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Excess Noise Characteristics of a-Si:H Avalanche Photodiode Films Using Functionally Graded Structure

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1. Introduction

High resolution and high sensitive image sensors have been desirable. So it is necessary to realize a photo-conversion device for a next generation imaging sensor that amplify photo-signals larger than 100% quantum efficiency with noise free. Photo-induced carriers can be directly amplified by avalanche multiplication a semiconductor. However, 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[1]. To realize an avalanche photodiode with excess noise free, the concept of the staircase avalanche photodiode with linearly graded multilayer structure is accepted[2]. On the staircase APD, the avalanche process is much less random than in a conventional APD, because each electrons are impact-ionized once at after each conduction band step and then the multiplication occurs only at a well-defined position in space.

2. Experiments

The a-Si:H film can be absorbed the visible light efficiently, and it is compatible with the conventional CCD and CMOS process. It seems that an a-Si:H photodiode film is suitable for a photo-conversion film of the stacked type image sensor[3]. Previously, we report the characteristics of an a-Si:H/a-SiC:H staircase photodiode with linearly graded-gap multiplication regions[4,5]. Fig.1 shows the energy band diagram of an a-Si:H/a-SiC:H staircase photodiode film with three band discontinuity under an extra-reverse bias. In this paper, we report noise characteristics of the a-Si:H/a-SiC:H staircase photodiode films with one and three linearly graded-gap region. A linearly graded-gap region was fabricated by a computer-controlled PECVD.

A shot noise characteristic of an avalanche photodiode was studied by McIntyer[1]. A shot noise per unit bandwidth during an avalanche multiplication is described by the formula; where I_{p0} is the photocurrent which is corresponded unit quantum efficiency, M is the multiplication gain, and F is the excess noise factor. This formula indicates that the increment of the shot noise during avalanche multiplication is bigger than

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

the increment of the signal current. If F is 1 during an avalanche multiplication, the photo-signal is multiplied without an extra noise.

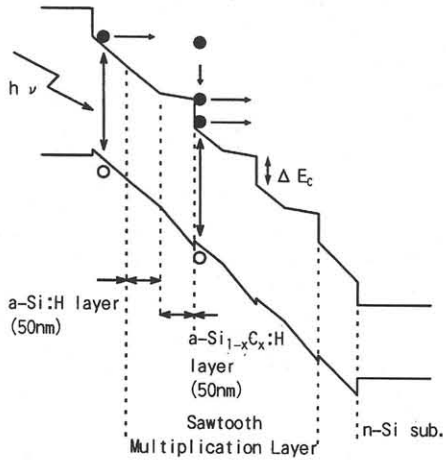

Fig.1 The energy band diagram of the a-Si:H/a-SiC:H staircase photodiode under an extra-reverse bias.

3. Results and Discussion

A shot noise characteristic of the staircase photodiode with one band offset is studied. A typical photocurrent versus applied reverse bias voltage characteristics obtained from the photodiode film is shown in Fig.2. The energy band offset of the photodiode is about 0.63[eV]. The photocurrent was reached to the current corresponded to the unit quantum

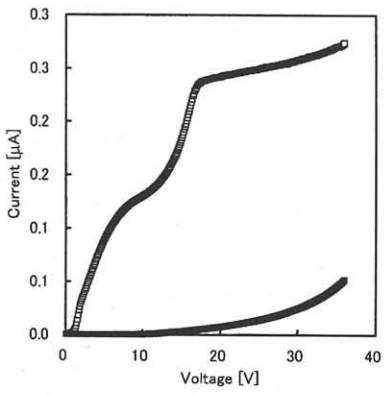

Fig.2 The photocurrent characteristics of the staircase photodiode film with one band discontinuity

