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# Hole-Tunneling $Si_{1-x}Ge_x$/Si ASDQW RTD with High Resonant Current and High Peak-to-Valley Current Ratio

Ayaka Shinkawa, Minoru Wakiya, Yuki Maeda, Takahiro Tsukamoto, and Yoshiyuki Suda

Graduate School of Engineering, Tokyo Univ. of Agriculture and Technology
2-24-16 Naka-cho, Koganei, Tokyo 184-8588, Japan
Phone: +81-42-388-7129, E-mail: sudayos@cc.tuat.ac.jp

**Hole-tunneling $Si_{1-x}Ge_x$/Si asymmetric-double-quantum-well resonant tunneling diode (ASDQW p-RTD) was optimized in terms of its structure and fabrication processes with the gas-source molecular beam epitaxy (GSMBE) method. From the aspect of crystallinity, the maximum Ge content was found to be ~0.18. We also designed the p-RTD so that the difference between the barrier height, in the collector side, and the resonant tunneling energy at the resonance voltage became larger. The fabricated $Si_{0.82}Ge_{0.18}$/Si p-RTD exhibited the highest performance with a resonant tunneling current density of 35 kA/cm$^2$ and a peak-to-valley current ratio (PVCR) of 16, with suppression of thermionic emission, which are larger than those reported by others by factors of 1.5 and 7, respectively.**

## 1. Introduction

Hole-tunneling $Si_{1-x}Ge_x$/Si asymmetric-double-quantum-well resonant tunneling diodes (ASDQW p-RTD) have been promising from the aspects of a high-speed device and their process compatibility with Si LSI circuits [1]. The $Si_{1-x}Ge_x$/Si p-RTDs can be formed by $Si_{1-x}Ge_x$ coherent growth on Si substrates without growth layer relaxation introduced by generation of misfit dislocations. Thus p-RTDs are also promising in terms of the performance reproduction. However, so far, the design rules for the structure and fabrication processes have not been fully understood. In this work, we performed investigations on the optimized structure and fabrication processes for the $Si_{1-x}Ge_x$/Si p-RTD.

## 2. Experimental

The structure of the ASDQW p-RTDs in this work is illustrated in Fig. 1. Because of the small barrier height in the $Si_{1-x}Ge_x$/Si material system, we applied the ASDQW, consisting of W1 and W2 well layers and B1, B2, and B3 barrier layers, to control the resonance voltage and obtain the large resonant current with a high peak-to-valley current ratio (PVCR) [2]. The $Si_{1-x}Ge_x$/Si layers were grown on 0.01 ± 0.005 Ω–cm p-type Si(001) substrates by the gas-source molecular beam epitaxy (GSMBE) method with $Si_2H_6$ and $GeH_4$ as resource gasses at a growth temperature of 600 ºC.

## 3. Results and Discussion

*Optimization of Emitter and Collector Fabrication Processes*

The lower intrinsic (i)-Si and i-$Si_{1-x}Ge_x$ were first grown on the substrate as emitter layers and the i-$Si_{1-x}Ge_x$ were grown as a top collector layer. To obtain the low-resistance emitter and collector layers, we optimized the layer thicknesses and annealing temperatures for the adequate impurity diffusion using the composition depth profile analyses. After the $Si_{1-x}Ge_x$/Si layer growth, the sample was annealed at 600 ºC for 20 min to obtain the low-resistance emitter layer by diffusing boron atoms in front of the B1 layer. After forming Al(Si) patterns as the top and bottom electrodes, the sample was annealed at 275 ºC for 7 min to obtain the low-resistance collector layer by diffusing Al atoms in front of the B3 layer.

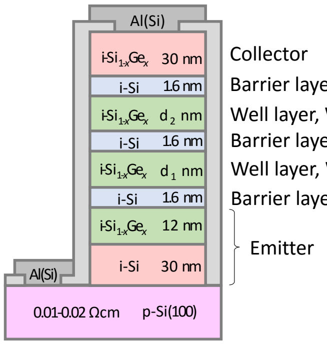


Fig. 1 Structure of hole tunneling SiGe/Si asymmetric double quantum well resonant tunneling dioide (ASDQW p-RTD) of this work.

*Optimization of Barrier Layer Thickness*

The optimum thickness of the barrier layer was investigated. The resonant current increases with decreasing the barrier layer, however, we have found the width of 1.6 nm is the minimum width because the thinner barrier layer causes a deterioration in the crystallinity by generation of island growth.

*Optimization of Ge Composition for Barrier Layers*

The optimum Ge composition ratio $x$ of $Si_{1-x}Ge_x$ well layer was investigated. To suppress the thermionic emission current and obtain high PVCRs for higher-speed RTDs, a higher barrier height induced by larger Ge composition is desirable. The relaxation rate and surface roughness were investigated with $x$ being changed. The results are shown in Fig. 2. We have found that when Ge composition $x$ is not more than 0.18, the relaxation rate and the root mean square (RMS) value of the $Si_{1-x}Ge_x$ layer are under 3% and 1 nm, respectively, with relatively good crystallinity.

