Symmetric Si/$Si_{1-x}Ge_x$ electron resonant tunneling diodes with an anomalous temperature behavior

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We report the fabrication of symmetric, n-type resonant tunneling diodes grown by rapid thermal chemical vapor deposition in the Si/$Si_{1-x}Ge_x$ material system. Up to four resonant features were observed for both positive and negative bias. This is the first time that such highly symmetric features are reported for electron resonant tunneling in the Si/SiGe material system. A peak-to-valley ratio of 2 was achieved at a temperature of 4 K and resonances were observed up to 240 K. An additional peak is observed at low voltages exhibiting an anomalous temperature behavior, disappearing at temperatures below 50 K. Models involving phonon absorption or emitter quantization are proposed to explain this behavior.

The resonant tunneling of electrons and holes has been studied extensively in recent years, especially in III–V material systems. In $Si_{1-x}Ge_x$ heterostructures, resonant tunneling of holes has received the most attention due to the energy band configuration, namely, the relatively large valence band offset of strained $Si_{1-x}Ge_x$ layer grown on Si substrate.[1-3] To achieve electron resonant tunneling, a certain offset in the conduction band is needed. This can be accomplished by exploiting a strained Si/relaxed $Si_{1-x}Ge_x$ heterojunction which can be grown on a relaxed $Si_{1-y}Ge_y$ buffer on a ⟨100⟩ Si substrate. To the knowledge of the authors there has been just one experimental report of the resonant tunneling of electrons in this material system grown by UHV/chemical vapor deposition (CVD),[4] which showed only one resonance at a positive bias point. In this letter we report the observation of up to four resonant features for both positive and negative biases in structures grown by rapid thermal chemical vapor deposition (RTCVD). Models are proposed to explain anomalous temperature behavior of the lowest voltage resonant feature.

The structures were grown by RTCVD[5] on a ⟨100⟩ n-type silicon substrate. A 0.5-μm-thick graded $Si_{1-x}Ge_x$ layer was grown at 625 °C, grading x continuously from 0.0 to 0.35, followed by a 1-μm-thick, n-type doped $Si_{0.65}Ge_{0.35}$ buffer. The buffer was doped $\approx 7\times10^{18}$ cm^{-3} using phosphine as the dopant source. The growth was followed by an *in situ* anneal at 800 °C for 1 h. The defect density measured by TEM on a sample with the same relaxed buffer growth procedure was $\sim 10^7$ cm^{-2}. The double barrier structure was grown on top of the relaxed buffer and consisted of a silicon quantum well (grown at 700 °C) between two $Si_{0.65}Ge_{0.35}$ barriers (grown at 625 °C), sandwiched between 175 Å thick, undoped silicon spacers to prevent dopant diffusion into the double barrier structure. The well widths varied from 20 to 50 Å, while the barrier thicknesses varied from 40 to 70 Å for different samples. On top of the double barrier structure another n-type $Si_{0.65}Ge_{0.35}$ ($\approx$0.1 μm) layer was grown, with the top 300 Å heavily doped ($\approx 10^{20}$ cm^{-3}) to provide ohmic contacts. The desired thicknesses were confirmed to within $\sim$10% by beveling and staining to obtain the growth rates for Si and $Si_{0.65}Ge_{0.35}$ from thicker layers in the sample. The contact metal (Ti/Al) was used as a mask for plasma etching to isolate devices into individual mesas. The contacts were annealed for 20 min in forming gas at 350 °C, and the mesa sidewalls were not passivated. The device areas ranged from 60×60 μm^2 to 130×130 μm^2.

In such a structure, the Si layers are subjected to tensile strain. The strain causes a splitting of the conduction band valleys, such that the bands with the light electron effective mass in the growth direction (fourfold degenerate) move upward while the bands with the heavy effective mass ($m_z^*\approx0.98$, twofold degenerate) move downward. As a result, the twofold conduction band minima lie well below (230 meV) the sixfold conduction band minima of the surrounding SiGe. The conduction band offset is calculated to be 200 meV for our structure, according to the model of Van de Walle and Martin.[6] The observed resonant tunneling is expected to be the tunneling of heavy electrons, and no interaction between heavy and light electrons is expected due to the large conduction band splitting in strained Si. The schematic conduction band diagram of the structure at zero bias is shown in Fig. 1.

We have observed symmetric resonant tunneling of electrons for devices with different well and barrier widths. Peak-to-valley ratios of 2 were observed for the sharpest

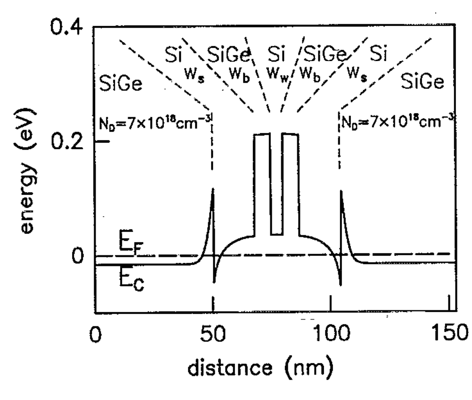

FIG. 1. Schematic conduction band diagram at zero bias. Also shown are the different layers: silicon spacers, w_s=175 Å; $Si_{0.65}Ge_{0.35}$ barriers, w_b=40–70 Å; and Si well, w_w=20–50 Å. The structure is grown on the top of a graded, $Si_{0.65}Ge_{0.35}$ relaxed buffer.

