SiGe double barrier resonant tunneling diodes on bulk SiGe substrates with high peak-to-valley current ratio

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The authors present high-quality *p*-type SiGe double barrier resonant tunneling diodes obtained from bulk SiGe substrates grown by the multicomponent zone-melting method and by the layer deposition with molecular beam epitaxy. Devices exhibit a high peak-to-valley current ratio up to 8.8 at 4.2 K and a negative differential resistance up to 340 K. The result demonstrates that bulk SiGe substrates have a clear potential impact for fabricating high-performance SiGe heterostructure devices based on quantum transport. © 2007 American Institute of Physics.

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The multicomponent zone-melting (MCZM) method has been developed to grow multicomponent semiconductor bulk crystals with arbitrary compositions. By this method, the growth temperature can be kept constant and the depletion of one constituent component can be prevented.^{1,2} The method is applicable for crystals such as SiGe (Ref. 3) and InGaAs (Ref. 4) which retain complete solubility in both liquid and solid states. In contrast with the bulk substrates grown by conventional methods,^{5–10} our homemade multicomponent semiconductor substrates consist of single crystal domains with uniform compositions and with the size of a few millimeters to centimeters in diameter and are almost free from microscopic structural imperfections.¹¹ These characteristics make our substrates applicable to device developments. To test the quality of bulk SiGe crystals with a high Ge content, we deposited double barrier resonant tunneling diodes (RTDs) by low-temperature molecular beam epitaxy (MBE) on (100)-oriented bulk $\text{Si}_{1-x}\text{Ge}_x$ substrates with x_s equal to ~ 0.9 and characterized the resonant tunneling properties at various temperatures.

We have studied three RTD samples A, B, and C. The layer sequence is shown in Fig. 1(a). RTDs A and B consist of a $\text{Si}_{1-x}\text{Ge}_x$ quantum well with thicknesses equal to 2.5 and 3.5 nm, respectively. The Ge content x of the quantum well, spacer layers, and contact layers was equal to 0.93 (see below), and the Ge content of the barriers was equal to 0.3. The quantum well of RTD C is a 3.5-nm-thick Ge layer. The substrates were semicircle shaped with diameter equal to ~ 15 mm. These were obtained from a bulk crystal grown by using a Ge(100) seed crystal, a polycrystalline Ge for melt, and a Si(100) crystal to feed Si to the melt.¹²

The wafer surface of the SiGe substrates were polished by the chemical-mechanical polishing process and chemically treated in $\text{NH}_4\text{OH}/\text{H}_2\text{O}_2$ solution. Prior to the MBE

growth, substrates were again chemically cleaned and followed by annealing in vacuum at 800 °C for 15 min. The double barrier structures were then deposited at 300 °C. The deposition rates of $\text{Si}_{1-x}\text{Ge}_x$ layers and of $\text{Si}_{1-y}\text{Ge}_y$ barriers were equal to 0.7 and 1.43 Å/s, respectively. 40 s long growth interruptions were inserted at the interfaces between $\text{Si}_{1-x}\text{Ge}_x$ layers and $\text{Si}_{1-y}\text{Ge}_y$ layers for the stabilization of the growth rate after the change of the Si and the Ge flux. p^+ - $\text{Si}_{1-x}\text{Ge}_x$ contact layers were doped by coevaporation of boron at the concentration equal to $1.2 \times 10^{18} \text{ cm}^{-3}$. From the reciprocal space map in the (224) direction, we found that the deposited layers are grown commensurately on the SiGe bulk substrates. The Ge content of the substrate x_s and that of the deposited layer (average value) x were determined by (004) x-ray diffraction; we obtained that x_s is equal to 0.88 ± 0.02 and x is equal to 0.93 ± 0.02 .

From these samples, square-shaped diodes were fabricated. At first, top Al electrodes were patterned by photolithography and lift-off. The sizes of the mesas are 30, 20, 10, and 6 μm . Secondly, using the Al electrodes as the mask, the top-contact layer and the double-barrier structure were patterned by reactive ion etching (RIE) using SF_6 gas. Thirdly, the Al electrodes were patterned on to the exposed bottom contact layer. Fourthly, 500-nm-thick SiN_x insulation layer was deposited at 300 °C by using plasma enhanced chemical vapor deposition. Finally, through holes to the top and the bottom Al electrodes were patterned by photolithography and RIE. Throughout the process, extreme care has been taken to minimize the temperature gradient across the sample substrates to avoid strain relaxation. The processed devices were mounted on ceramic chip carriers. After the wire bonding, the chip carriers were mounted on a variable temperature insert for measurement.

In Fig. 2, two-terminal current-voltage characteristics of 6 μm square mesa devices measured at three different temperatures are shown. Nearly symmetric current-voltage characteristics were observed at all temperatures. For B, total of

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FIG. 1. (Color online) (a) Layer sequence of the p -SiGe double barrier resonant tunneling diode (RTD) structures on bulk SiGe substrates. RTDs A and B consist of 2.5-nm-thick and 3.5-nm-thick Si_{1- x} Ge _{x} quantum well, respectively, with 4-nm-thick Si_{1- y} Ge _{y} barriers clad by p^+ -Si_{1- x} Ge _{x} contact layers, where x is equal to 0.93 and y is equal to 0.3. RTD C consists of a 3.5-nm-thick Ge well. The Ge content x_s of the bulk substrate is equal to 0.88. (b) Schematic band diagram of RTD B calculated at the bias equal to 0.9 V. Only representative states are shown by solid curves. HHn ($n=1,2$) are the two highest heavy-hole (HH) states, HHem is the highest emitter state originated from the HH band, and LH1 is the highest light-hole (LH) state. V-HH, V-LH, and V-SO denote the band edge of the HH band, the LH band, and the split-off (SO) band, respectively, including the effect of strain.

