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Amorphous Silicon Avalanche Photodiode Films Using Functionally Graded Superlattice Structure

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1. Introduction

It is necessary for a photoconversion device of a next generation imaging sensor to amplify photo-signals larger than 100% quantum efficiency with noise free. Recently we observed the avalanche multiplication in an a-Si:H p-i-n photodiode[1]. 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 excess noise.[2]. On the conventional avalanche photodiodes, the increment of the noise is exceeded the increment of the signal. To realize an avalanche photodiode with excess noise free, the concept of a staircase avalanche photodiode (APD) with compositionally graded multilayer structure is accepted[3]. On the staircase APD, avalanche process is much less random than in a conventional APD, because each electrons impact-ionize once at after each conduction band step and then the multiplication occurs only at well-defined position in space. In this paper, we report the characteristics of a-Si:H/a-SiC:H staircase photodiode with linearly graded-gap multiplication regions.

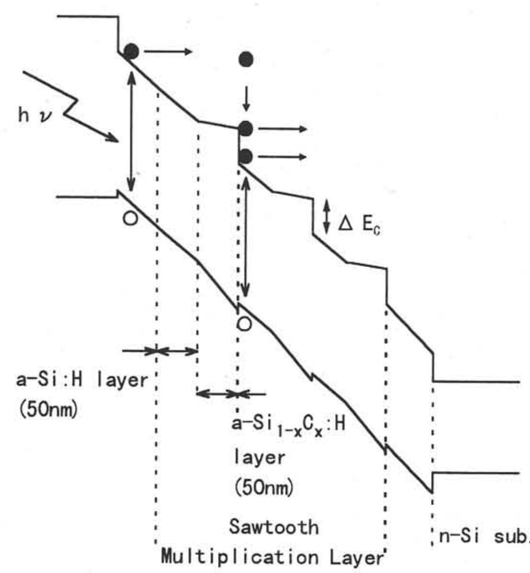

Fig.1 The energy band diagram of the a-Si:H/a-SiC:H staircase photodiode under an extra-reverse bias.

2. Experiments

A linearly graded-gap region was fabricated by a computer-controlled PECVD apparatus at a substrate temperature of 250℃, a RF power density of 25mW/cm^2 and a pressure of 0.5Torr. Fig.1 shows the energy band diagram of cross-section of a-Si:H/a-SiC:H staircase photodiode film with 3 band offsets under an extra-reverse bias. A highly doped n-type Si wafer (0.01 Ω cm) was used as the substrate. The bandgap of the undoped a-Si:H is 1.7eV. Each graded region was deposited by using SiH_4 (10%) and C_2H_4 (10%) diluted with H_2 simultaneously. The flow rate of C_2H_4 gas was continuously controlled by a computer system to establish desirable conduction band profile. The bandgap of a-SiC:H films can be varied from 1.7 to 2.3eV by changing the ratio of the flow rate (C_2H_4/SiH_4). The conduction band discontinuity (Δ Ec) between a-Si:H and a-SiC:H layer was also varied from 0 to 0.4eV.

3. Results and Discussion

Staircase Photodiode with One Band Offset

To confirm a function of the band offset, a simple photodiode with one band offset is studied. The schematic band structure of this photodiode is shown in Fig.2. The band offset is exsisted a interface between the Si substrate and a-$Si_{1-x}C_x$:H, and it can be varied from 0.2 to 0.7[eV] by changing the C_2H_4 flow rate.

A typical photocurrent versus applied reverse bias voltage characteristics obtained from the photodiode film is shown in Fig.3, and the photocurrent characteristics of the conventional a-Si:H pin photodiode is superimposed. The energy band offset of the photodiode is about 0.63[eV]. The photocurrent was reached to the current corresponded to the

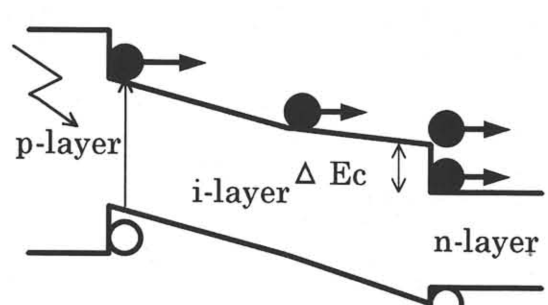

Fig.2 Scematic Band Structure of a photodiode films with one band offset.

