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Hot Electron Generation Using Amorphous Super Structure of $Si:H/Si_{1-x}C_x:H$

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A-Si:H/a-$Si_{1-x}C_x$:H multilayer super structures (a-Si:H : well, a-$Si_{1-x}C_x$:H : barrier) were prepared by glow discharge deposition. X-ray diffraction shows that the super structure was fabricated controllably. Tunneling conduction was observed across the super structure. The tunneling current density and the effective barrier height can be controlled by changing the optical energy gap of the barrier layer. Generation of hot electron using the amorphous super structure was verified experimentally for the first time.

1. Introduction

In recent years there has been interest in multilayer structures consisting of hydrogenated amorphous silicon (a-Si:H) and silicon-based amorphous ternary alloys, e.g., a-$Si_{1-x}C_x$:H and a-SiN_x:H. There are several reports on both optical properties[1-4] of the amorphous multilayer and electrical properties along the multilayer plane.[1-3] On the other hand, very little is known about electrical properties across the amorphous multilayer plane,[5,6] while the electron conduction across the multilayer has been received considerable interest as resonance tunneling and hot carrier conduction in crystalline semiconductor super lattices. One expects generation of hot electrons by tunneling conduction through barrier layers in the amorphous multilayer structure.

We reported the first observation of the tunneling current in the a-Si:H/a-$Si_{1-x}C_x$:H multilayer super structure.[5] The tunneling conduction can be easily controlled by varying the energy gap of the barrier layer(a-$Si_{1-x}C_x$:H), since the optical energy gap of a-$Si_{1-x}C_x$:H can be easily controlled by changing the relative carbon content.[7]

In this paper, we report control of tunneling conduction by changing the optical energy gap of the barrier layer(a-$Si_{1-x}C_x$:H). We verify generation of hot electrons in a-Si:H/a-$Si_{1-x}C_x$:H super structures using a newly devised structure, experimentally. This fundamental result is important for the application of the a-$Si_{1-x}C_x$:H super structure to a hot carrier injector or a wide gap injector.

2. Preparation

The super structure (a-Si:H : well, a-$Si_{1-x}C_x$:H : barrier) was prepared by glow discharge deposition on a heavily doped n-type c-Si (0.007-0.02 Ωcm) or Au predeposited glass (Corning 7059). The a-Si:H layers deposited from SiH_4 (10 % H_2 diluted) were undoped or doped with PH_3 having the dark conductivity of 7.4×10^{-3} S/cm and the activation energy of 0.3 eV. The thickness of the a-Si:H layer (d_s) was varied from 17 Å to 200 Å.

The barrier layer of a-$Si_{1-x}C_x$:H deposited from SiH_4 (10 % H_2 diluted) and C_2H_4 was undoped with the conductivity less than 10^{-11} S/cm. The thickness of the a-$Si_{1-x}C_x$:H layer (d_c)was 40 Å except for a special experiment. The optical energy gap of a-$Si_{1-x}C_x$:H is varied by changing the carbon content.

Both a-Si:H and a-$Si_{1-x}C_x$:H were deposited at 220 °C with the r.f. power density of 0.12 W/cm^2.[7] In order to avoid carbon contamination in the a-Si:H layer, the discharge was stopped at the end of each layer deposition and the source gases were completely changed. The upper electrode of Al was evaporated.

3. X-ray diffraction

The construction of the multilayer structure was confirmed by the depth profile of Auger electron spectroscopy[5] and X-ray diffraction. Figure 1 shows dependence of the thickness d_s+d_c in 20 periods multilayers estimated from the X-ray diffraction pattern on the deposition time for the a-Si:H layer, where the deposition time for the a-$Si_{0.2}C_{0.8}$:H was kept constant. The value of d_s+d_c linearly varied with the deposition time for the a-Si:H, which indicates that the super structures were fabricated controllably. The intercept with the ordinate indicates the thickness d_c (20.3 Å) and the slope shows the deposition rate of a-Si:H; the deposition rate of a-Si:H is 1.69 Å/s, whereas the deposition rate of a-$Si_{0.2}C_{0.8}$:H was kept constant, 0.675 Å/s.

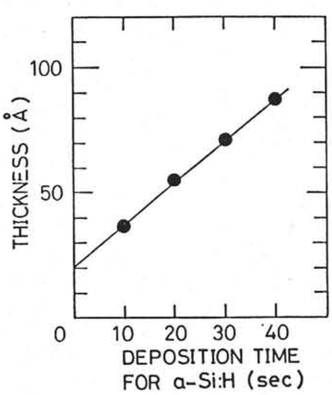

Fig. 1. Thickness of d_s+d_c estimated from X-ray diffraction pattern vs. deposition time for a-Si:H. Deposition time for a-$Si_{0.2}C_{0.8}$:H was kept constant.

