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Resonant Tunneling Through Amorphous Silicon/Silicon Nitride Double Barrier Structures

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We have studied the resonant tunneling of electrons through a-Si_3N_4:H/phosphorus doped a-Si:H/a-Si_3N_4:H double barrier structures. The observed current bumps in the dc current-voltage characteristics have been explained in term of the electron tunneling through the quantized states in the conduction band of a-Si:H well layer. The effective mass of tunneling electrons is obtained to be $0.6m_0$ from the numerical analysis of the tunneling current by using the WKB apporoximation. The effective mass is in consistence with the value determined from the optical band gap data for a-Si:H/a-Si_3N_4:H multilayers with various a-Si:H well layer thicknesses.

1. Introduction

Ultra-thin multiple layered structures consisting of amorphous silicon (a-Si:H) and silicon-based materials such as amorphous silicon nitride (a-$Si_{1-x}N_x$:H), silicon carbide (a-$Si_{1-x}C_x$:H), or silicon germanium (a-$Si_{1-x}Ge_x$:H) have found to exhibit very unique properties which could be interpreted in terms of quantum size effects in amorphous semiconductor potential well layers[1-7], as in the case of crystalline semiconductor superlattices. For instance, the optical band gap of amorphous silicon-based multilayer structures systematically increases as the well layer thickness decreases from 50 A to 8 A[2,5]. Correspondingly the activation energy of conductivity is also increased with decreasing the well layer thickness[3,6]. These results have been satisfactorily explained by assuming the presence of quantized states in the conduction and valence bands of the potential well layers[1-6]. However, there has been a current question whether or not the quantum size effect is really existing in ultra-thin amorphous semiconductor multilayers. The purpose of this paper is to answer the question by showing the first direct evidence of the quantization effect in an amorphous silicon well layer sandwithed with stoichiometric silicon nitride barriers.

2. Experimental

Phosphorus doped a-Si:H/a-Si_3N_4:H double barrier structures were fabricated on n^+ c-Si substrates with resistivities $1.8\times10^{-3} \sim 5\times10^{-3}$ Ωcm by using an rf glow discharge technique. The ultra-thin (13 to 40 A thick) phosphorus doped a-Si:H well layer was deposited from a SiH_4 (10.2% in H_2)+ PH_3 (9.71% in H_2) gas mixture which has a molar fraction of $[PH_3]/[SiH_4]=0.05$, and the insulating stoichiometric a-Si_3N_4:H barrier layers with a thickness of 46 A were grown from SiH_4 (10.2% in H_2) + pure NH_3 plasma, in which the

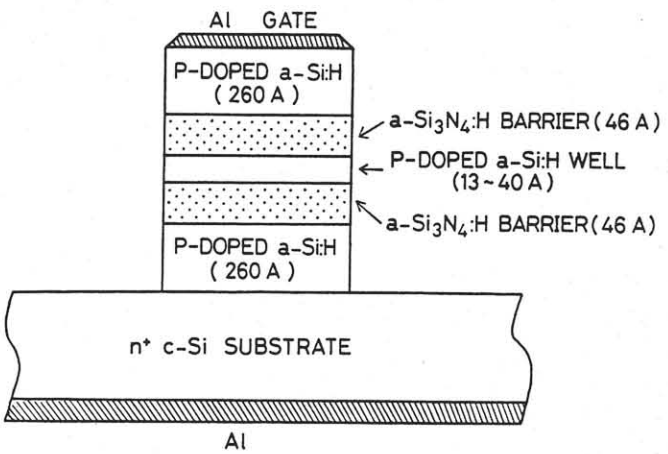

Fig. 1 Schematic structure of an a-Si:H /a-Si_3N_4:H double barrier structure.

molar fraction $[NH_3]/[SiH_4]$ was held at 10. During the growth of each layer, substrate temperature, rf power, and gas pressure was maintained at 300 °C, 5W, and 0.2 Torr, respectively. In order to prepare the abrupt interfaces and to obtain the uniform ultra-thin layers with the desired chemical compositions, the glow discharge was turned off at each step of the individual layer deposition and the reactor was purged with hydrogen gas. For designing a symmetric potential barrier system, the double barrier was sandwithed with 260 A thick phosphorus doped a-Si:H contact layers as illustrated in Fig. 1. The evaporated aluminum gate electrode (1 mm in diameter) was used as a dry etching mask of the specimen and the etching was carried out in a $SiF_4 + O_2$ plasma ($[O_2]/[SiF_4]=0.04$) at a pressure of 0.1 Torr.

3. Results and Discussion

Measured current-voltage characteristics of two typical double barrier systems with well layer thicknesses of 13 A and 40 A are shown in Fig. 2 (a) and (b), respectively. In the both cases, no significant structure is observed at 288 K because of the thermal smearing effect, while at 77 K the current bumps are clearly observed at voltages indicated by arrows in the figure. The current density is less sensitive to temperature as expected for the tunneling transport case. In order for clarifying whether or not these current bumps are due to the resonant tunneling of electrons through the quantized states in the a-Si:H well, the measured results are compared with the theoretical analysis.

