a-Si:H avalanche multiplication p-i-n photodiode films.

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1. Introduction

The hydrogenated amorphous silicon (a-Si:H) is widely used for solar cells and imaging sensors. Recently, a 2-million-pixel CCD image sensor overlaid with an a-Si:H photo-conversion layer was reported[1]. This is because the absorption efficiency of a-Si:H for visible light is excellent, and it can be fabricated on a wide variety substrate at low-cost. On a next generation imaging sensor with high-definition and wide dynamic rage, a high-sensitive and low-noise photo-conversion device is desirable. A quantum efficiency of the photo-conversion device used in the conventional CCD imager is nearly 100%. Therefore it is necessary for a next generation imaging sensor to amplify photo-signals larger than 100% quantum efficiency with noise free.

We have been asserted that a photocurrent amplification in the photo-conversion device is the best way to realize high sensitive imaging sensors. The avalanche multiplication in amorphous silicon photo-conversion films is expected to amplify photocurrent. Some attempts to obtain photocurrent multiplication in a-Si:H and its alloy materials have been reported[2,3]. However these multiplication are due to the fact that the injection current is modurated dependently upon incident light intensity. Consequently the multiplication current has slow response time and the gamma value is less than 1.0. Recently we observed the avalanche multiplication in an a-Si:H p-i-n photodiode, which was fabricated on a highly doped n-type Si substrate by using a high vacuum plasma chemical vapor deposition system[4]. The typical photocurrent and bias voltage characteristic is shown in Fig.1. In this sample, it was confirmed that maximum multiplication gain measured in the p-i-n photodiode with 500nm thick intrinsic a-Si:H layer was about 2, when the electric field of about 9×10^5V/cm was applied to the intrinsic layer. The response time is less than 20μsec. and the gamma value is 1.0 indicating that there are no excess injection carriers.

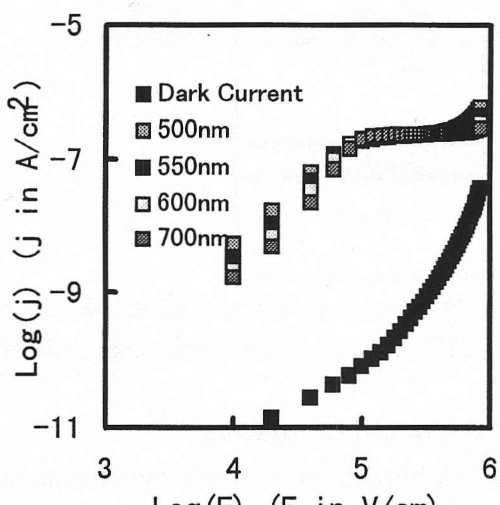

Fig.1 A photocurrent and dark current characteristics of an a-Si:H pin photodiode films.

2. The a-Si:H staircase photodiode films

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.[5]. On the conventional avalanche photodiodes, the increment of the noise is exceeded the increment of the signal (photocurrent). To realize an avalanche photodiode with excess noise free, the concept of a staircase avalanche photodiode (APD) with compositionally graded multilayer structure is acceptable[6]. 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. On this report, we studied the characteristics of a-Si:H/a-SiC:H staircase photodiode with linearly graded-gap multi-plication regions[7].

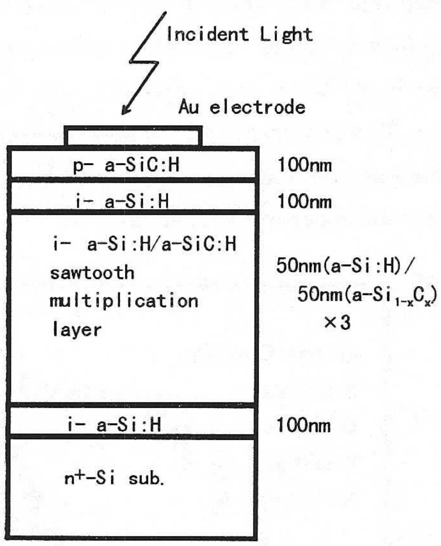

Fig.2 Schematic diagram of cross section of a-Si:H/a-$Si_{1-x}C_x$:H staircase photodiode film.

