Photocurrent Multiplication in a-Si:H Photoconversion Layer.

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Abstract

The stacked type CCD image sensor with an overlaid a-Si:H photoconversion layer, in which photocurrent multiplication with avalanche process occurs, is desirable to get high resolution and high sensitivity image sensors. It is described that the photocurrent of more than unit quantum efficiency is observed on highly reverse biased a-Si:H SAM (Separated Absorption and Multiplication) type photodiode with a-SiN layer, which prevent excess hole entrance from the electrode. From the photocurrent-reverse bias characteristic, the photocurrent exceeded the value corresponding to unit quantum efficiency. The photocurrent of the electron injection type was grater than that of the hole injection type in saturation region, because the impact ionization rate of electron could be larger than that of holes. The gamma value was 1. The small dark current($10^{-9} A/cm^2$ at 5V) and the fast photoresponce time(less than $100 \mu s$) was realized first by using the a-SiN film as blocking structure. These results indicated that photocurrent multiplication with avalanche process was occurred and there were no excess carrier entering from the electrode and no interband tunneling on the a-Si:H SAM type photodiodes.

1 Introduction

To get high resolution image sensors on the same chip size, reduction of the active pixel area is necessitated. This leads to degrade the signal-to-noise ratio. Carrier multiplication in the avalanche process is effective for increasing the signal-to-noise ratio and sensitivity of the image sensor [1, 2]. The stacked type CCD image sensor with an overlaid a-Si:H photoconversion layer, in which photocurrent multiplication with avalanche process occurs, is proposed. This image sensor has 100% optical aperture ratio and output signal more than unit quantum efficiency, resulting in high sensitivity and high resolution. However, high electric field effects such as avalanche and tunneling processes in a-Si:H are still not well known. Some attempts to obtain the photocurrent multiplication in amorphous Si based films have been reported. Photocurrent multiplication was observed in a reverse- biased p-i-n junction, in which the i layer consists of a-Si/a-SiC multilayers [3], but the mechanism of photocurrent multiplication was not clear. On a p-i/a-SiN/i-n multiplication system, photocurrent multiplication was also confirmed [4]. Response time under a light pulse on this device was slow. The mechanism of photocurrent multiplication should be interband tunneling via the localized state in an a-SiN layer. Photocurrent multiplication caused by excess carriers entering from the electrode was widely observed, but this phenomenon had very slow photoresponce time. A photoconversion film in the image sensor requires a fast photoresponce time to reduce the afterimage. Hence, it is important to make a blocking contact stable against excess carriers and to reduce the dark current.

In this paper, it is described that the photocurrent more than unit quantum efficiency (η=1) is observed on highly reverse biased a-Si:H SAM (Separated Absorption and Multiplication) type photodiode with a-SiN layer, which prevent excess hole entrance from the electrode.

2 Device Structure and operation

Fig.1 shows a cross-sectional view and a schematic band diagram of an a-Si:H SAM photodiode with a-SiN layer. An SnO_2 coated glass plate was used as the substrate. The $40nm$ p^+-type a-SiC:H layer, $500nm$ lightly B_2H_6 doped intrinsic a-Si:H layer, $26nm$ p^+-type a-Si:H layer, which was called "sheet doped layer", $40nm$ intrinsic high field layer and heavily doped n^+-type a-Si:H layer were respectively deposited by PECVD (Plasma Enhanced Chemical Vapor Deposition), and a-SiN film was deposited by means of sputtering. To improve the performance of a-Si p-i-n junction photodiode, the SAM structure was adopted [5]. It was separated into a wide absorption region and a narrow multiplication region. Excess electron entrance from the transparent electrode was prevented because the field near the transparent electrode was low and wide-band-gap a-SiC:H was used as window material [6]. The carrier multiplication in the avalanche process is expected in the multiplication region. The avalanche gain can be adjusted by changing the width and the electric field of multiplication region. The width and field were $40nm$ and $7 \times 10^5 V/cm$ in this experiment. There is a problem in this structure, which is the excess hole entrance from the Al electrode affected by the high field of multiplication region. Then thin a-SiN film, which allows electrons to pass through in tunneling process but blocks holes, was deposited between n^+-type a-Si:H layer and Al electrode to block this hole entrance.

3 Results and discussion

Fig.2 shows the photocurrent and dark current characteristics of the a-Si:H SAM photodiode. The wavelength of illumination was 600nm, so that light was absorbed in the wide photosensitive region, and the light intensity was $19 \mu W/cm^2$. The photocurrent of the photodiode without a-SiN rapidly increased at 2V, and exceed the η=1 at 4.5V, reaching η=30 at maximum reverse voltage used in this experiment. For the SAM structure, the electric field in the high-field region is fixed after the wide absorption region is fully depleted, so the photocurrent characteristic of the SAM-type photodiode must be saturated. Since the photocurrent of this photodiode was increased constantly. it was supposed that excess carriers entered into this photodiode. On the other hand. the photocurrent of the photodiode with a-SiN layer exceeded the current of η =1 at 5V and was saturated at the high reverse-bias condition as designed. A difference was also observed in dark current characteristics. The dark current of the photodiode with a-SiN film was 10 times smaller than that without a-SiN film, as shown in Fig.2(a) and 2(b). It was found that the a-SiN layer could also suppress the dark current.

