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Novel Si Resonant Tunneling Device

K.Yuki,Y.Hirai,K.Morimoto,K.Inoue,M.Niwa, and J.Yasui

Semiconductor Research Center, Matsushita Electric Ind. Co.,
3-1-1,Yagumo-nakamachi,Moriguchi, Osaka 570, Japan

A novel Si based double barrier structure (DBS) is newly proposed to study the Si resonant tunneling devices. Anisotropic wet chemical etching and thermal oxidation are adopted to form thin Si single-crystal plate as a quantum well. The fabricated DBS has 43nm wide quantum well and 2.3nm thick potential barriers. The electric characteristic exhibits negative differential conductance (NDC).

1. INTRODUCTION

Since the negative differential conductance (NDC) by the resonant tunneling effect was reported[1], the phenomena have attracted considerable attention with respect to both the fundamental physics and new functional devices. Most works have been so far focused on compound semiconductor devices such as GaAs/AlGaAs and some arithmetic logic circuits have been proposed[2]. On the other hand, to break through the operation limits of the conventional Si devices, researches on the Si based new functional devices such as resonant tunneling devices are strongly required. However, only few works has been done for Si resonant tunneling devices[3][4] because the fabrication technology has not well established for Si double barrier structures .

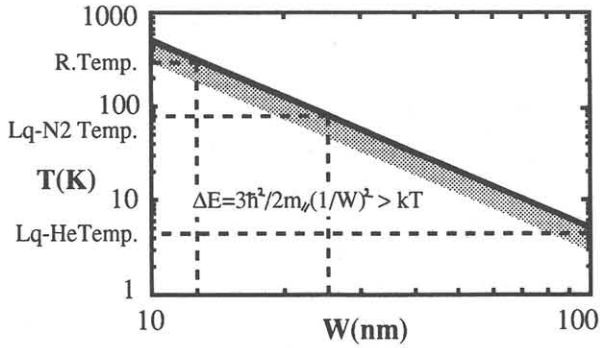


Fig.1. The requirement for the well width W versus temperature T to obtain discrete quantum levels whose separation ΔE is larger than the thermal broadening kT.

2. FABRICATION OF THE DOUBLE BARRIER STRUCTURE

In order to obtain discrete energies in the quantum well, the separation of energies between the lowest two subband must be made larger than the thermal broadening of the quantum states, which is about kT[5]. Based on this idea, the relation between the Si quantum well width W and the maximum temperature T has been calculated, the results of which is shown in Fig.1. As seen in this figure, at liquid He temperature, at least less than 100nm width is needed. Also, flat and clean surface of the well is required to eliminate electron scattering at the boundaries, and also to prevent the further broadening of quantum states. In order to meet these requirements we newly developed novel fabrication method using anisotropic wet chemical etching[6] and thermal oxidation.

The proposed process is shown in Fig.2. After formation of the etching protection mask with a pair of parallel space pattern on the (100) Si substrate, a deep vertical trench is formed on one side of space as shown in Fig.2-(a). Next, anisotropic etching is performed. The etching rate for (111) plane is around 20 times smaller than (100) plane, and the substrate is etched to be V shaped and diamond shaped trenches with (111) plane side walls. Proceeding the anisotropic etching, the Si thin crystal plate with (111) surface plane is formed as shown in Fig.2-(b). After thermal oxidation of the plate surface, the Si quantum well, which is covered with the SiO_2, is formed as shown in Fig.2-(c). Finally, the n+doped Poly-Si is deposited by the CVD

(Chemical Vapor Deposition) and the electrodes are patterned at both sides of the well. The Si double barrier structure with crystal Si quantum well is formed as shown in Fig.2-(d).