3. Results and Discussion

A linearly graded-gap region was fabricated by a computer-controlled PECVD apparatus at a substrate temperature of 250°C, a RF power density of 25mW/cm^2 and a pressure of 0.5Torr. Fig.2 shows the schematic diagram of cross section of a-Si:H/a-$Si_{1-x}C_x$:H staircase photodiode film. A highly doped n-type Si wafer was used as the substrate. A undoped 100nm thick intrinsic layer, three layers of a-$Si_{1-x}C_x$:H (50nm) / a-Si:H (50nm) staircase superlattice structure, a undoped 100nm thick intrinsic layer and a heavily boron doped a-SiC layer were successively deposited. Finally, a thin (20nm thick) Au film was deposited as the top electrode. 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) as shown in Fig.3.

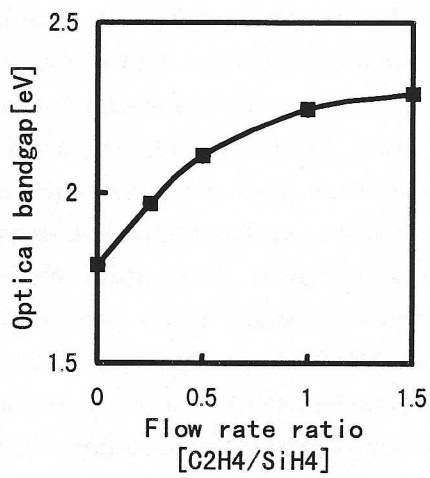

Fig.3 Flow rate ratio [C_2H_4/SiH_4] dependencies of the optical bandgap of a-SiC:H.

Consequently, the conduction band discontinuity(Δ Ec) between a-Si:H and a-SiC:H layer was also varied from 0 to 0.5eV. These values were confirmed from the activation energy measurements of a n-type a-Si:H/ undoped a-SiC:H/ n-type a-Si:H sample. Fig.4 shows the energy band diagram of the a-Si:H/a-SiC:H staircase photodiode under an extra-reverse bias. In order to obtain a sharp band discontinuity, the reaction chamber was completely pumped out after deposition of each a-SiC:H layer and then the next a-Si:H layer was deposited.

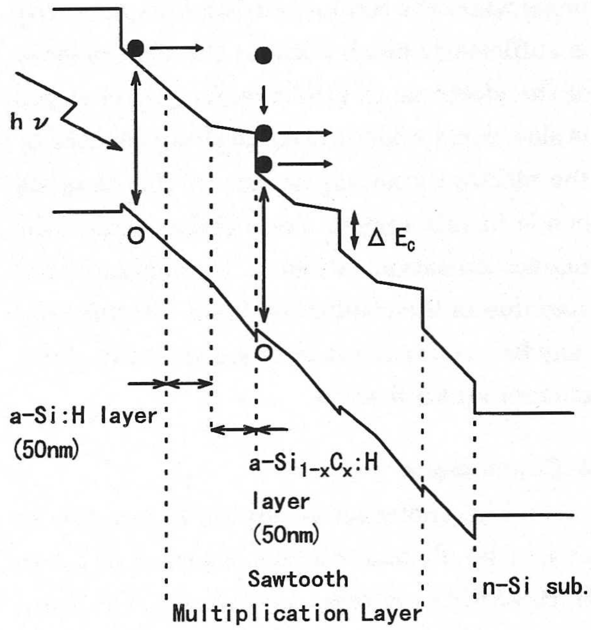

Fig.4 The energy band diagram of the a-Si:H/a-SiC:H staircase photodiode under an extra-reverse bias.

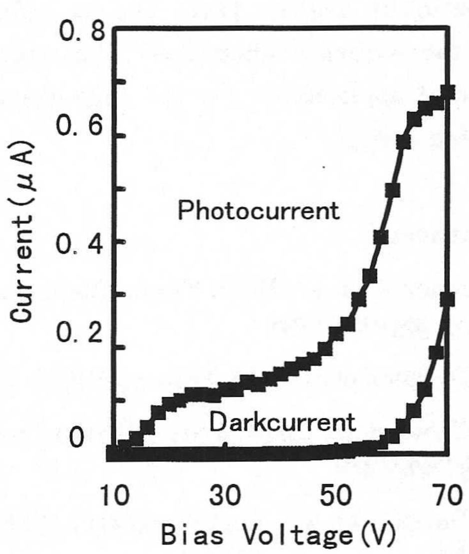

Fig.5 The photocurrent and dark current versus applied reverse bias voltage characteristics obtained from the staircase photodiode films

The photocurrent and dark current versus applied reverse bias voltage characteristics obtained from the staircase photodiode having 3 conduction band steps (ΔEc=0.45eV) are shown in Fig.5. The size of the test device is 1mm×1mm. The center-wavelength and the intensity of the light incident on the samples are 500nm and 19μW/mm^2, respectively. The sample was illuminated through the Au electrode. This light is completely absorbed in the a-Si:H layer close to the incident surface. 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 gain saturates again at η=6.4.

