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An Amorphous Avalanche Photo-Diode with a Large Conduction Band Edge Discontinuity

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An amorphous Avalanche Photo-Diode(APD) with a heterojunction of a-SiC:H and a-SiGe:H was formed. The bandgaps of a-SiC:H and a-SiGe:H are 3.5eV and 1.55eV, respectively. The heterojunction has larger conduction band discontinuity than the bandgap of a-SiGe:H. In this amorphous APD, the photo-current multiplication was observed under low electric field. This multiplication is explained by the impact ionization process at the band edge discontinuity region.

1. INTRODUCTION

Recently, many III-V compound multilayer Avalanche Photo-Diodes(APD) have been studied theoretically and experimentally[1]-[3]. Some characteristics of photo-current multiplication with a-Si:H/a-SiC:H or a-Si:H/a-SiN:H amorphous multi-junction structures have also been reported[4]-[6]. These devices have been not suitable for portable electronic systems, because the applied electric fields have been very high due to small band edge discontinuities. In this report, we formed an APD with a heterojunction of a-SiC:H and a-SiGe:H, which has larger conduction band discontinuity than the bandgap of a multiplication layer, and observed the photo-current multiplication under low electric field.

2. EXPERIMENT

The wide bandgap a-SiC:H films were deposited from SiH_4 and CH_4 gases by radio-frequency PECVD. The substrate temperature, the RF power and the pressure were 250°C, 30mW/cm^2 and 0.2Torr, respectively. Fig.1 shows the CH_4/SiH_4 flow ratio dependence of the optical bandgap of a-SiC:H. The bandgap reached 3.5eV at the ratio of about 50. According to the results of FTIR analyses, the optical bandgap of the a-SiC:H is increased with Si-C bonds below 2.5eV and with C-H bonds above this bandgap.

It has been reported the carrier multiplication in a-Si:H single layer under low electric field by high energy photo-injection[7]. Recently, we have also measured the photo-induced carrier multiplication in a-SiGe:H single layer. The results are shown in Fig.2. A stepwise increase of quantum efficiency is observed in the a-SiGe:H of Eg 1.55eV at lower photon energy than in the a-Si:H of Eg 1.7eV. Thus we have selected a-SiGe:H for the carrier

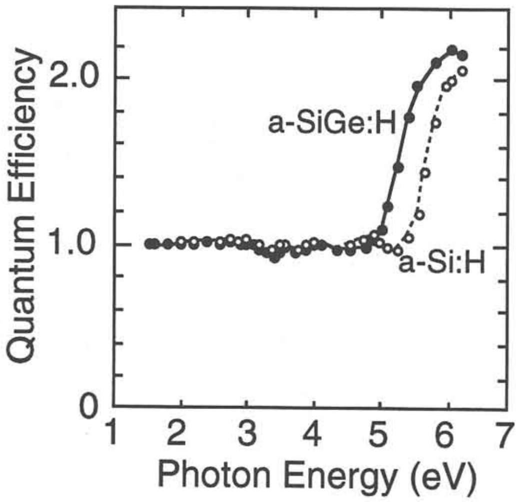

Fig.2. The photo-induced carrier multiplication in a-Si:H and a-SiGe:H

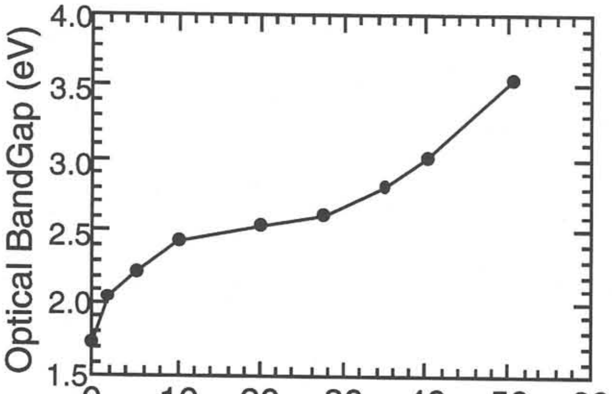

Fig.1. The CH_4/SiH_4 flow ratio dependence of the optical bandgap of a-SiC:H

multiplication layer in the amorphous APD because the threshold energy of impact ionization is expected to be lower in a-SiGe:H than in a-Si:H.