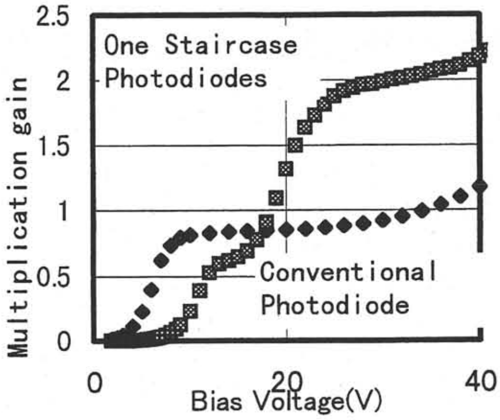

Fig.3 Photocurrent characteristics of the photodiode

unit quantum efficiency (η=1) 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 (η=2) and saturated. From this result, it was found that the photo-generated 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. Therefore, the saturated photocurrent of amplified by two times was observed. A dependence of the threshold voltage at which the multiplication start upon the conduction band offset is shown in Fig.4. From this figure, it is found that the best suitable value of the conduction band offset exists and it is about 0.4[eV]. The photodiode with the bigger band offset needs higher threshold voltage to generate photocurrent multiplication. We assume that the cause is degradation of the a-SiC:H film quality by increasing carbon atoms.

Photodiode Film with 3 Conduction Band Offsets

The photocurrent and dark current versus applied reverse bias voltage characteristics obtained from the staircase photodiode having 3 conduction band steps (ΔEc=0.40eV) are shown in Fig.5. From these results, it is found that the photocurrent reaches the unit quantum efficiency (η =1) at about 20V and increases sharply over 40V. At about 65V, the photocurrent saturates again at η =6.4. The gamma characteristics was investigated and its values are 1.0 indicating that there are no excess carriers entering from the electrode and no interband tunneling affected on photoinduced current.

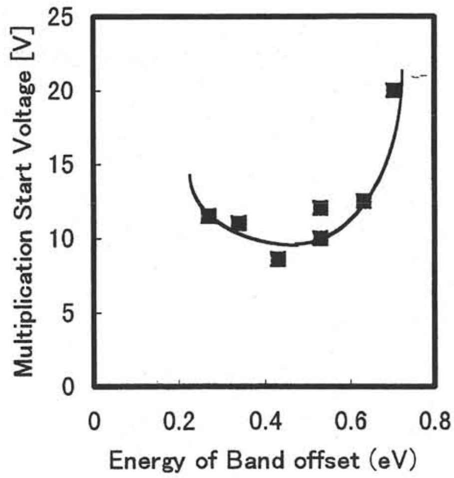

Fig.4 The multiplication start voltage dependence on the energy band offsets.

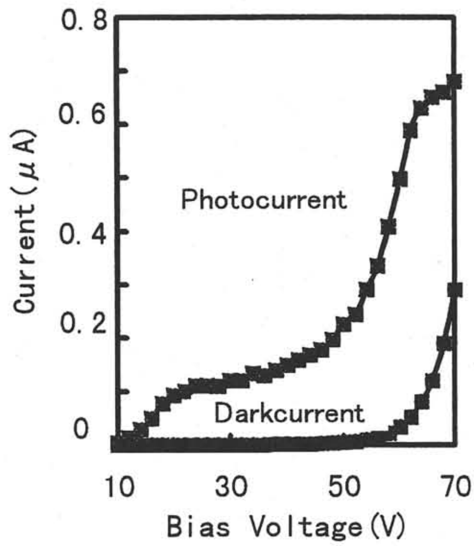

Fig.5 The photocurrent and dark current versus applied reverse bias voltage characteristics obtained from the staircase photodiode films

4. Conclusion

The photocurrent multiplication due to avalanche phenomena was observed in the a-Si:H/a-SiC:H staircase photodiode. The saturated multiplication gain of about 6 was obtained. From the saturated multiplication gain, it can be seen that the photogenerated electrons are mainly ionized in the band edge discontinuity region. These results indicate that the staircase photodiode films have a potential applicability for the high-sensitive imaging sensor.

Acknowledgment

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References

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