Resonant Tunneling Through Amorphous Silicon–Silicon Nitride Double-Barrier Structures

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The electron tunneling through quantized states in an ultrathin hydrogenated amorphous silicon (*a*-Si:H) layer sandwiched with stoichiometric silicon nitride (*a*-Si_3N_4:H) barriers has been systematically investigated. The *I-V* characteristics have exhibited current bumps arising from resonant tunneling through the double barriers. The effective mass of the tunneling electron is obtained to be $0.6m_0$, consistent with the value determined from optical band-gap data for *a*-Si:H/*a*-Si_3N_4:H multilayers.

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Ultrathin multiple-layered structures consisting of amorphous silicon sequentially alternating with silicon-based materials have been extensively studied so far by many groups.[1-8] It has been found that multilayers with smooth heterojunction interfaces on an atomic scale and abrupt chemical composition profiles can be produced by careful control of the deposition processes.[2,4,6] The unique optical and electrical properties of the multilayer structures have been attributed to the quantized effect in the potential-well layer[1-5] as manifested in crystalline superlattices. However, there has been no direct answer to the question of whether or not the quantum size effect really exists in ultrathin amorphous-semiconductor multilayers. In this paper, we report on the resonant tunneling phenomena through *a*-Si_3N_4:H/*a*-Si:H/*a*-Si_3N_4:H double-barrier structures for demonstrating the existence of quantized levels in the ultrathin *a*-Si:H well layers.

Phosphorus-doped *a*-Si:H/*a*-Si_3N_4:H double-barrier structures were prepared by an rf glow-discharge technique. Antimony-doped crystalline Si with a resistivity of 1.8×10^{-3} cm was used as a substrate. The ultrathin 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 with a molar fraction of $[PH_3]/[SiH_4]=0.05$. The *a*-Si:H well-layer thickness was varied from 10 to 40 Å. The insulating stoichiometric *a*-Si_3N_4:H barrier layers with a thickness of 46 Å were grown from an SiH_4 (10.2% in H_2) + pure NH_3 gas mixture with a fraction of $[NH_3]/[SiH_4]=10$. During the layer growth, rf power, total pressure, and substrate temperature were held constant at 5W, 0.2 Torr, and 300 °C, respectively. In order to design a symmetric potential-barrier profile, the double barrier was sandwiched with 260-Å-thick phosphorus-doped *a*-Si:H contact layers, as illustrated in Fig. 1(a). Hence the energy-band diagram of the system can be derived as illustrated in Fig. 1(b), where the conduction-band discontinuity of 1.7 eV is estimated from the result of internal photoemission measurements of *c*-Si/*a*-Si_3N_4:H,[9] *a*-Si:H/SiO_2,[10] and *c*-Si/SiO_2[11] systems. For the purpose of obtaining the abrupt interfaces and the uniform ultrathin layers with the desired chemical compositions, the glow discharge was turned off at each step of the individual layer deposition, and the reactor was pumped down to 10^{-3} Torr to be purged with hydrogen gas. The evaporated aluminum gate electrode with a diameter of 1 mm was employed as a dry etching mask of the sample. The dry etching was achieved at room temperature in a SiF_4+O_2 plasma with a molar fraction of $[O_2]/[SiF_4]=0.04$ and a gas pressure of 0.1 Torr. Measured current-voltage characteristics of a typical double barrier with a well layer thickness of 40 Å