A capacitance-voltage characteristics of the photodiodes with a-SiN and without a-SiN layer was studied, and the results are shown in Fig.3. The measurement frequency was $10KHz$, and white light was irradiated during measurements. The capacity of the photodiode with a-SiN was decreased until the depletion layer reached the boundary between the light absorption region and the n^+-type a-Si:H layer, and fixed at the value of the width of this photodiode. However the capacity of the photodiode without a-SiN layer was rapidly increased at high reverse bias voltage because of excess carrier entrance.

The response time characteristics under a light pulse were investigated, and the results are shown in Fig.4. The light was illuminated at $50Hz$. The photodiodes with and without a-SiN film were biased 21V reverse bias voltage, and the photocurrent of both photodiodes exceeded unit quantum efficiency at that voltage. The response of the photodiode without a-SiN was relatively slow, as shown Fig.4(b). For the photodiode with the a-SiN layer, a fast photoresponce time was observed, as shown Fig.4(a). The turn-on and turn-off times were less than $100\mu sec$. It was found that the photoresponce became faster with the insertion of thin a-SiN film.

Fig.5 shows photoconversion characteristics of the photodiodes with and without a-SiN layer, indicating the output currents versus the incident light intensity. The the slope of the curves, that is a gamma value, was about 0.7 on the photodiode without a-SiN film. It indicated that the observed current was not directly proportional to incident light and some excess current affected by photo induced current occurred. On the diode with a-SiN layer, the gamma value was 1. The photocurrent was directly proportional to the incidence light. From these four results, it was inferred that there were no excess carrier entering from electrode affected by photo induced current and no interband tunneling in the high-field region on the photodiode with thin a-SiN film.

On the photodiode with a-SiN film, photocurrent exceeded unit quantum efficiency was observed. To make sure of the photocurrent multiplication, two kinds of photodiode were prepared. One was electron injection type, which injects photoinduced electrons into the high-field region, and the other is hole injection type. The impact ionization rates for electron (α) and hole (β) are dissimilar, and it is expected that α would be larger than β in a-Si:H film. Obtained photocurrent-voltage characteristics for pure electron injection and hole injection are shown in Fig.6. In high reverse bias condition, absorption layer and high-field layer were completely depleted; the same electric field is expected to arise in the high-field region of two photodiodes. However, the photocurrent of the electron injection type was more than that of the hole injection type in saturation region, and exceeded unit quantum efficiency. The current of hole injection type did not exceeded unit quantum efficiency. These results indicated the possibility of avalanche multiplication in high-field region.

4 Conclusion

Excess hole entering from the electrode in highly reverse biased a-Si:H SAM type photodiode were successfully blocked using thin a-SiN layer. The photocurrent versus bias voltage characteristics was similar to theoretically predicted one and smaller dark current was confirmed. The photoresponce time became faster with a-SiN layer. The gamma value was 1. These results indicated that there were no excess carrier entering from electrode and no interband tunneling in the high-field region. The photo-current of more than unit quantum efficiency was observed on this photodiode. The dependence of electrons and holes injected into the high-field region on multiplication effect was examined and indicated the possibility of avalanche multiplication. This work was partially supported by a Grant-in Aid for General Scientific Research from the Ministry of Education, Science and Culture of Japan.

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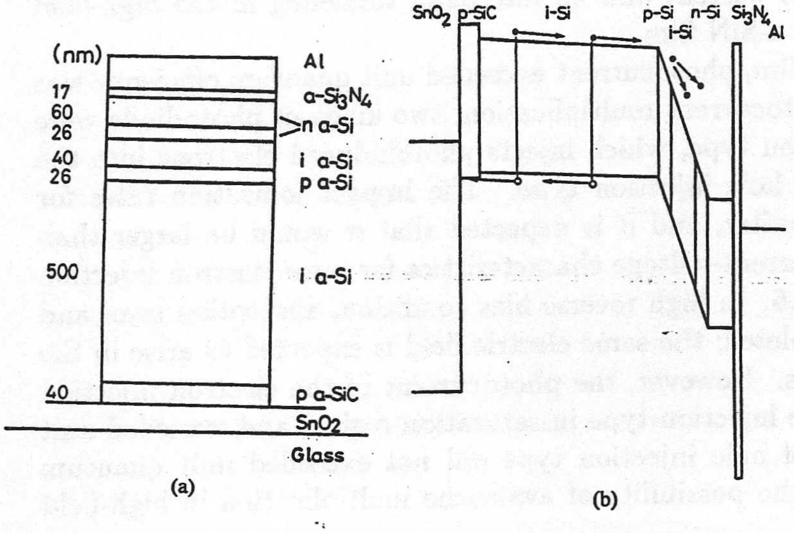

Fig.1 (a) Cross-sectional view and (b) schematic band diagram of the photodiode.