20 devices with various sizes were tested. Among those, nine devices show nearly identical current-voltage characteristics, as the one in Fig. 2 (see also Fig. 3). For A and B, two resonances were observed at low temperatures in both polarities. These are ascribed to the resonant tunneling via the first two quantized states in the quantum well assigned as the first two heavy-hole (HH) state HH1 and the first light-hole (LH) state LH1. The assignment is consistent to a self-consistent 6-band $\mathbf{k} \cdot \mathbf{p}$ theory [Fig. 1(b)].¹³ The precise shape and the oscillation of the current at the bias beyond LH1 resonances are affected by extrinsic and intrinsic bistabilities which have been observed for RTDs with large negative differential resistance (NDR).¹⁴ Detailed comparison of experiment with theory, including the bias- and temperature-dependent accumulation profiles at the emitter, the in-plane momentum dependent tunneling rate, and the nonequilibrium hole transport, is out of the scope of this letter. Here, we point out that the above peak assignment is consistent with the fact that the two peaks move to higher bias (confinement shift) by decreasing the well thickness from 3.5 nm (B) to 2.5 nm (A). The assignment is also consistent with the observation that the separation between the two peaks increases by the increase of Ge content and compressive strain in the well from Si_{0.07}Ge_{0.93} (B) to Ge (C). The larger asymmetry of the current-voltage characteristic in C is likely due to partial islanding in the Ge well enhanced by the strain.^{15,16}

For B shown in Fig. 2(b), we found that the peak-to-valley current ratio (PVR) of the LH1 peak at 4.2 K amounts to 8.0 in negative bias and 7.8 in positive bias. Figure 3 summarizes the LH1 peak properties of B for nine devices at 4.2 K. The highest PVR equal to 8.8 was observed in a 30 μm square mesa device. The peak current divided by nominal device area is approximately constant for each polarity. There is a slight tendency that the valley current per area increases with the decrease of the device size. This indicates that leak current through defects, for example via the sidewall of the etched mesa, partly limits the PVR. Nevertheless, these PVR values are the highest for the resonant tunneling via quasi-two-dimensional states in p -type SiGe RTDs. The highest PVR for a resonant tunneling through the quasi-two-dimensional states in p -type SiGe quantum well previously reported in literature is equal to ~ 5 observed at 4.2 K in 6 μm diameter Si_{0.2}Ge_{0.8}/Si RTDs on Si_{0.5}Ge_{0.5} virtual substrates.¹⁷ The highest reported PVR in p -type SiGe

FIG. 2. (Color online) Current-voltage characteristics of three SiGe RTDs with 6 μm square mesa measured at 4.2, 77 K, and near room temperature. For A and B, two resonances assigned as HH₁ and LH₁ are observed at low temperatures in both polarities. For C, HH₁ peak is observed only at the lowest temperature and in positive bias, and HH₂ is also observed in negative bias. A record PV current ratio of 8.0 is observed in RTD B at 4.2 K in negative polarity. The negative differential resistance of the LH₁ peak remains at and above room temperature for A and B.

FIG. 3. (Color online) Summary of the resonant tunneling characteristics of LH1 peak of RTD B obtained from nine devices with various mesa sizes measured at 4.2 K. The top panel shows the peak-to-valley current ratios. The bottom panel shows the peak and valley current divided by device area for positive (+, empty signs) and negative (–, filled signs) polarities.

RTDs is equal to 12, which was observed at 11 mK in a 480 nm diameter p -Si_{0.83}Ge_{0.17}/Si RTD; however, this resonance is not likely due to the tunneling via the two-dimensional states but is rather ascribed to the tunneling through zero-dimensional states or defects.¹⁸

Figure 2 also shows that the NDR of the LH1 peak remains at 297 K for B and up to 342 K for A. Above 77 K, NDR decreased rapidly because of the increase of the valley current I_v as well as the decrease of the peak resonant current I_p . PVR in negative bias decreased to two at 255 K for A and at 192 K for B, respectively (not shown). I_v is increased by thermally assisted tunneling via excited states and thermal excitation of holes over the barriers.¹⁹ Hence, to suppress the temperature-induced increase of I_v , the use of higher barriers will be required.²⁰ On the other hand, more than a factor of 2 reduction of I_p is due to the temperature-induced increase of the quasi-Fermi energy in the hole accumulation region in the emitter.²¹ Therefore, this can be improved by optimization of the device structure such as the concentration and profile of the contact doping.

The observed stable operation, especially the high PVR, is ascribed to the low defect density of our SiGe bulk substrates and the consecutive high-quality heterostructures. The low defect density enhances the NDR by minimizing the background current due to nonresonant current paths and the level broadening of the quantum states. Therefore, compared with virtual substrates, i.e., strain-relaxed thick films on commercially available Si or Ge substrate, the lack of defects such as threading dislocations and the concomitant fluctuation of the lattice orientation in submicrometer scale appears to be an advantage of our SiGe bulk substrates for fabricating high-performance heterostructure devices based on quantum transport.

In summary, we demonstrated the excellent quality of high Ge-content SiGe substrates grown by MCZM by means

of the temperature-dependent electrical transport characteristics of RTDs deposited by MBE. Our results indicate that PVR at room temperature can be further improved by optimization of the device structure and the device processing. It should be remarked that an efficient resonant tunneling, as is demonstrated here, is a prerequisite to achieve lasing in SiGe electroluminescence devices such as quantum cascade emitters.^{22,23} Such RTDs also have a potential for the realization of Si-based quantum functional devices and circuits at room temperature.²⁴

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