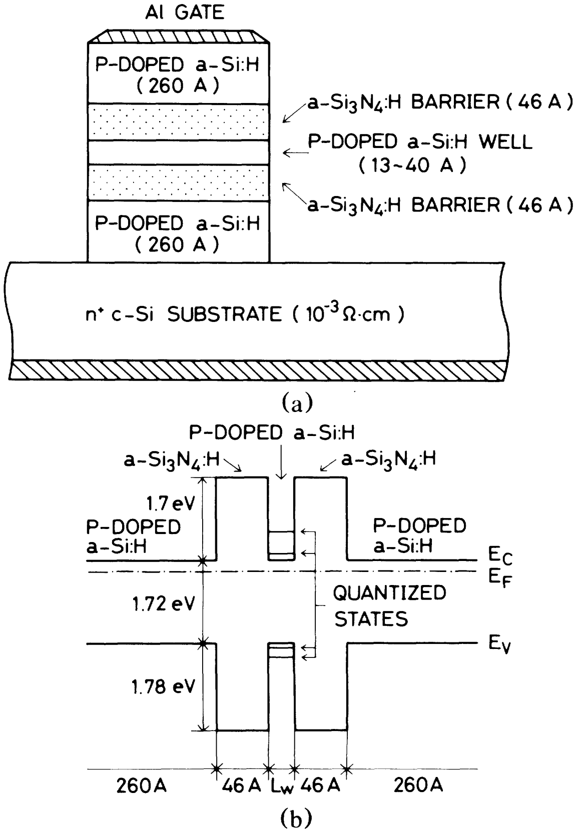

FIG. 1. Schematic structure of (a) an *a*-Si:H/*a*-Si_3N_4:H double-barrier structure and (b) its energy-band diagram.

are shown in Fig. 2. No significant structure is observed at 288 K presumably because of the thermal smearing effect, while at 77 K current bumps are clearly observed at applied biases of about 0.2, 0.4, and 0.9 V. The current density is less sensitive to temperature as expected for the tunneling transport case.

In order to clarify 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 result was compared with the theoretical analysis. The current-voltage characteristics for the opposite polarity of the applied bias does not exhibit a symmetric behavior mainly because the P-doped *a*-Si:H/Al contact acts as a poor reverse-biased Schottky barrier whose series resistance significantly suppresses the current bump.

The electron transmission coefficient in the double-barrier structure was calculated by the WKB approximation.[12] It was assumed that an electron in the symmetric double-barrier system has a thermal energy of $kT/2$ at zero bias and that externally applied bias is divided among the *a*-Si_3N_4:H barrier layers and the phosphorus-doped *a*-Si:H well layer according to the respective film thicknesses and permittivities. Also, the distribution of applied electric field strength in the individual layers was approximated to be homogeneous because the total number of free electrons in the doped *a*-Si:H well layer is significantly lower than that necessary for screening of the internal electric field. The calculated electron transmission coefficient T^*T for the same sample as shown in Fig. 2 is also represented in the figure. Sharp resonant tunneling is expected to take place at voltages corresponding to $T^*T \simeq 1$. In the real double-barrier system, however, the thermal smearing of the electron energy distribution, electron scattering by structural defects in *a*-Si:H, and microscopic fluctuations of the *a*-Si:H layer thicknesses must give rise to a significant broadening of the quantized levels, resulting in reduction of the measured resonance peak height. It is also likely that the spatial fluctuations of the conduction-band edge arising from the lack of long-range order smear the quantized energy levels even if they exist. The calculated resonance voltage is consistent with the bias at which current bumps are observed, when the tunneling electron effective mass m^* is chosen as $0.6m_0$ where m_0 is the free-electron mass. In Fig. 3 the calculated resonance voltage as a function of well-layer thickness is shown together with the experimental results. The higher eigenstates in the thinner well-layer thickness (≤ 25 A) were not experimentally observed because the thermal tunneling current rapidly increases at bias voltages above 1.2 V, and hence the current bumps arising from the resonant tunneling through the higher eigenstates for the cases of well layer thicknesses below 25 A could not clearly be detected. 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 *a*-Si:H layer thicknesses ranging from 8 to 500 Å.[5] The inelastic diffusion length of conduction electrons in *a*-Si:H is estimated to be 45 Å for an extended-state electron mobility of 30 cm^2/V sec.[13] This implies that the quantization effect can be observed for well-layer thicknesses of less than 50 Å. In fact, the optical energy gap starts to increase when the *a*-Si:H well-layer thickness becomes less than 50 Å,[1-3,5] being explained in terms of one-dimensional quantum size effect. In a previous work[5] the authors have demonstrated that electron and hole wave functions in an *a*-Si:H potential well with thickness of less than 25 Å cannot be spatially separated when a strong electron field exceeding 10^6 V/cm is ap-