4. Double barrier super structures

4.1 Band diagram

Photoemission study on the a-Si:H/a-$Si_{1-x}C_x$:H heterojunction implies that the energy difference of the valence band edge is very small and the band discontinuity in the heterojunction mainly leads to the energy difference of the conduction band.[8] The electronic band diagram of the double barrier (d_c = 40.4 Å) structure with d_s = 50.3 Å is thought to be as shown in Fig. 2, where the a-Si:H layer is doped and the optical energy gap of a-$Si_{0.2}C_{0.8}$:H is 3.1 eV.

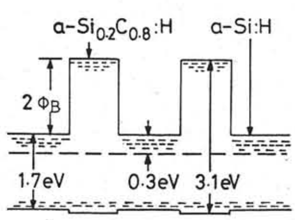

Fig. 2. Schematic electronic band diagram of the a-Si:H/a-$Si_{0.2}C_{0.8}$:H double barrier structure.

4.2 Conduction mechanism

Figure 3 shows current (I) - voltage (V) characteristics of a-$Si_{0.2}C_{0.8}$:H (1000 Å). Below the applied voltage of 4 V, estimated to be 4×10^5 V/cm, the current shows Ohm's law. Above 4 V, the characteristics of the I-V curve deviates from Ohm's law. The current component superposed on the ohmic conduction shown by the dotted line in Fig. 3 may be due to space charge limited current (SCLC).

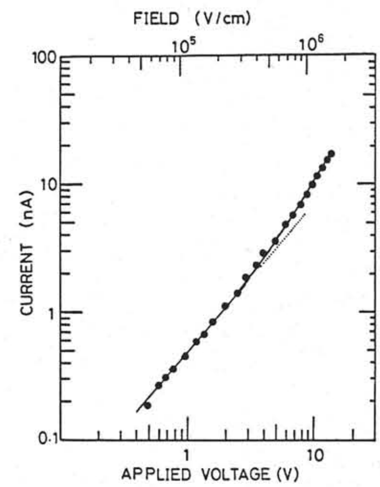

Fig.3. I-V characteristics of a-$Si_{0.2}C_{0.8}$:H (1000 Å).

Figure 4 shows I - V characteristics across the a-Si:H/a-$Si_{0.2}C_{0.8}$:H (d_c=40.4 Å, d_s= 50.3 Å) double barrier super structure. Below the applied

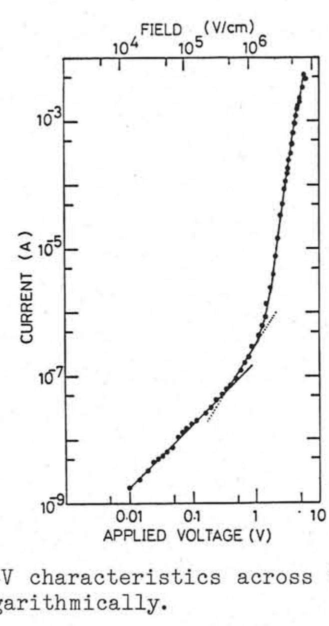

Fig. 4. I-V characteristics across the multilayer plotted logarithmically.

voltage of 1V, ohmic conduction and space charge limited conduction were dominant in the applied voltage of 0-0.15V and 0.15-1V, respectively. The conductivity is 1.31×10^{-11} S/cm corresponding to that of a-$Si_{0.2}C_{0.8}$:H. Above the applied voltage of 1V, the current increases drastically. Considering the difference in conductivities between a-Si:H and a-$Si_{0.2}C_{0.8}$:H as mentioned above, the voltage is mainly applied to the a-$Si_{0.2}C_{0.8}$:H barrier layers. The field in the a-$Si_{0.2}C_{0.8}$:H barrier layer is estimated to be 1.3×10^{6} V/cm at the applied voltage of 1 V where the current increases drastically. The value of 1.3×10^{6} V/cm is comparable to the well-known value [9] for the onset of the tunneling current.