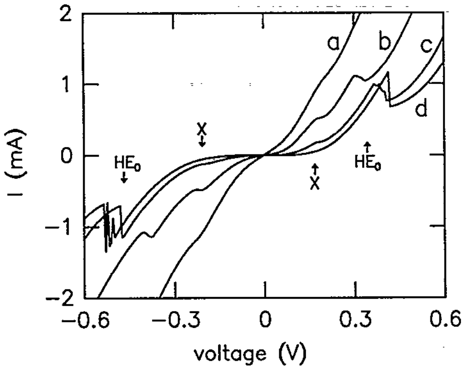

FIG. 2. *I-V* curves of a device with 25 Å well and 60 Å barriers at various temperatures: (a) 220 K, (b) 150 K, (c) 80 K, (d) 4.2 K.

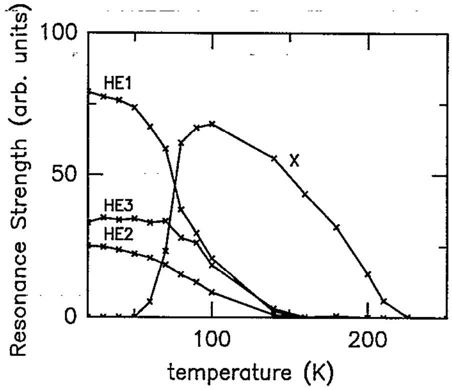

FIG. 4. Temperature dependence of the resonances for the device shown in Fig. 3. The qualitative resonance strength vs temperature clearly shows the disappearance of the lowest bias peak at low temperatures.

resonance at 4.2 K for the devices with well widths of 25 Å and barrier widths of 60 Å (Fig. 2). Resonant features appear at approximately 225 K. At 150 K two distinct peaks are obvious. When the temperature is further decreased the higher bias peak becomes sharper. At 4.2 K the peak-to-valley ratio is at its largest value for the higher bias resonance but the lower bias peak has surprisingly disappeared. The peak current density of the higher bias peak of the device shown in Fig. 2 at 80 K is 20 A/cm^2, and increases to 800 A/cm^2 as the barrier width is reduced to 40 Å (the well width remains constant). Devices with different well and barrier widths all exhibit similar temperature behavior, except that the number and strengths of resonances varies.

For a device with a 50 Å well and 70 Å barriers, at 80 K, there are four distinct resonances observed in the dI/dV curve (Fig. 3). The resonant features are symmetric for positive and negative biases (with respect to the top layer in the structure). In general, the position of resonances for opposite bias polarities are within 15% for all devices. Assuming the depletion region at the collector side stops at the n^+ layer under applied bias, a calculation, assuming constant electric field across the double barrier structure, shows that the Si spacers are symmetric within 25 Å. This implies that there is no excessive phosphorous segregation at the lower n^+ SiGe/Si interface.

A simple first-order model was used to assign resonant

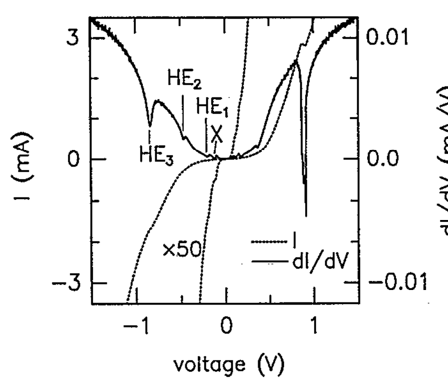

FIG. 3. Typical *I-V* and *dI/dV-V* curves of a 50 Å well/70 Å barriers device with four distinct resonances at 80 K.

features to the calculated states in the well assuming an electron effective mass of 0.98 m_0, no charge buildup in the well, and full depletion of the collector spacer. For the device of Fig. 3 the calculated biases for the four resonances are 42, 165, 369, and 627 mV, for the ground state, first, second, and third excited state in the well, respectively (HE_0–HE_3). The measured bias points for peak positions for several devices were 112–120, 162–180, 365–400, and 700–900 mV, which suggests that the three higher bias resonances are associated with tunneling to the HE_1, HE_2, and HE_3 states. Since the ground state energy level in the well is calculated to be only 11 meV and some initial bias to form an accumulation layer is required, it is indeed possible that the resonance to the ground level might not be observed. The lowest bias resonance (labeled *X* in Fig. 3), however, does not fit into the first-order model.