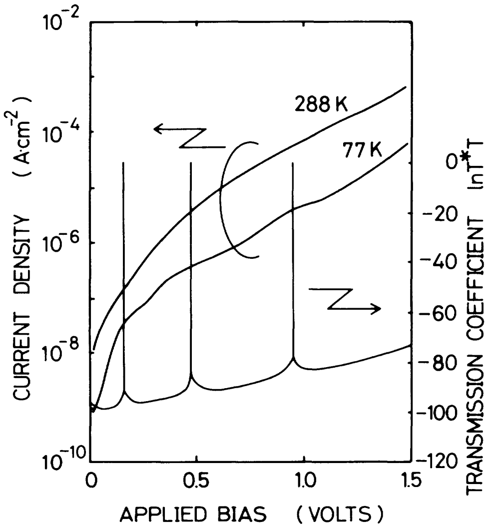

FIG. 2. Measured current-voltage characteristics of a double barrier with the well-layer thickness $L_W = 40$ Å. Metal contact is positively biased. Also the calculated electron transmission coefficient T^*T at 77 K through the double barrier against applied bias is indicated.

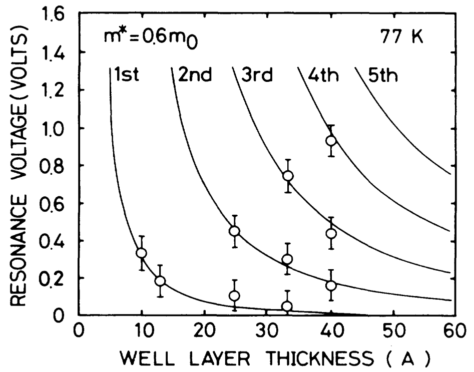

FIG. 3. Resonance voltage vs well-layer thickness. The solid lines are calculated curves corresponding to the first to fifth quantized states, and open circles experimental data.

plied perpendicularly to the a-Si:H layer. This suggests that the electron wave function must extend over 25 Å. By considering these results, we may conclude that the resonant tunneling through the quantized states in an a-Si:H well layer is definitely observable as experimentally demonstrated from the current-voltage characteristics of the a-Si:H/a-Si$_3$N$_4$:H double-barrier structures.

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[1] H. Munekata and H. Kukimoto, Jpn. J. Appl. Phys. Part 2 **22**, L544 (1983).

[2] B. Abeles and T. Tiedje, Phys. Rev. Lett. **51**, 2003 (1983).

[3] J. Kakalios, H. Fritzsche, N. Ibaraki, and S. R. Ovshinsky, J. Non-Cryst. Solids **66**, 339 (1984).

[4] M. Hirose and S. Miyazaki, J. Non-Cryst. Solids **66**, 327 (1984).

[5] S. Miyazaki, N. Murayama, M. Hirose, and M. Yamanishi, in *Technical Digest of the First International Photovoltaic Sciences and Engineering Conference, Kobe, 1984,* edited by M. Konagi (Nippon, Tokyo, 1984), p. 425.

[6] T. Tiedje, B. Abeles, H. Deckman, P. Persans, and C. Roxlo, J. Non-Cryst. Solids **77&78**, 1031 (1985).

[7] S. Miyazaki, N. Murayama, and M. Hirose, J. Non-Cryst. Solids **77&78**, 1089 (1985).

[8] S. Miyazaki, Y. Ihara, and M. Hirose, in Extended Abstracts of The Sixth International Conference on Solid State Devices and Materials, Tokyo, 1986 (to be published), p. 675.

[9] S. Yokoyama, S. Kajihara, M. Hirose, and Y. Osaka, J. Appl. Phys. **51**, 547 (1980).

[10] T. Yamamoto, Y. Mishima, M. Hirose, and Y. Osaka, Jpn. J. Appl. Phys. Suppl. **20**, 185 (1981).

.RF 11 R. Williams, Phys. Rev. **140**, A569 (1965).

[12] H. Davis and H. H. Hosack, J. Appl. Phys. **34**, 864 (1963).

[13] W. E. Spear, J. Non-Cryst. Solids **59&60**, 1 (1983).