Fig.3 and 4 illustrate the schematic cross-section and the energy band diagram of the amorphous APD, respectively. Firstly, a Ti electrode was deposited on a quartz substrate. The 1000Å n^+-μc-Si:H layer, 2000Å undoped a-SiGe:H layer, 600Å a-SiC:H graded bandgap layer(3.5eV~1.7eV), and 6000Å undoped a-Si:H layer were grown. Finally a thin Pt electrode was deposited. The bandgaps for the undoped a-SiGe:H and a-Si:H are 1.55 and 1.7eV, respectively. The bandgap of the graded bandgap layer is approximately linearly changed from 3.5eV to 1.7eV. The graded bandgap layer in which the carriers can smoothly transport from the absorption layer to the heterojunction was made by varying the flow rates of SiH_4 and CH_4 gases. In order to obtain a sharp energy step and a low dark current, when the heterojunction was formed, the reactive gases in the chamber were completely pumped out at the end of a-SiGe:H was exposed before the next a-SiC:H deposition. The conduction and valence band discontinuities of the heterojunction by the XPS measurement is 1.85eV and 0.1eV, respectively.

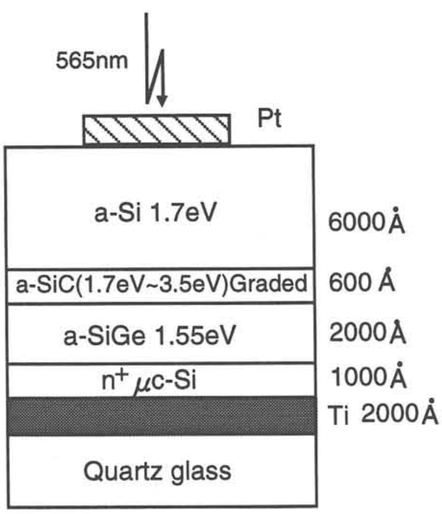

Fig.3. The schematic cross-section of the amorphous APD. The heterojunction of a-SiC:H and a-SiGe:H has a large conduction band edge discontinuity.

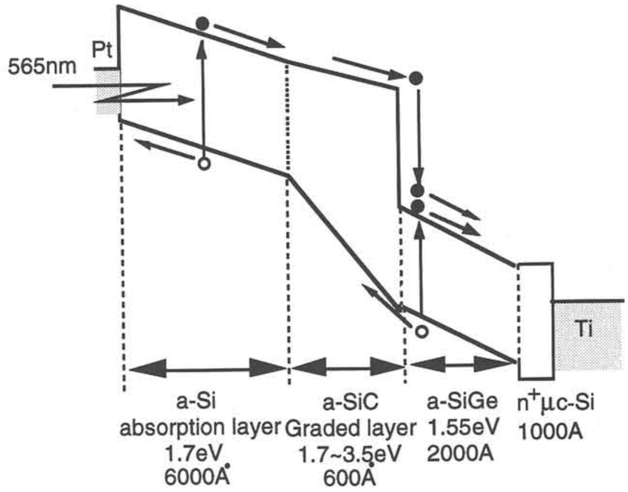

Fig.4. The energy band diagram of the amorphous APD

3. RESULTS

Fig.5 shows the reverse biased voltage dependence of the photo-current illuminated through the Pt Schottky electrode with high transparency by 565nm light which was absorbed 99% in the absorption layer. It is found that the quantum efficiency of the photo-current is equal to $\eta=1$ at 12V, exceeds $\eta=1$ at about 25V, and is saturated at $\eta=2$. The dark current is $80nA/cm^2$ at 25V at room temperature. The photo-electric conversion characteristics is shown in Fig.6. The γ value of the photo-electric conversion characteristics is 1.00. The rise response characteristics under a light pulse is shown in Fig.7. The responses have two steps, whether the currents are multiplied or not.