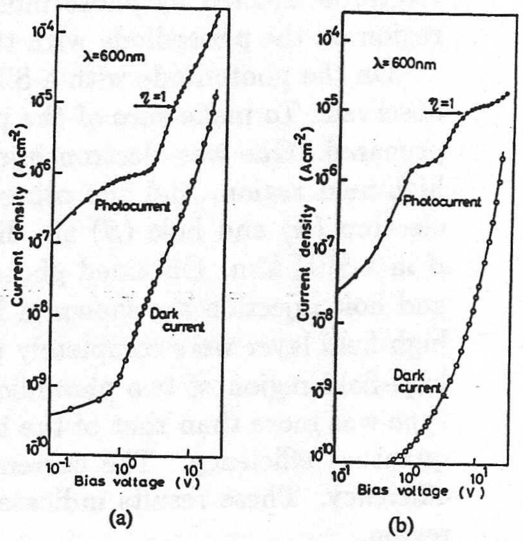

Fig.2 Photocurrent and dark current versus bias voltage characteristics

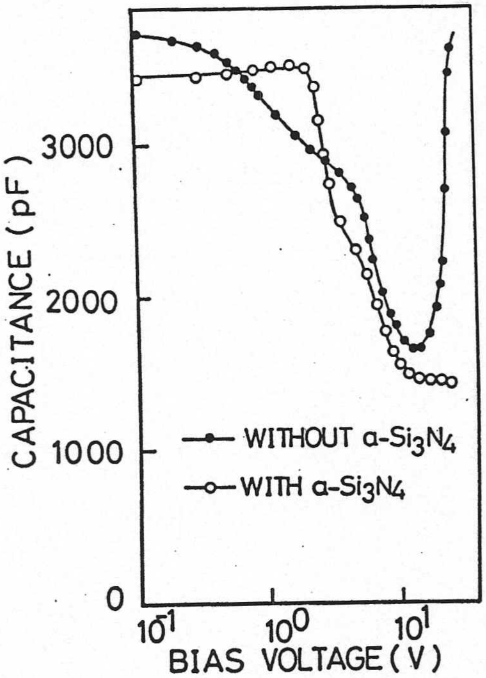

Fig.3 Capacitance versus voltage characteristics.

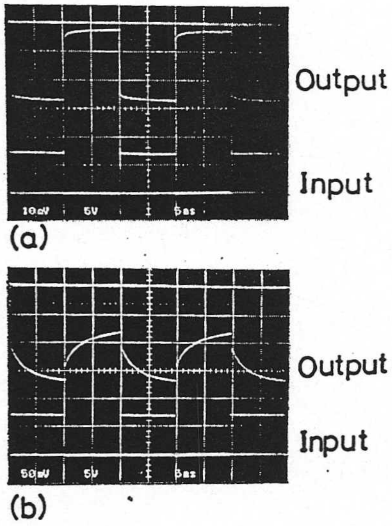

Fig.4 Response time characteristics under a light pulse of photodiode (a) with a-SiN and (b) without a-SiN.

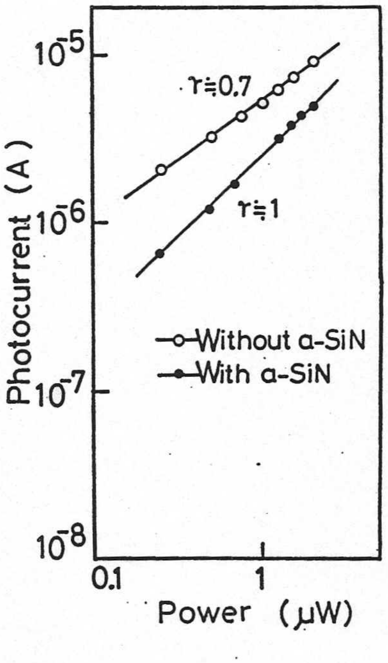

Fig.5 Photoconversion characteristics.

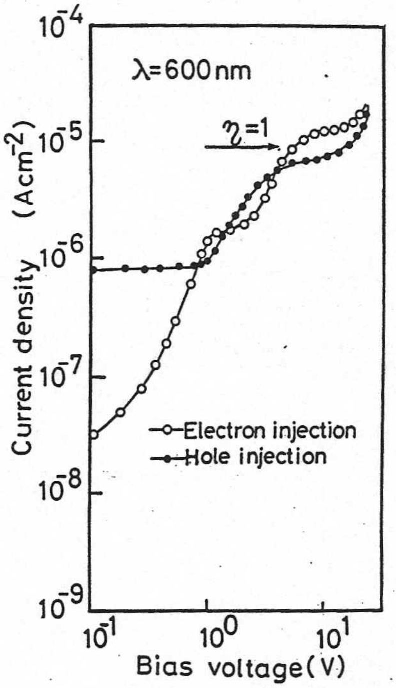

Fig.6 Photocurrent-voltage characteristics under conditions of pure electron injection and pure hole injection.