The numerical calculation of the electron transmission coefficient in the double barrier structures was carried out by assuming the potential profile as shown in Fig. 3, where the conduction band discontinuity is estimated to be 1.7 eV from the measured electron affinities of the both materials[5]. In the caluculation based on the WKB approximation[8], we assumed that electrons in the symmetric double barrier system without applying bias have the thermal energy kT/2 and that externally applied bias is divided among the $a\text{-}Si_3N_4$:H barrier layers and the phosphorus doped

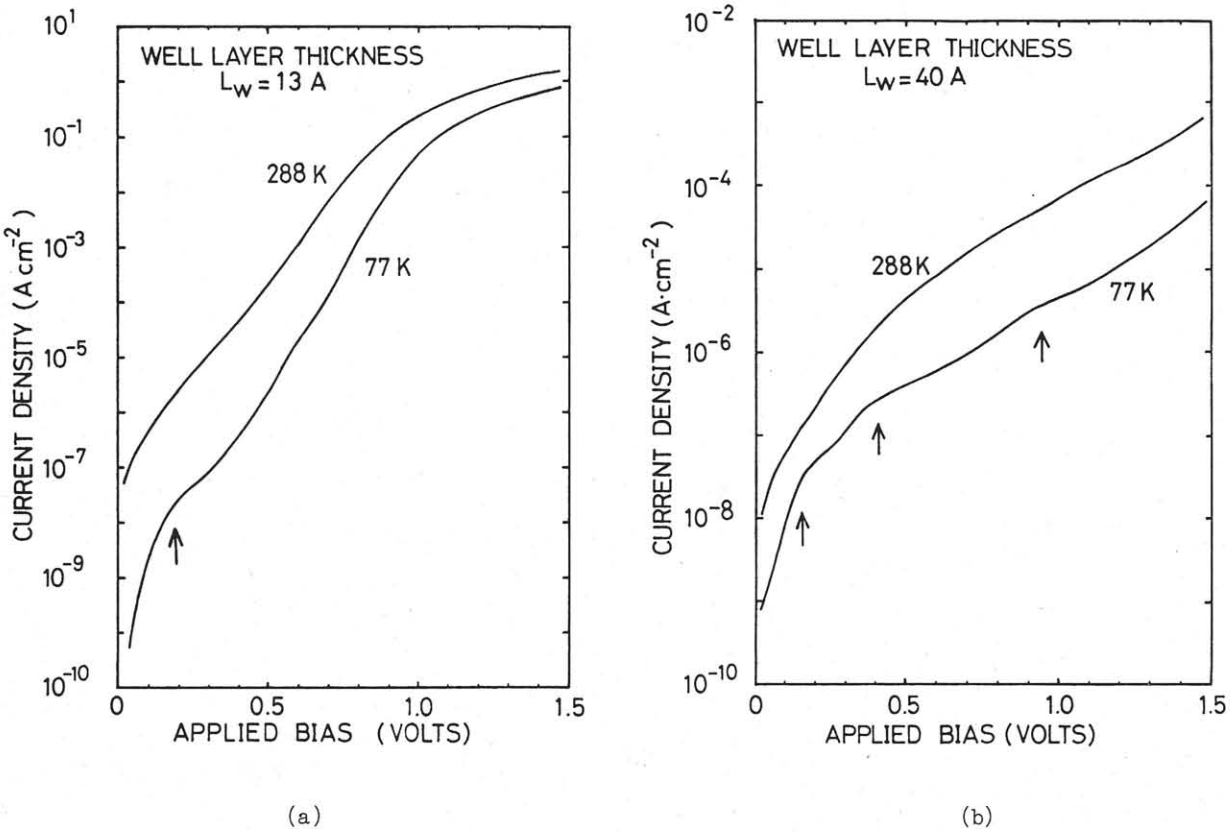

Fig. 2 Measured current-voltage characteristics of double barriers with well layer thicknesses of L_W = 13 A (a) and 40 A (b).

a-Si:H well layer by taking into account the respective film thickness and permittivity. Further, the distribution of applied electric field strength in the individual layer was approximated to be homogeneous. Figure 4 repesents the calculated electron transmission coefficient T^*T through the double barrier as a function of applied bias. Sharp resonant tunneling occurs at applied voltages corresponding to $T^*T \simeq 1$. In the real double barrier system, however, a considerable reduction of the resonance peak height and a significant broadening of the resonance bands are caused by the thermal smearing of the electron energy distribution, electron scattering by structural defects, and spatial fluctuations of the layer thicknesses. Note that theoretically predicted biases at which the resonant tunneling takes place are in excellent agreement with the voltages indicated by arrows in Fig. 2 when the electron effective mass m^* is chosen as 0.6 m_0, where m_0 is the free electron mass. It must be emphasized that the electron effective mass obtained from the resonant tunneling experiments is consistent with that determined from the optical energy gap data for a-Si:H/a-Si_3N_4:H multilayers with various a-Si:H layer thicknesses ranging 8 to 500 A[5]. So far the increase of the optical energy gap with decreasing the a-Si:H well layer thickness has been interpreted in terms of one dimensional quantum size effect[2]. The estimated values of the effective mass are in the range of $0.2m_0 \sim 0.6m_0$[5,6]. However this is not the direct