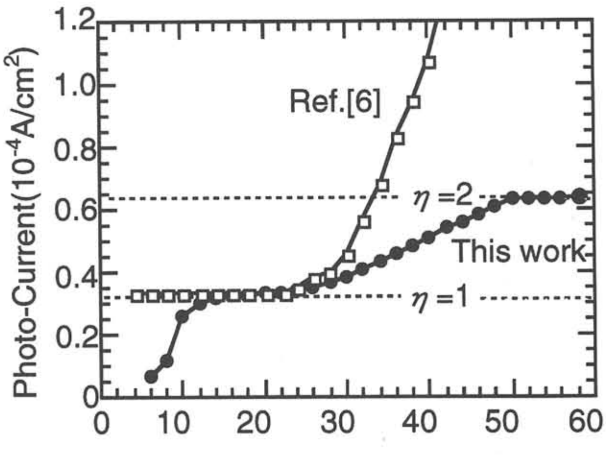

Fig.5. The reverse biased voltage dependence of the photo-current

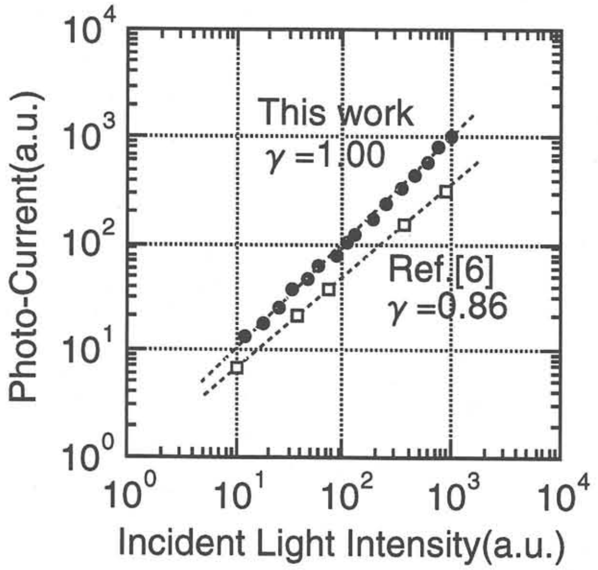

Fig.6. The photo-electric conversion characteristics

4. DISCUSSION

The measured photo-current multiplication is explained by the impact ionization process triggered by the electrons which are generated in the absorption layer, traverse the graded a-SiC:H region and are injected to the a-SiGe:H layer with a kinetic energy equal to the band edge discontinuity. This interpretation is supported by the results of the saturation of η=2 and the unity of γ which is clearly different from a secondary multiplied current occurred by an interband-tunneling process[6] as also shown in Fig.5 and 6. The average internal electric field at the bias exceeding η=1 is 3×10^5V/cm.

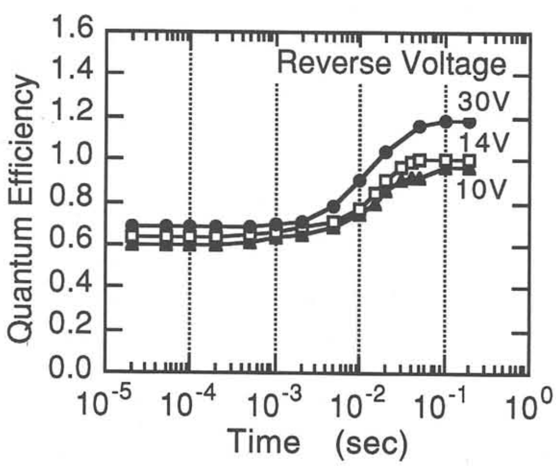

Fig.7. The rise response characteristics

The response characteristics can be explained by the existence of carrier trapping sites in a-SiC:H. The electrons transported from the absorption layer, and some of them are trapped and delayed to arrive at the heterojunction. The response of the region faster than about 10^{-3}sec shows the charging process of the trapping sites in a-SiC:H. The dangling bonds in wide gap a-SiC:H region estimated from the ESR measurements is 2×10^{12} cm^{-2}. These trapping sites act also as space charges, and cause the high bias voltage in order to transport the carriers to the heterojunction region as shown in Fig.4. If these trap sites decrease, it will be possible to lowering the bias voltage, and improving the response characteristics.

5. CONCLUSION

An amorphous APD including the multiplication layers with the larger conduction band edge discontinuities than the bandgap of narrow-gap material was formed. The photo-current multiplication was observed under low electric field. This photo-current multiplication is explained by the impact ionization process at the band edge discontinuity region. It will be able to obtain the multiplication factor of 2^n by forming the structure in which n steps of the heterojunction are stacked. From the result of this study, it is expected to realize an imaging device with very high S/N ratio.

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