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Double-Quantum-Well $Si_{1-x}Ge_x$/Si Electron Resonant Tunneling Diode with a High Peak-to-Valley Ratio at RT

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1. Introduction

Resonant tunneling diode (RTD) quantum devices have attracted much attention as promising devices for future ultra-high-speed and low-dissipation applications. SiGe RTDs have been focused for their potential feasibility of being integrated with Si CMOS circuits [1]. However, only a few simple III-V RTDs have been applied in practice. For quantum devices to be useful, they must operate at room temperature.

In SiGe, RTD structures were first designed for hole tunneling, since it is easier to get large valence band offsets [2-4]. However, the large hole mass also resulted in bad temperature performance for these devices with a peak-to-valley ratio (PVR) of 3 at 10 K. The PVR smeared out at higher temperatures of > 80-100 K. For electron tunneling, Ismail *et. al* have reported a PVR value of 1.2 at RT using a single quantum well (SQW) RTD [5]. So far the highest PVR value at lower temperatures has been 2, the value of which was measured using a SQW RTD at 4.2 K [6,7].

In this paper, we first report the performance of a $Si_{1-x}Ge_x$/Si electron tunneling RTD with a double quantum well (DQW) structure. With the $Si_{1-x}Ge_x$/Si DQW RTDs, we have obtained PVR values as high as more than 7.6 even at RT. The results give rise to great potential to SiGe RTDs for future practical integrated device applications.

2. Device Fabrication

For electron tunneling, type II heterostructures, where the conduction band of SiGe lies above that of Si [8], were formed. It is known that the type II heterostructures are realized by forming an unstrained $Si_{1-x}Ge_x$ layer on a strained Si layer with tensile stress [8,9]. In this case, a strained Si layer surrounded with unstrained $Si_{1-x}Ge_x$ layers functions as a quantum well for electrons. The $Si_{1-x}Ge_x$ layers are provided as barriers for electrons.

In this work, we first applied a double quantum well structure for electrons to $Si_{1-x}Ge_x$/Si electron resonant tunneling diodes (RTD) and compared the performance of a DQW RTD with that of a SQW RTD. These structures were formed on 0.8-1.2 Ω-cm n-type Si(001) substrates using a gas-source MBE (molecular beam epitaxy) technique with GeH_4 and Si_2H_6. Figure 1 shows a schematic of the structure of the $Si_{1-x}Ge_x$/Si DQW RTD. To obtain the unstrained $Si_{1-x}Ge_x$ layer, strain relief $Si_{1-x}Ge_x$ buffer layers were first grown on the substrate. Then the Si strained layer with tensile stress were formed on the strain relief buffer layers. A SQW or DQW structure was coherently formed on the strained Si layer. The well and barrier widths were 50 Å and 30 Å, respectively. Finally a Si capping layer were grown. The Type II band structure is also illustrated in Fig. 1. The compositions of the $Si_{1-x}Ge_x$ layers of the quantum well structures were $Si_{0.7}Ge_{0.3}$ The all layers shown in Fig. 1 were grown with a substrate temperature of 600 °C. Al metal was deposited on the front and back of the substrate and sintered at 400 °C for ohmic contacts.

3. Results and Discussion

Typical I-V curves obtained from the SQW and DQW RTDs are shown in Fig. 2. The measurements were carried out at RT. In the SQW RTD, one clear negative differential conductance (NDC), denoted by P_2, was observed. The PVR value was 1.3, the value of which is very close to the previously reported value of 1.2 which was also measured at RT using a $Si_{0.7}Ge_{0.3}$/Si SQW RTD [5]. In the DQW RTD, two sharp NDCs, denoted by P_{12} and P_{23}, were observed. The corresponding PVR values at RT were ~7.6 and 1.3, respectively. It is noted that the P_{12} PVR value at RT is 4 times as high

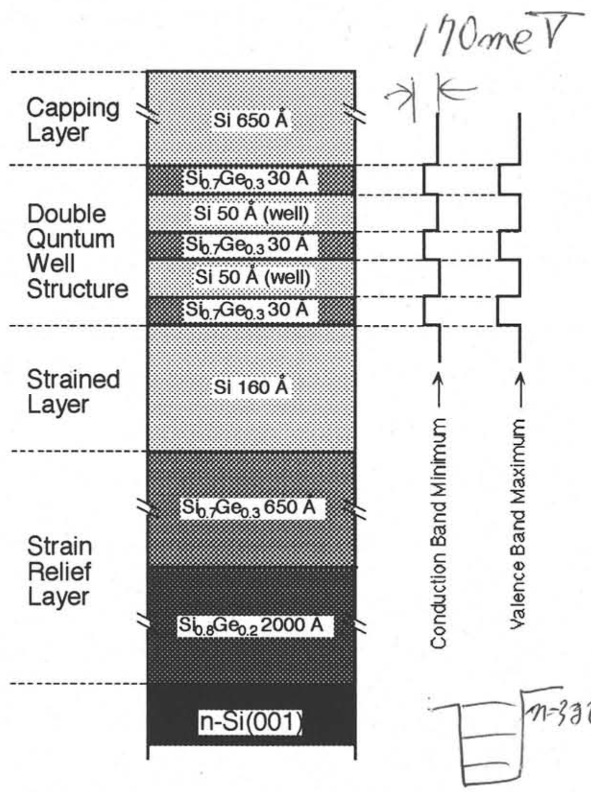

Fig.1 The structure of a double-quantum-well $Si_{0.7}Ge_{0.3}$/Si electron resonant tunneling diode (RTD) and the energy band diagram of the double quantum layers.

as the previously reported highest value of 2 which was measured at 4.2 K using a $Si_{0.65}Ge_{0.35}/Si$ SQW RTD [6,7]. The comparison of these PVR data are summarized in Table I.