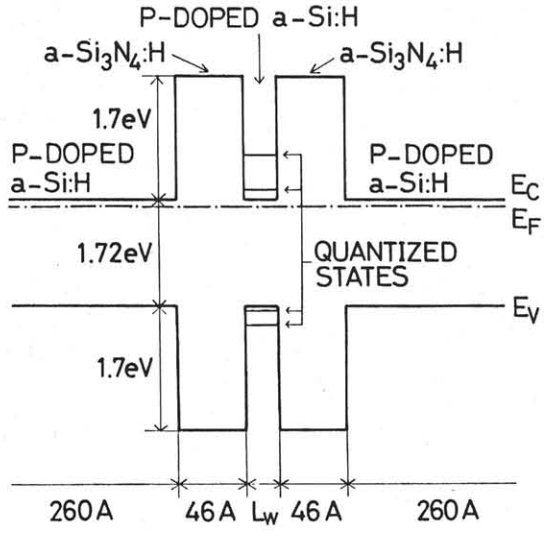

Fig. 3 Energy band diagram of an a-Si:H/a-Si_3N_4:H double barrier.

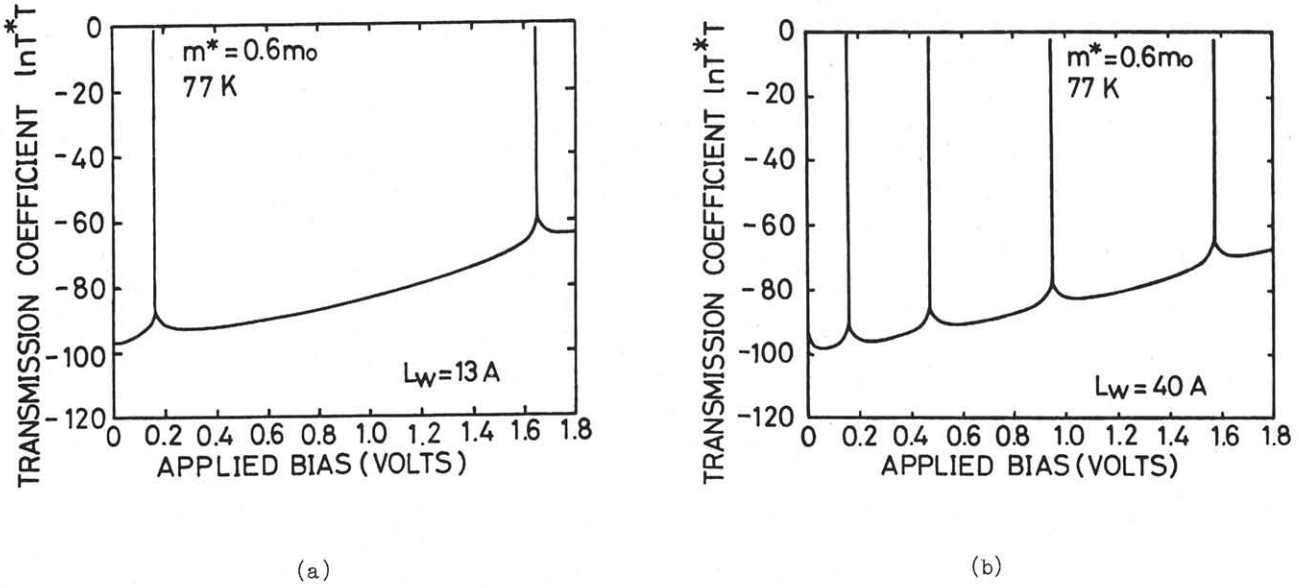

Fig. 4 Calculated electron transmission coefficient T^*T through double barriers with well layer thicknesses of L_W = 13 A (a) and 40 A (b) plotted against applied bias.

proof of the existence of quantum size effect in amorphous silicon mutilayers. Further problem is that the inelastic diffusion length of conduction electrons in a-Si:H is estimated to be about 25 A because of the low electron mobility. This value is significantly short compared with that of a typical crystalline semiconductor. Also, it is likely that the fluctuations of the conduction band edge arising from the lack of long range order remarkably smears the quantized energy levels even if they are existing. Despite of such negative aspects for observing the quantized levels in a-Si:H, the present result definitely indicates that conduction electrons in a-Si:H can be quantized even in the potential well with a layer thickness of 40 A, implying that the free electron wave function in a-Si:H must extend over at least 40 A.

4. Conclusion

The evidence of resonant tunneling of electrons through the quantized states in an a-Si:H well layer has been demonstrated for the first time in a-Si_3N_4:H/a-Si:H/a-Si_3N_4:H double barrier structures at a temperature of 77 K. We may expect that the resonant tunneling through the double barriers can be more conspicuously observed at temperatures lower than 77 K.

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