Figure 4 shows the temperature dependence of the resonances for the same device. The resonance strength is plotted vs temperature for the four resonances at negative biases, as the difference between the local maximum and minimum values of dI/dV divided by the local maximum value at the particular resonance. This is used in this plot to show the qualitative temperature dependence of the resonances, since not all the resonant features exhibit clear peaks in the *I-V* characteristics. When decreasing the temperature from 300 K, the lowest bias resonance always appears first (220–250 K), followed by higher bias resonances. All the resonances become stronger with the decrease in temperature due to the suppression of the background current (thermionic current component and scattering effects). When the temperature is further decreased below 150 K the peaks associated with the calculated levels in the well become even stronger, as expected, but the lowest bias peak has a maximum at a certain temperature ($\approx$110 K) and then decreases, totally disappearing at temperatures below 50 K. A similar plot is obtained from the positive bias resonances. All the samples exhibit qualitatively the same temperature behavior, regardless of the well and barrier widths, the number and the strengths of the resonances. The peak temperature of the lowest resonance varies in the range 100–150 K for different samples,

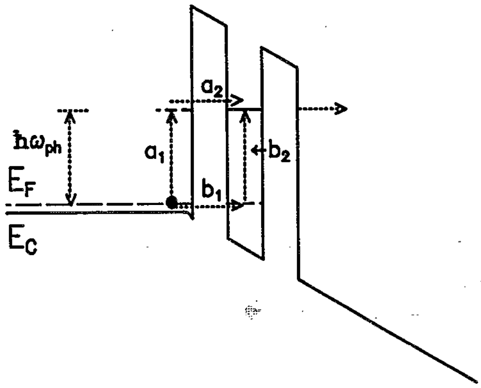

FIG. 5. Schematic diagram of phonon-absorption-assisted tunneling indicating phonon absorption prior to tunneling (path a_1–a_2) and after tunneling (path b_1–b_2).

while the higher lying resonances become monotonically stronger at low temperatures. To our knowledge, this is the first time that such an anomalous temperature dependence of a resonant peak has been reported.

A first possible explanation involves the quantization of levels in the accumulation layer expected to form in the emitter [assuming two-dimensional (2D) to 2D tunneling]. At low temperature, only the ground state in the emitter would be occupied, but at high temperatures tunneling could also occur from thermal electrons in the first excited state, yielding a low bias replica from the emitter ground state resonance. For a given bias, one can calculate the electric field and hence the charge and the levels in the emitter. For the HE_1 resonance, a separation of 11.8 meV between the first two emitter states is expected using a triangular well model, but for the HE_2 resonance a much larger separation of 21.5 meV is calculated, explaining why no replicas are observed for the high energy features. Note that in III–V systems, it would be harder to detect this behavior due to the light electron effective mass, which would further separate emitter states.

A second model for the low bias feature is tunneling via absorption of momentum conserving phonons (Fig. 5) to yield a low bias replica. The twofold degenerate conduction band minima in silicon lie at the $\Delta-$ point ($k_z \approx \pm 0.85\pi/a$, where z is the tunneling direction). This enables phonon-assisted Umklapp scattering from one valley to another during the tunneling process. The transverse ($k_\perp$) momentum could still be conserved while the phonon contibutes to k_z, $q=2k_z+G\simeq 0.3\pi/a$, which would correspond to an energy of ≈ 13 meV for transverse acoustic phonons in silicon.[7] Phonon absorption would give a peak in the I-V curve corresponding to an energy of 13 meV below the true state, which corresponds to a bias of ≈ 50 mV lower than that for the no-phonon resonance in our devices. This resonance would also increase strongly with the phonon population and hence temperature. In the device of Fig. 3, the bias shift was 50–60 mV at 80 K for the HE_1 peak, surprisingly well in agreement with prediction. Further temperature dependent measurements of tunneling current at the lowest bias resonance showed an agreement with phonon energies of 12–16 meV (close to predicted 13 meV), supporting the phonon-absorption-assisted model.[8] That this feature is not observed for higher resonant levels is possibly due to the significant increase in the background current at higher biases.

There has been evidence of tunneling by longitudinal optical phonon emission in III–V material systems.[9] In this case the high energy replica is much weaker ($\approx 10\times$) than the no-phonon tunneling. No high energy replicas, corresponding to phonon-emission-assisted tunneling were observed in our structures. This can be understood by examining the allowed paths in Fig. 5. For the proposed phonon-absorption-assisted process the electron-phonon interaction could first occur in the emitter, followed by tunneling (path a_1–a_2), or the tunneling could occur first with the phonon-absorption occurring in the well (path b_1–b_2). If the electron-phonon interaction is restricted to the well (path b_1–b_2), the emission and absorption-assisted tunneling processes should have comparable strengths.[10] However, due to the lower effective tunneling barrier, it is expected that the a_1–a_2 process is stronger than b_1–b_2. The fact that the intermediate state for a_1–a_2 path may be a "real" state, as opposed to a "virtual" state for b_1–b_2, would strongly favor the a_1–a_2 path. Hence, it is reasonable that phonon-emission-assisted tunneling is not observed.

In summary, we have demonstrated highly symmetric electron resonant tunneling in Si/SiGe material system grown by RTCVD and observed up to four resonances. An anomalous temperature behavior for a low bias resonance has been observed which may be due to either phonon-absorption-assisted tunneling or quantization of emitter states.

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