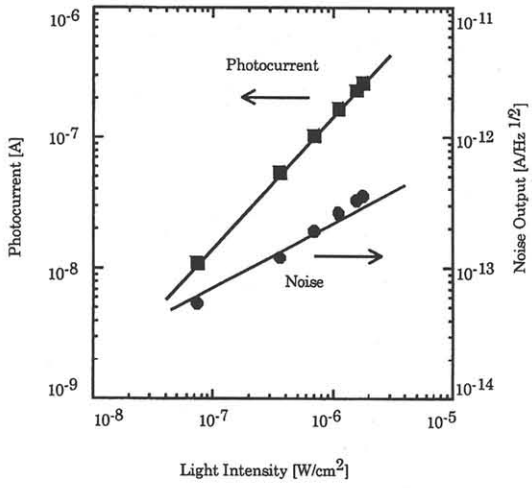

Fig.3 Dependence of signal and noise outputs on incident light intensity.

efficiency at 15[V], and was began to increase at around 20[V]. At 30[V], it was reached a value corresponded the two times of unit quantum efficiency and saturated. It was found that the photogenerated electrons flow through the a-$Si_{1-x}C_x$:H region which high electric field is applied, and the almost all electrons are multiplied after they cross the band offset.

A noise spectrum from the photocurrent of the staircase photodiode with one band discontinuity 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=2. 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, for example, at a frequency of 10kHz, 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 staircase

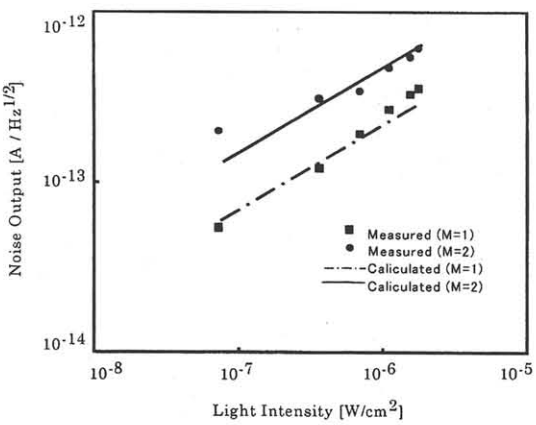

Fig.4 Dependence of noise outputs of a stair-case photodiode with one band discontinuity on incident light intensity.

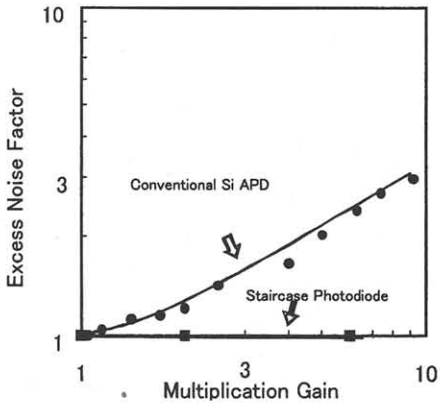

Fig.5 Comparison between excess noise factor of the conventional Si APD and of the a-Si/a-SiC staircase photodiode films.

photodiode film, shot noise characteristics of the photodiode film was investigated. The measurement was carried out at saturation regions of the each photocurrent levels, which is corresponded to M=1 and M=2, as a function of the incident light intensity. The noise characteristic of the staircase photodiode film with one band discontinuity is shown in Fig.4. The solid squares show the measured noise value of the photodiode film at the unit multiplication factor, and the dotted line indicates a shot noise calculated by eq.(1). The solid circles indicate the measured noise value at M=2. The solid line shows a calculated value when an excess noise is free (F=1). It can be found that the measured data multiplied double agreed with ideal value which is calculated as excess noise free. The shot noise characteristic of the a-Si:H/a-SiC:H staircase photodiode film with 3 band offset, which multiplication factor is about 6, was investigated. The results also indicate that the excess noise is not generated in the staircase photodiode films when the photocurrent is multiplied about 6 times.

Fig.5 shows the excess noise factor F calculated by the experimental data and also shows the excess noise factor of a conventional crystal silicon APD which is measured using a same measurement setup. The excess noise of the conventional silicon APD is increased as the multiplication gain is increased. On the other hand, the excess noise factor of the staircase photodiode is remained one even the photocurrent is multiplied.

4. Conclusion

The a-Si:H/a-SiC:H staircase photodiode film with the graded-gap region is not generated extra noise during the photocurrent multiplication. These results indicate that the staircase photodiode films have a potential applicability for the high-sensitive imaging sensor.

References

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