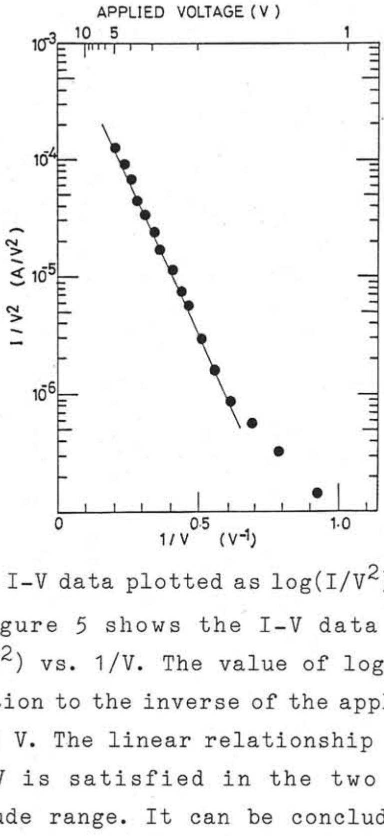

Fig. 5. I-V data plotted as $\log(I/V^2)$ vs. 1/V.

Figure 5 shows the I-V data plotted as $\log(I/V^2)$ vs. 1/V. The value of $\log(I/V^2)$ is in proportion to the inverse of the applied voltage above 1 V. The linear relationship of $\log(I/V^2)$ vs. 1/V is satisfied in the two orders-of-magnitude range. It can be concluded that the current component superposed above 1 V is the tunneling current through the a-$Si_{0.2}C_{0.8}$:H barrier layer, because the tunneling current is expressed as :[10]

$$J \propto E^2 \exp(-4\sqrt{2m^*}(2q\phi_B)^{3/2}/3q\hbar E), \qquad (1)$$

where J is the current density, E the applied field, q the charge of the carrier, $\hbar$ the Planck constant, m^* the effective mass of the carrier and ϕ_B the effective barrier height for tunneling.

The effective barrier height ϕ_B can be estimated as 0.38 eV from the slope of the curve in Fig. 5, assuming the effective mass of an electron equals the free-electron mass.

5. Control of barrier height

The relative carbon content in a-$Si_{1-x}C_x$:H for the barrier layer was varied from 0.60 to 0.80 in the triple barrier super structure (d_c=150 Å and d_s=200 Å); the barrier height in the conduction band might be increased with increasing the relative carbon content. The value of ϕ_B can be controlled by varying the optical energy gap of a-$Si_{1-x}C_x$:H as shown in Table I. Tunneling current in Table I was defined as the current at a certain applied voltage above which the current increased drastically. Tunneling current increases with decreasing optical energy gap as shown in Table I.

Table I. The value of effective barrier height for tunneling and the tunneling current as a function of optical energy gap of a-$Si_{1-x}C_x$:H.

	Barrier C content	layer E_{opt} (eV)	ϕ_B (eV)	Tunnel current (A/cm^2)
#1	0.60	2.6	0.22	10^{-1}
#2	0.67	2.8	0.42	10^{-3}
#3	0.80	3.1	0.58	10^{-3}

6. Detection of hot electron

In the single heterojunction of a-Si:H (n-type, 7.4×10^{-3} S/cm) and a-$Si_{0.2}C_{0.8}$:H as shown in Fig. 6(a), the I-V characteristics shows ohmic conduction below the applied voltage of 4 V (2.5×10^{5} V/cm) as shown with squares (■) in Fig.7.

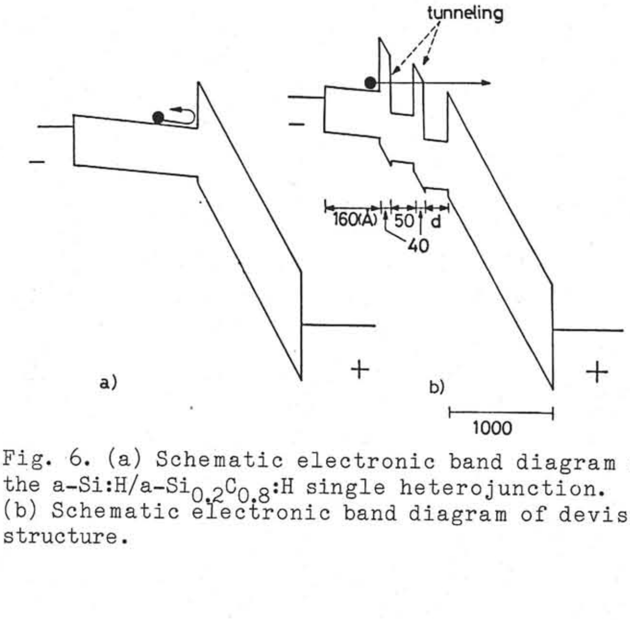

Fig. 6. (a) Schematic electronic band diagram of the a-Si:H/a-$Si_{0.2}C_{0.8}$:H single heterojunction.
(b) Schematic electronic band diagram of devised structure.

