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Resonant Tunneling through Si/SiO_2 Double Barriers

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Recently, the most advanced technique of molecular beam epitaxy of $Ga_{1-x}Al_xAs$ systems has been applied to produce one-dimensional monocrystalline superlattice or double-barrier structures, in which resonant tunneling phenomenon has been observed.[1,2] These tunneling barriers are about 0.4 eV, being rather small to observe negative conductance at room temperature. In order to overcome this limitation, we have tried to fabricate Si/SiO_2 double barriers. Evidence of resonant tunneling has been found in the structure made as follows: Thin amorphous Si film (50-120Å thick) has been deposited by electron beam onto n-type Si substrate covered with a tunnelable SiO_2 film (30Å thick). Then the amorphous Si has been crystallized at 1050°C in N_2 atmosphere prior to the thermal oxidation (30Å thick) of the film. N-type conduction has been found in the polycrystalline Si film from the field effect measurements.[3]

Figure 1 represents the bias dependence of DC tunneling conductance for a nSi(N_D=$4x10^{15}cm^{-3}$)/SiO_2(30Å)/poly Si(50Å)/SiO_2(30Å)/Au double barrier. Fine structures of the conductance arising from the resonant tunneling and related negative conductance at 1.26 V and 1.61 V have been seen. Tunneling into surface states at poly Si/SiO_2 or nSi/SiO_2 interface provides only broad peaks or humps in the conductance curve.[4,5] Trap levels in poly Si band gap cause a weak hysteresis of the conductance-bias relation by capture and emission of electrons. If polycrystalline Si is changed into a structure of islands after oxidation, resonant tunneling takes place only through these islands. All of these problems have little influence on the resonant transmission of electrons. The bias voltages at which the resonant tunneling occurs are indicated by arrows in Fig.1. They have been obtained from the calculated transmission coefficient of electron waves in the Si/SiO_2 double barrier (Fig.2) and the bias dependence of the surface potential for the substrate Si. Relatively weak structures of the conductance near the main singularities could be explained

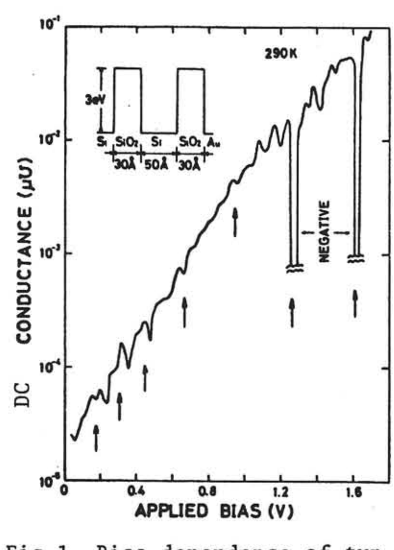

Fig.1. Bias dependence of tunneling conductance for a Si/SiO_2 double barrier. Voltage polarity refers to that applied to Au electrode.

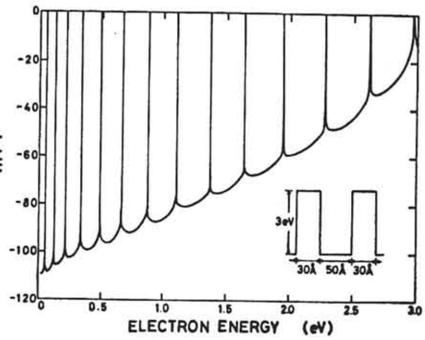

Fig.2. Calculated transmission coefficient of electrons in the Si/SiO_2 double barrier as a function of electron energy.

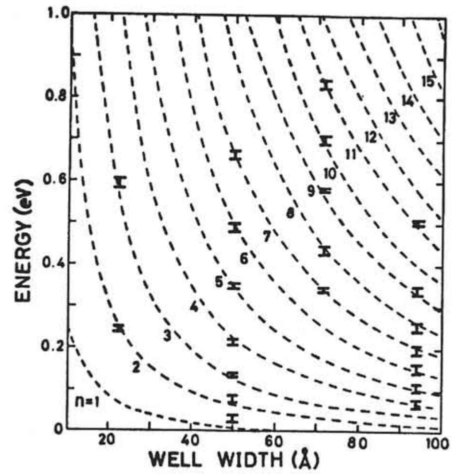

Fig.3. Resonant energies (indicated by spread of values;I) measured on samples with different well width and calculated resonant states (broken lines) as a function of well width. n is the quantum number.

by the spatial fluctuations of the effective well width. In order to illustrate the degree of reproducibility, the resonant energies obtained from the singularities of DC tunneling conductance on other samples with different well width are shown in Fig.3 together with the calculated quasistationary states of Si/SiO_2 double-barrier structures as a function of poly Si well width. In some samples, singularities corresponding to lower resonant energies have not been well distinguished on account of the thermal broadening of electron distribution, the fluctuations of poly Si grain-size or the scattering of electrons by structural imperfections. Clear negative conductance has not always been observed because the structural fluctuations in the barrier restrict the sharp resonance as seen in Fig.2.

In spite of these circumstances, the excellent agreement has been obtained between the theoretical and experimental results shown in Figs.1 and 3. Therefore, we may conclude that the resonant tunneling through Si/SiO_2 double barriers has been observed as the fine structures of the conductance curves and often as the negative conductance. This is the first observation of resonant tunneling in a polycrystalline/amorphous oxide double-barrier, providing some possibilities for the device application of multiple layer structures by proper choise of materials.

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