*Tested Design Concept for Increasing Resonant Current*

The resonance voltages of p-RTDs were designed on the basis of simulation results by calculation with the Schrödinger equation and box-shape potential wells. Barrier height

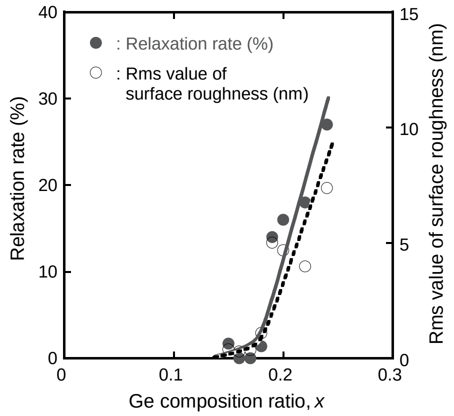


Fig. 2 Relaxation rates and surface RMS values of p-RTD top surfaces formed with different Ge composition ratio, $x$ .

was estimated by the deformation potential method for heavy and light holes [3]. Two types of p-RTDs, RTD1 and RTD2 were designed and fabricated. According to the optimization described above, Ge composition ratio was set at 0.18 and the Si barrier widths were set at 1.6 nm. The widths of W1 and W2 were 4.1 and 2.5 nm for RTD1, and 3.9 and 5.6 nm for RTD2, which were determined on the basis of the preliminary simulation according to the concept described below.

The shifts of barrier heights of the B1, B2, and B3 barriers and the valence band maximum energies $E_{W1}$, $E_{W2}$, $E_{coll}$ for the W1 and W2 well layers and the collector layer and quantized levels for heavy and light holes were calculated with reference to the valence band maximum energies of the emitter layers with increasing applied voltage for the RTD1 and RTD2 and the results are shown in Fig. 3. With these well width designs, the difference between the barrier height of B3 and the resonant tunneling energy, at the resonance voltage, denoted by $\Delta E$ in Fig. 3 was larger for RTD1 than for RTD2.

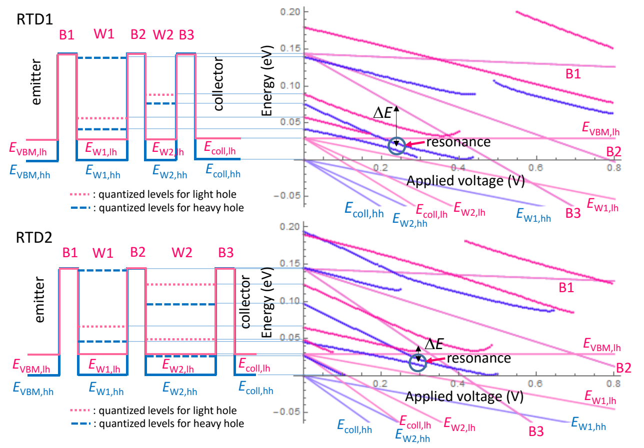


Fig. 3 Quantized level structures and shifts of the quantized levels as a function of applied voltage for RTD1 and RTD2 investigated. In these figures, the upper energy is illustrated to be higher for holes.

*Substantial Improvement in Resonance Performance with RTD1 Compared to RTD2*

RTD1 exhibits a larger resonant current density $J_R$, indicated in Fig. 4, and a higher PVCR than those of RTD2, and

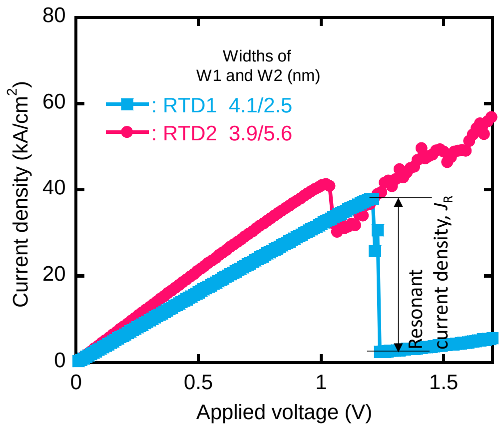


Fig. 4 Current density and applied voltage characteristics obtained for RTD1 and RTD2. The performance is substantially improved with RTD1 which exhibits the suppressed valley current.

the values were 35 kA/cm$^2$ and 7, respectively. These increases are probably due to the suppression of the thermionic emission, because the B3 barrier height with reference to the resonance energy level at the resonance voltage is higher with RTD1 than with RTD2 as shown in Fig. 3. The difference of the resonance voltages between Figs. 3 and 4 are due to the series resistance included in the practical RTD1 and RTD2. The resistance is estimated to be 0.018 mΩ-cm$^2$, obtained by fitting to theoretical curves [4], which causes a shift of ~0.7V. The obtained $J_R$ and PVCR values are also larger than those reported by others by factors of 1.5 and 7, respectively [5], and the $Si_{1-x}Ge_x/Si$ ASDQW p-RTD described in this work exhibits the highest performance so far.

## 4. Conclusions

Hole-tunneling $Si_{1-x}Ge_x/Si$ ASDQW RTD (p-RTD) was optimized in terms of its structure and fabrication processes with the gas-source molecular beam epitaxy (GSMBE) method. From the aspect of crystallinity, the maximum Ge content was found to be ~0.18. We also designed the p-RTD so that the difference between the barrier height, in the collector side, and the resonant tunneling energy at the resonance voltage became larger. The fabricated $Si_{0.82}Ge_{0.18}$ p-RTD exhibited the highest performance with a resonant tunneling current density of 35 kA/cm$^2$ and a PVCR of 16, with suppression of thermionic emission, which are larger than those reported by others by factors of 1.5 and 7, respectively.

## References

[1] H. Hanafusa, N. Hirose, A. Kasamatsu, T. Mimura, T. Matsui, H. M. H. Chong, H. Mizuta, and Yoshiyuki Suda, Appl. Phys. Express **4** (2011) 024102.
[2] Y. Suda and H. Koyama, Appl. Phys. Lett. **79** (2001) 2273.
[3] C. G. Van de Walle and R. M. Martin, Phys. Rev. B **34** (1986) 5621.
[4] T. Okubo, T. Tsukamoto, and Y. Suda, Appl. Phys. Express **7** (2014) 034001.
[5] C. Xiong, Y. Wang, P. Chen, and Z. Yu, Mater. Sci. Semicond. Process. **7** (2004) 379.