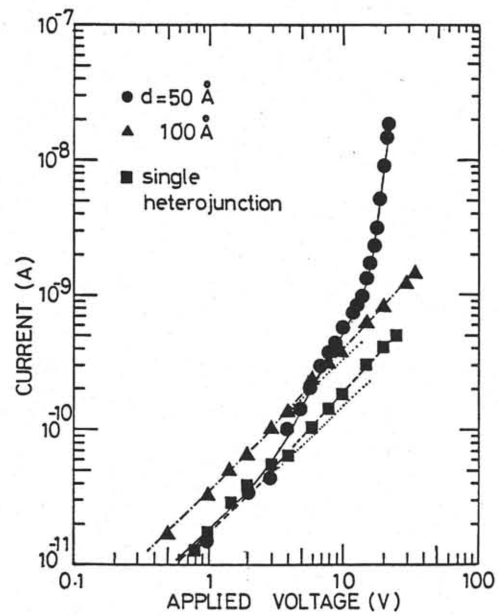

Fig.7. I-V characteristics of single heterojunction and devised structures.

The conductivity is 1.66×10^{-12} S/cm corresponding to that of a-$Si_{0.2}C_{0.8}$:H. Above 4 V (2.5×10^5 V/cm), the current component superposed on the ohmic conduction shown by the dotted line in Fig. 7 is SCLC conduction. The carrier injection from a-Si:H to the conduction band of a-$Si_{0.2}C_{0.8}$:H does not occur in this single heterojunction.

We carried out the detection of the hot electron injection to a-$Si_{0.2}C_{0.8}$:H using a newly devised structure shown in Fig. 6(b). The thickness d of the buffer layer between the super structure and the bulk in the figure was changed. In the device, if the tunneling electron does not lose kinetic energy (i.e. electron becomes "hot"), the electron can be injected to a-$Si_{0.2}C_{0.8}$:H as shown in Fig.6(b). In Fig. 7, I-V curves of the devices with different d are shown with circles (●) and triangles (▲).

In the case of d=50 Å, the current increased drastically above the applied voltage of 15 V giving the electric field of 1.4×10^6V/cm. The electric field corresponds to the onset of tunneling current through the super structure. Above the applied voltage where the tunneling current starts to flow, hot electron injection occurs. The drastic increase in the current was not observed when the multilayer side was positively biased to the a-$Si_{0.2}C_{0.8}$:H side, i.e. reverse bias.

When the thickness d increased above 100 Å, the electron injection was not observed as well as in the case of the single heterojunction. The result implies the tunneling electron is scattered in the buffer layer and loses kinetic energy for d=100 Å.

7. Summary

We fabricated a-Si:H/a-$Si_{1-x}C_x$:H super structures controllably and measured the I-V characteristics across the amorphous super structure. The tunneling current through the amorphous multilayer has been demonstrated at room temperature. The tunneling current density and the effective barrier height can be controlled by changing the optical energy gap of the barrier layer. Above the applied voltage where tunneling current starts to flow, hot electron injection occurs through the buffer layer of 50 Å thick. This a-Si:H/a-$Si_{0.2}C_{0.8}$:H super structure with a thin buffer layer can be used as a hot electron injector.

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References

1) B.Abels and T.Tiedje : Appl. Phys. Lett. 45 (1984) 179.

2) N.Ibaraki and H.Fritzche : Phys. Rev. B 30 (1984) 5761.

3) M.Hirose an S.Miyazaki: J.Non-Cryst.Solids 66 (1984) 327.

4) H.Munekata and H.Kukimoto : Jpn. J. Appl. Phys. 22 (1983) L544.

5) M.Yoshimoto, K.Du, T.Fuyuki and H.Matsunami : Jpn.J.Appl.Phys.25(1986) L21.

6) S.Tsuda, T.Takahama, H.Tarui, K.Watanabe, N.Nakamura, H.Shibuya, S.Nakano, M.Ohnishi and Y.Kuwano: Proc. 18th IEEE Photovoltaic Spec. Conf. Lasvegas (1985)

7) J.Saraie, Y.Fujii, M.Yoshimoto, K.Yamazoe and H.Matsunami : Thin Solid Films 117 (1984) 59.

8) F.Evangelisti, P.Fiorini, C.Giovannella, F.Patella, P.Perfetti, C.Quavesima and M.Capozi: Appl.Phys.Lett. 44 (1984) 764.

9) S.M.Sze : Physics of Semiconductor Devices (John Weily & Sons, New York, 1981) 2nd ed., p.402

10) J.G.Simmons : J. Appl. Phys. 34 (1963) 1793.