The result indicate that the excess noise is generated in the a-Si:H photodiode films when the photocurrent is multiplied.

The excess noise factor is determined by the formula below

$$F = \frac{(i_n / i_{n0})^2}{M^2} \qquad (2)$$

where in is noise current measured at a given multiplication gain, i_{n0} is the noise current measured without multiplication, and M is a multiplication factor. Figure 5 shows the excess noise factor (F) calculated by substituting the experimental data in eq.(2).

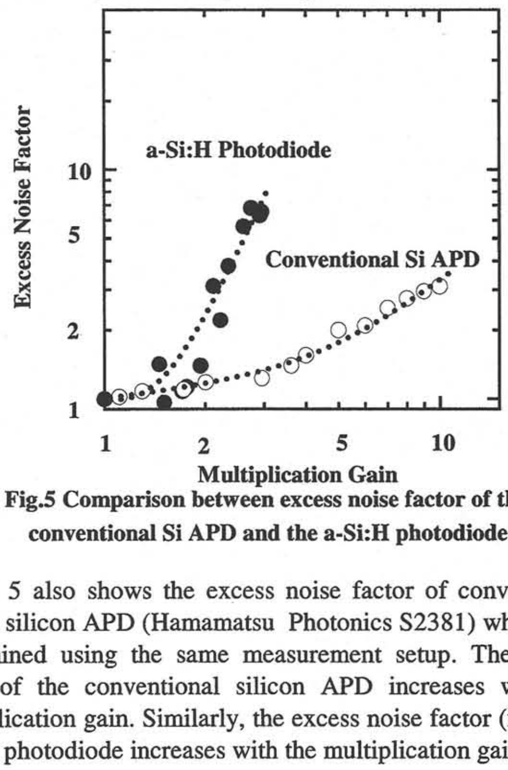

Fig.5 Comparison between excess noise factor of the conventional Si APD and the a-Si:H photodiode films

Figure 5 also shows the excess noise factor of conventional crystal silicon APD (Hamamatsu Photonics S2381) which was determined using the same measurement setup. The excess noise of the conventional silicon APD increases with the multiplication gain. Similarly, the excess noise factor (f) of the a-Si:H photodiode increases with the multiplication gain.

3. Conclusion

The a-Si:H photodiode film is generated extra noise during the photocurrent multiplication according to the McIntyer equation. These results indicate that multiplication mechanism is occurred by avalanche phenomenon.

References

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