Fabrication of Avalanche Multiplication type CMOS Imager using a-Si:H photodiode film

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Abstract

A highly sensitive CMOS imager, composed by stacked a-Si:H photodiode film on the CMOS readout circuit, has been proposed and the readout circuit has been fabricated. On a TEG (Test Element Group) in the circuit, we confirmed the photocurrent multiplication in a-Si:H type avalanche photodiode by an image sensor operation for the first time. The stacked type image sensor was successively fabricated. A highly sensitive stacked type imager will be realized by using a-Si:H photodiode film.

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[1,2,3]. 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. It seems that the a-Si:H photodiode film is suitable for photo-conversion film to construct stacked-type image sensors. If an avalanche phenomenon can be occurred in an a-Si:H p-i-n photodiode film, the highly sensitive image sensor can be realized. Figure 1 shows a schematic diagram of the proposed image sensor. The a-Si:H avalanche photodiode film is stacked on the read out circuit. Previously photocurrent multiplication phenomenon in an a-Si:H p-i-n photodiode film fabricated on a n-type Si substrate was observed[4].

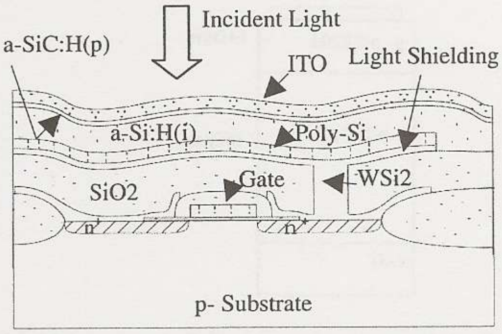

Figure.1 Cross-sectional view of the propose image sensor.

a-Si:H type p-i-n photodiode film

An a-Si:H type p-i-n photodiode has a Au / 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 20 mW/cm^2 and a pressure of 0.12 Torr. The thicknesses of the intrinsic a-Si:H layer (light absorbance layer) and the p-type a-SiC:H layer were 360 nm and 140 nm, respectively. Semitransparent 1 mm×1 mm gold films with 10 nm thickness were sputtered as electrodes. Figure 2 shows the a-Si:H p-i-n photodiode structure. The typical photocurrent and dark current characteristics are shown in Fig. 3 as functions of reverse bias voltage. The photocurrent was measured under irradiation of 500-nm-wavelength light. In this photodiode film, a maximum multiplication gain of 40 times was confirmed. Figure 4 shows the wavelength dependence of the photocurrent multiplication rate in the device. The unit multiplication rate was defined as the saturation photocurrent. The quantum efficiency was 70-80%.

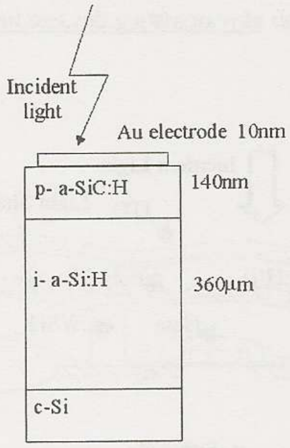

Figure 2. Schematic structure of Au/p-type a-SiC:H/ i-type a-Si:H/ n-type c-Si substrate photodiode.

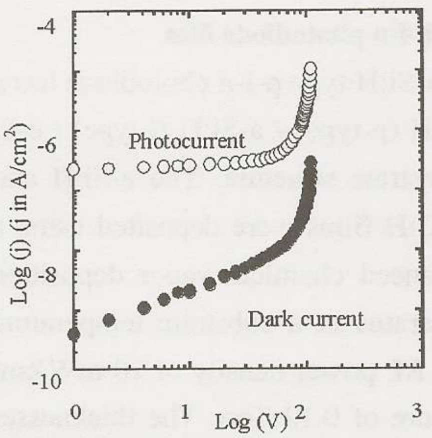

Figure.3 Photocurrent and dark current characteristics of a-Si:H photodiode.

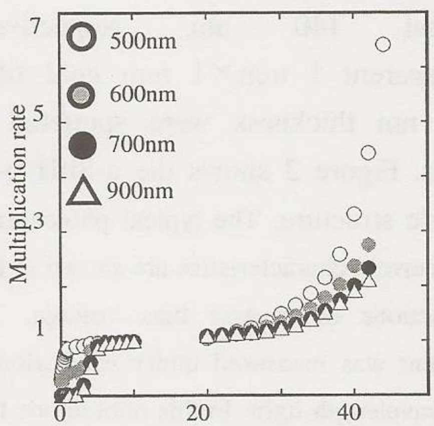

Figure 4. Wavelength dependence of the photocurrent multiplication rate in the device.

It is found that the multiplication rate is higher at shorter wavelengths. Since carriers were generated close to the surface by shorter wavelength light irradiation, carriers travel a longer distance in the film. This phenomena leads to a higher multiplication rate. This is evidence that the multiplication was caused by the avalanche multiplication in the a-Si:H film.

If the avalanche photodiode film can be stacked to a read out circuit, a highly sensitive image sensor will be realized. In this work, we confirmed the photocurrent multiplication in an a-Si:H type avalanche photodiode by an image sensor operation.