Figure 3 illustrates the mechanisms of the first (P_{12}) and second (P_{23}) negative differential resistances shown in Fig. 2. Calculated quantized energy levels for electrons in the wells using the envelope wavefunction method are 11±1, and 42±4, and 91±10 meV for the ground state E_1 and the higher energy states E_2 and E_3 assuming that the conduction band offset is 0.15 ± 0.05 eV [5, 6, 9] and the effective electron mass m^*_z is ~0.98 [6]. The bias voltage ratio for the P_{12} and P_{23} NDC peaks shown in Fig. 2 is ~2. It is easily found from a simple estimation that this bias voltage ratio depends only on the energy difference between quantized energy levels on condition that the two well potentials linearly varies with the electric field intensity applied across the wells. As illustrated

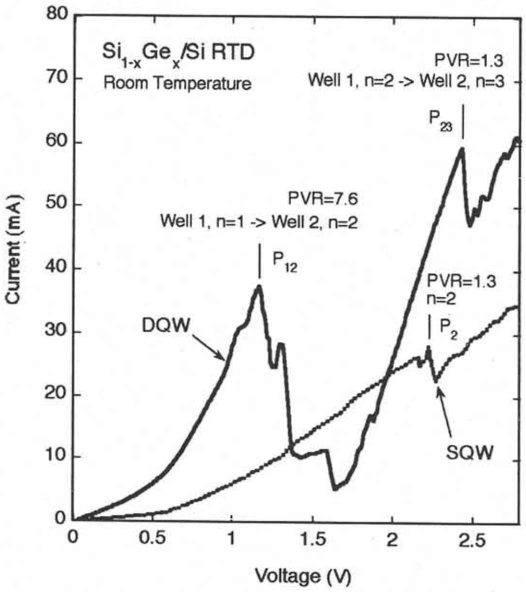

Fig. 2 Typical I-V curves obtained at RT from the SQW and DQW $Si_{0.7}Ge_{0.3}/Si$ electron resonant tunneling diode (RTD) .

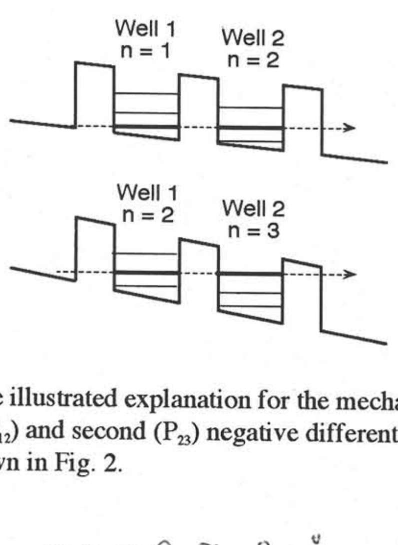

Fig. 3 The illustrated explanation for the mechanisms of the first (P_{12}) and second (P_{23}) negative differential resistances shown in Fig. 2.

Table I Peak-to-valley ratios (PVRs) obtained for $Si_{1-x}Ge_x/Si$ electron resonant tunneling diode (RTD)

Previous Work			This Work	
SQW(RT)	SQW(77K)	SQW(4.2K)	SQW(RT)	DQW(RT)
1.2[5]	1.5[5]	2.0[6]	1.3	7.6/1.3

in Fig. 3, the most probable tunnelings for P_{12} and P_{23} correspond to transitions from E_1 in well 1 (denoted by E_1(W1)) to E_2(W2) and from E_2(W1) to E_3(W2). The ratio of the electric field intensities when the E_1(W1) and E2(W2) levels and the E_2(W1) and E_3(W2) levels are aligned is > 1.6±0.1. Considering the thermionic energy for electrons at RT, the corresponding bias voltage ratio for the P_{12} and P_{23} tunnelings have been estimated to be close to the value of around 2±0.5. This value is in good agreement with the experimental result. The P_2 tunneling in the SQW RTD is assigned to the transition through E_2. It is expected that the E_1 ground state does not contribute to the NDC effect due to its small energy level of 11 m eV far less than the RT thermionic energy, 26 meV. These assignments are also supported by the fact that bias voltages for the P_{23} and P_2 tunnelings are close to each other. Because, if the same E_2(W1) and E_2 levels are related to these transitions, electric field intensities and then bias voltages for these transitions are close to each other.

4. Conclusions

We first apply the double quantum well (DQW) structure to $Si_{1-x}Ge_x/Si$ electron resonant tunneling diode and demonstrate that the $Si_{0.7}Ge_{0.3}/Si$ DQW electron resonant tunneling diode exhibits a high peak-to-valley ratio of more than 7.6 at even RT. The origins of negative differential conductance peaks are well explained with a simple quantum well model. The results are expected to widen the $Si_{1-x}Ge_x/Si$ RTD application researches.

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