Figure 6 shows photocurrent as a function of incident light intensity for the present photodiode at 30V (η=1) and 65V (η=6.4). It is found that the slopes of these curves (gamma values) are 1.0 indicateing that there are no excess carriers entering from the electrode and no interband tunneling affected on photoinduced current.

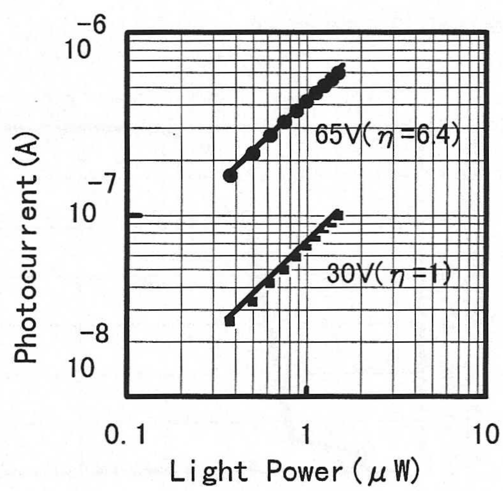

Fig.6 A gamma characteristics of the staircase photodiode films.

The band discontinuity (ΔEc) dependence of the multiplication gain is shown in Fig.7. The maximum multiplication gain is defined as a ratio of the photocurrent under the bias at which the darkcurrent reaches up to 10% of the photocurrent to the photocurrent obtained at η=1. It can be seen that magnitude of the step larger than about 0.25eV is necessary to multiply the photocurrent. The saturated multiplication gain over 6 was obtained for a conduction band discontinuity greater than 0.4eV. This gain is 3 times larger than the maximum multiplication gain of the conventional a-Si:H p-i-n structure under the same bias conditions. The multiplication factor is about 1.8 per conduction band step under the saturated bias condition. In the case of the conventional avalanche photodiode, the multiplication gain grows up monotonously with increasing the bias, but the multiplication gain of the staircase photodiode films was saturated at $\Delta Ec \geqq 0.4eV$. It is supposed that the saturated photocurrent gain is determined by the number of conduction band steps because the photogenerated electrons drift towered the first conduction band step and after electrons reached the step, the electron impact-ionization is assisted by the band offset energy (ΔEc). This ionization process is repeated in each stage.

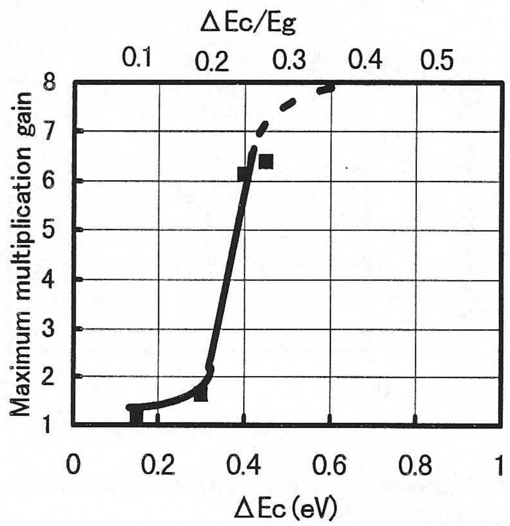

Fig.7 The band discontinuity (ΔEc) dependence of the multiplication gain

On the other hand, when the discontinuity less than 0.3eV, the photocurrent multiplication gain was small as compared with the conventional a-Si:H p-i-n photodiode films with the same intrinsic layer thickness operated under the same conditions and, the photocurrent was not saturated. Such a phenomenon is explained as follows: the staircase photodiode operates in the conventional APD mode when the conduction-band discontinuity is sufficiently small because the drift velocity of the electrons in graded a-$Si_{1-x}C_x$:H region is slow down under the space charge caused by the electron trapping effects of the dangling bonds in this region. From these results, the impact-ionization at each conduction band step due to the conduction-band discontinuity may be the dominant mechanism of the photocurrent multiplication.

4. Conclusions

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.

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