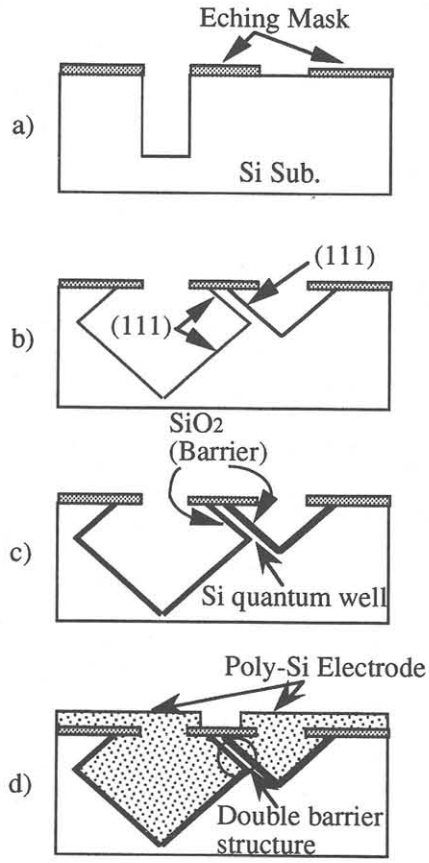


Fig.2 Fabrication process for the Si double barrier structure.

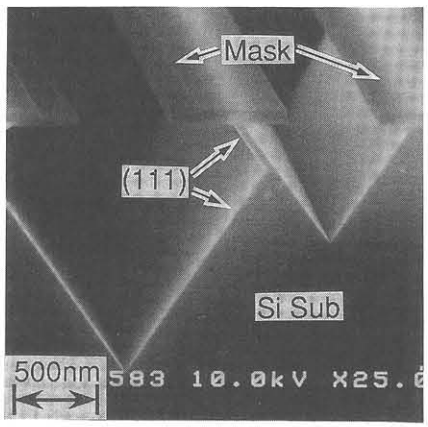


Fig.3 SEM image of the sample after anisotropic etching.

The scanning electron microscopy (SEM) image after anisotropic etching is shown in Fig.3. The V and diamond shaped trenches with (111) surfaces are successfully formed. The surfaces are extremely flat without etching damages. Figure 4 shows the transmission electron microscopy (TEM) image after formation of the barrier structure. In this sample, the well is about 43nm in width and the SiO_2 barrier is about 2.3nm. It is confirmed by the high magnification TEM image that the crystalline quality of the Si quantum well is excellent being almost indiscernible from Si substrate without any damages. Also, the Si/SiO_2 interface is flat. The evaluated roughness by the TEM image is less than than 1nm in Δrms. Using this process, the Si double barrier structure, which has single-crystal Si well and SiO_2 barriers with flat boundary, is successfully obtained using anisotropic wet etching and conventional VLSI process.

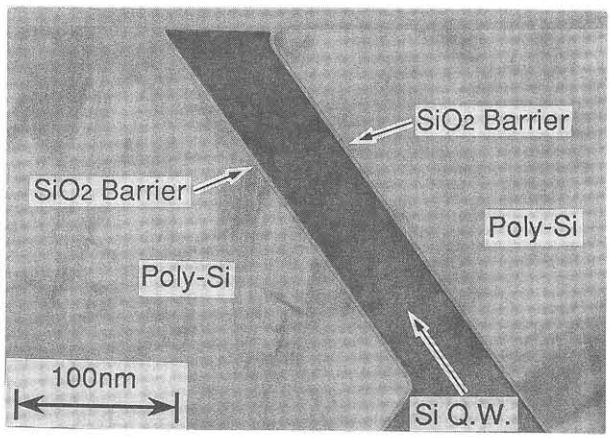


Fig.4. TEM image of the Si double barrier structure. The well width W is 43nm and SiO_2 barrier thickness is 2.3nm. The n doped Poly-Si electrode is formed on the both sides.