Test Element Group

The read out structure uses 3 transistors type Active Pixel Sensor (APS) configuration. Figure 5 shows a schematic diagram of the unit cell. A TEG of a readout circuit was fabricated using 10μm rule CMOS process. The photograph is shown in Fig.6. The amorphous silicon APD was externally connected to the TEG circuit.

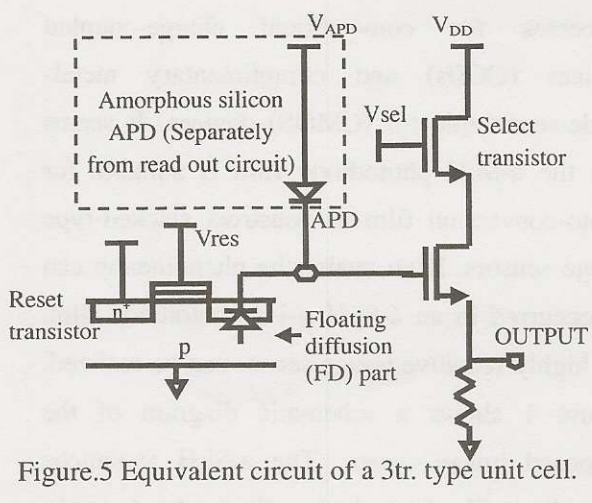

Figure.5 Equivalent circuit of a 3tr. type unit cell.

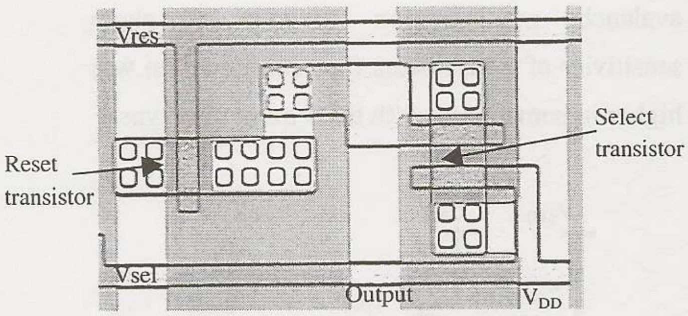

Figure.6 TEG (Test Element Group) of a 3 transistors type read out circuit.

Operation of a signal integration mode

A conventional image sensor is operated signal integration mode. The elements, constructed the 3 transistors circuit and the photodiode film, was operated by the signal integration mode. The integration time and operation voltage conditions were maintained as a conventional CMOS image sensor. To multiply photocurrent, a voltage of APD film (V_{APD}) was applied. Figure 7 shows V_{APD} dependences of the photocurrent multiplication. The measurement was carried out at 224K. It was found that photocurrent was multiplied in CMOS image sensor operation. It was the first observation of photocurrent multiplication in a-Si:H photodiode by image sensor operation.

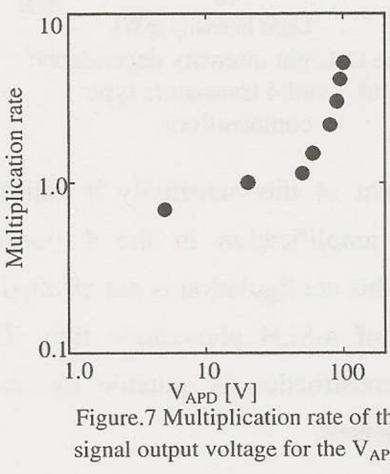

Figure.7 Multiplication rate of the signal output voltage for the V_{APD}.

The photocurrent multiplication was started at V_{APD}=50V, and multiplication rate reached 5.5 at V_{APD}=100V. It is expected the highly sensitive image sensor is fabricated using a-Si:H film. Previously γ-characteristics of an avalanche multiplication type image sensor using crystal Si photodiode was studied by Ando et al[2]. In multiplication conditions, γ value decreases, because applied voltage of APD decrease during signal integral period. A γ-characteristics of the proposed a-Si:H pixel construction was measured, and it is shown in Figure 8. It was confirmed that the γ-value decreased as V_{APD} increased. It is evident that the photocurrent was multiplied in these circuits.

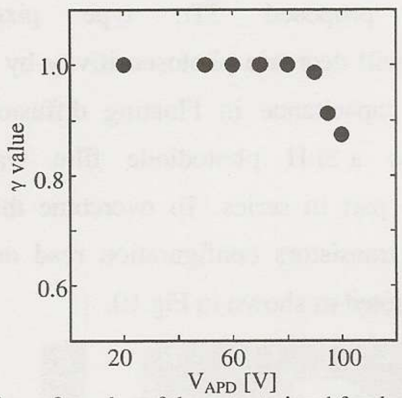

Figure.8 γ value of the output signal for the V_{APD}.

The decrease of γ value is called Self-Quenching Effect of multiplication gain. If γ value is low, multiplication gain declines when high light intensity, and it is maintained when low light intensity. This result indicated that the dynamic range can be expanded, and also this phenomenon is occurred in each pixel independently.