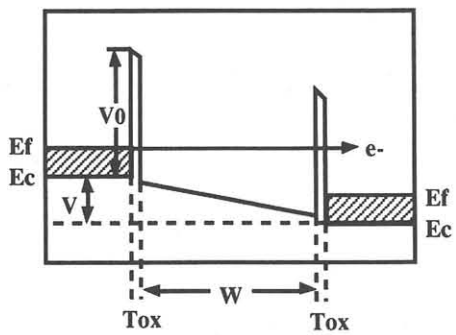
3. ELECTRIC CHARACTERISTICS OF THE DEVICE

The current-voltage characteristics of the resonant tunneling diode by this double barrier structure is evaluated. Instead of evaluating the tunneling current, the electron transmission coefficient (TT^*) through the double barrier structure is calculated based on the conventional model[1]. To simplify the analysis, the electron transmission coefficient at Fermi level is calculated. Also, the potential profile is approximated to be linear to the applied voltage without solving the Poisson's equation as shown in Fig.5-(a). The Fermi energy E_f in the electrode is assumed to be 70meV above the bottom of the conduction band E_c. The calculation result of the transmission coefficient is shown in Fig.5-(b).

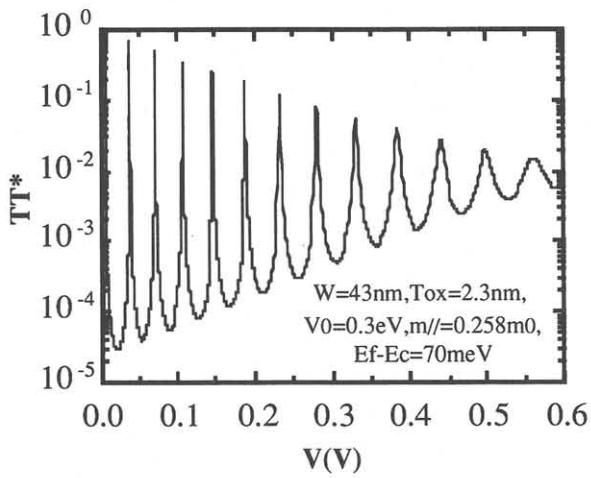
The electrical characteristics is measured at 3.3K. Figure 6 shows the experimental results of the I/V and dI/dV curves. The arrows in the figure show the

estimated current peaks. At present, we can't find negative resistance characteristics. Nevertheless, the negative differential conductance (NDC) can be observed. However, the peak voltages are different from the estimated values. The reasons of the deference are supposed to be as follows; The potential profile would be modulated in the quantum well by the electrons and/or ionized impurities existing in the quantum well, which would cause the shifts of the estimated transmission peaks. Such a band bending would not be negligible when the quantum well width W is large. Also, the energies of incoming electrons from the electrode may distributed over a wider range than the voltage separation between the local peaks, which would lead to the broadening of resonant current peaks.

At present, the origin of the NDC is not clear, but the observed NDC is probably related to the resonant tunneling phenomena by the double barrier structure.



(a)



(b)

Fig.5 (a)Calculation model for the electron transmission coefficient (TT^*). (b)The electron transmission coefficient at the Fermi level energy as a function of the applied voltage.

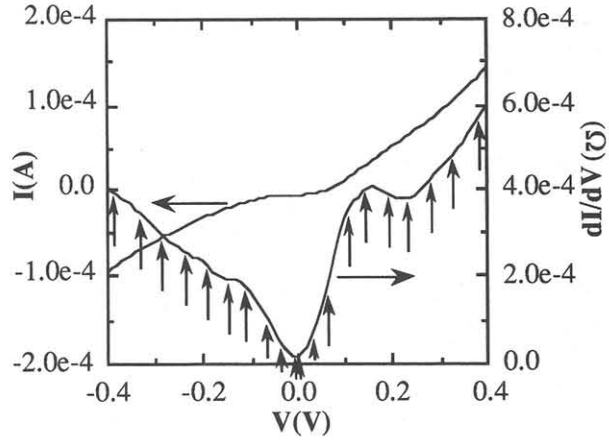


Fig.6 The measured electric characteristics at T=3.3K. The arrows show the predicted peak position by resonant tunneling current. The effective tunneling area of this device is $3.0\times10^{-5}cm^2$.

4. CONCLUSION

We have newly developed a novel Si double barrier structure with fine Si crystal well and Si/SiO2 boundaries, also demonstrated negative differential conductance. This paves the promising way toward the new functional Si devices utilizing quantum effects.

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