Stacked structure

The stacked type image sensor overlaid with a hydrogenated amorphous silicon (a-Si:H) has been developed. Figure 1 shows Cross-sectional view of the fabricated stacked type image sensor. A SEM photograph of a fabricated stacked type image sensor is shown in Fig.9. The stacked type image sensor was successively fabricated.

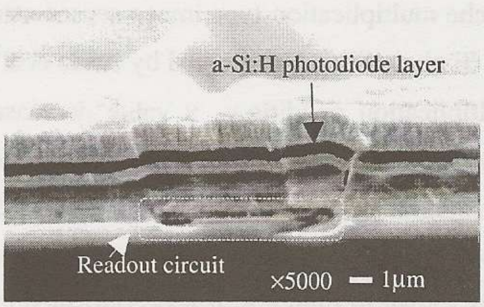

Figure.9 A SEM photograph of a fabricated stacked type image sensor.

Four transistors type configuration

The proposed 3Tr. type pixel configuration will decrease photosensitivity by a increment of capacitance in Floating diffusion (FD) part, as a-Si:H photodiode film was connected FD part in series. To overcome this problem, a 4 transistors configuration read out circuit was adopted as shown in Fig.10.

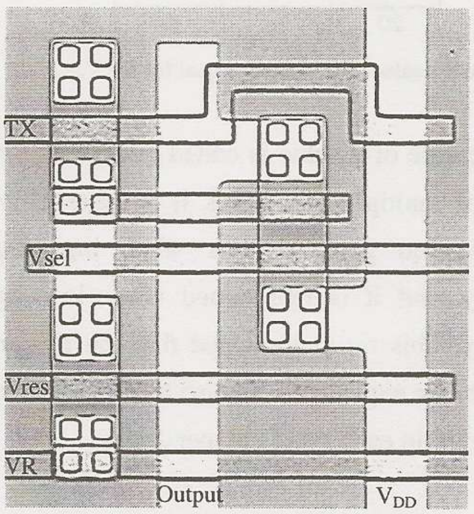

Figure.10 TEG (Test Element Group) of a 4transistors type read out circuit.

Figure 11 shows a schematic diagram of the unit cell. A discrete c-Si APD (Hamamatsu Photonics:S2381) was used to confirm this estimation. Light intensity dependence of 3 and 4 transistors type compositions were measured and it is shown in Figure 12. As the result, it was found that photo sensitivity was increased by avalanche multiplication (M=15), and photo sensitivity of 4 transistors type configuration was higher in comparison with the 3 transistors type.

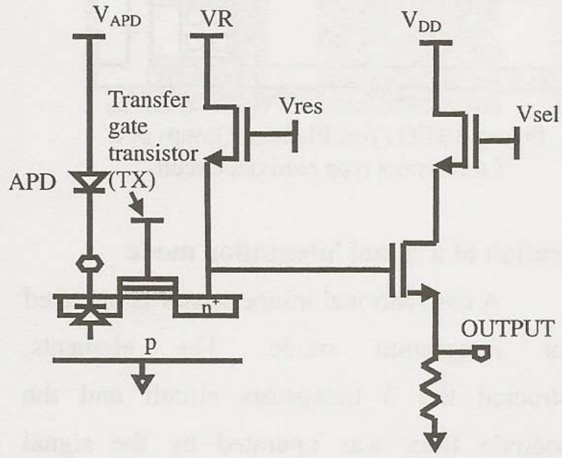

Figure.11 Equivalent circuit of a 4tr. type unit cell.

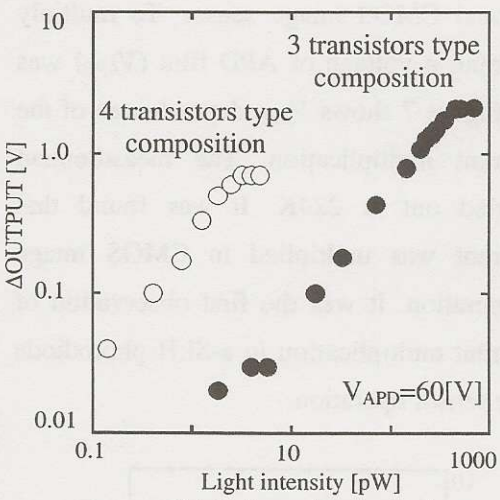

Figure.12 Light intensity dependence of 3 and 4 transistors type compositions.

The increment of this sensitivity is caused by capacitance amplification in the 4 transistors circuit, and this configulation is not affected by a capacitance of a-Si:H photodiode film. The 4 transistors construction is suitable for stacked type image sensor.

Conclusion

A highly sensitive CMOS imager,

composed by stacked a-Si:H photodiode film on the CMOS readout circuit, has been proposed and the readout circuit has been fabricated. On a TEG (Test Element Group) in the circuit, we confirmed the photocurrent multiplication in a-Si:H type avalanche photodiode by an image sensor operation for the first time. And the dynamic range can be expanded. The stacked type image sensor was successively fabricated. It considers that stacked type image sensor using a-Si:H APD can be realized by using the circuit made this time from these results.

References

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