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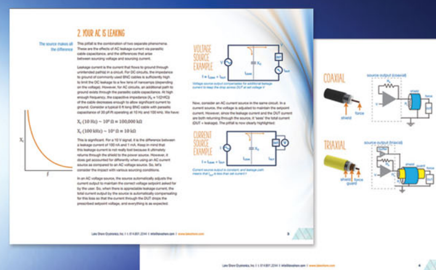

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Resonant tunneling diodes made up of stacked self-assembled Ge/Si islands

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Multiple layers of self-assembled Ge/Si islands are used for resonant tunneling diodes (RTDs). The extremely closely stacked Ge nanostructures form vertical channels with energetically deep thermalization layers and high Si double barriers. Two resonances are found in the RTD current–voltage curve, which are attributed to the heavy-heavy hole (hh) and heavy-light hole (lh) transition. The lh resonance shows negative differential resistance up to 50 K. With increasing magnetic field, the lh resonance slightly shifts to higher voltages. © *2000 American Institute of Physics.* [S0003-6951(00)01951-3]

Self-assembled Ge/Si islands have been of broad interest during the last years and a lot of work has been put into their structural,[1–4] vibrational,[5] optical,[4,6–9] and electronic investigation.[10] Despite the large effort to understand their fundamental properties, devices incorporating Ge/Si islands as active material are only scarcely found. Resonant tunneling diodes (RTDs) with pseudomorphic SiGe/Si quantum wells on Si substrates are commonly described in the literature.[11–13] However, their preformance is rather poor, yielding negative differential resistance (NDR) only up to temperatures of about 77 K. Valence band (VB) offsets of typical RTDs are about 200 meV (Ge concentrations of 20%) and thermal quenching plays a major role at higher temperatures. In this letter we introduce a new concept for resonant tunneling diodes, which makes use of self-assembled Ge islands. First results of an island based RTD are presented. The purpose of the concept is twofold: First, the large valence band offsets of Ge islands are used to create deep Ge rich vertical channels with high Si double barriers. Second, vertically self-aligned Ge/Si island stacks offer the possibility of perfect side passivation, since they are coherently embedded in the Si matrix.

Figure 1(a) shows a cross-sectional transmission electron microscopy (TEM) image of a typical active layer arrangement in quantum well RTDs. Two thick $Si_{1-x}Ge_x$ quantum wells at the bottom and the top serve as thermalization layers for holes. The actual RTD is created by a thin $Si_{1-x}Ge_x$ quantum well, sandwiched between two Si barriers. The schematic band edge alignment for the VB is given next to the TEM image.

A different concept is presented in Fig. 1(b). It is based on the vertical self-alignment of closely stacked Ge/Si islands.[14–18] In this case the thermalization layers are created by very closely stacked Ge islands yielding small minibands due to strong electronic carrier coupling. The two Si barriers are formed by leaving a slightly thicker spacer layer between the fifth and sixth as well as the sixth and seventh island layer. The schematic band edge alignment (without bias and doping) yields much larger valence band offsets than for the quantum well case. A slight modification of this concept can be found in Fig. 1(c), where the first two island layers are substituted by a thick SiGe quantum well.

We concentrate our tunneling experiments on one sample which was grown by solid source molecular beam epitaxy. The exact growth procedure follows the concept of Fig. 1(c)-with five instead of nine island layers: On a p^+Si(001) substrate a 100 nm Si:B $(1\times10^{19}\,\mathrm{cm}^{-2})$ layer is grown followed by a 12 nm thick $Si_{0.82}Ge_{0.12}$ quantum well. After that a stack of five bilayers of 6 ML Ge and Si layers is deposited, where the Si spacer layer between the first and second and second and third island layer is 9 nm and the other Si spacers are only 5 nm thick. The structure is finished with a 150 nm thick Si:B $(1\times10^{19}\,\mathrm{cm}^{-2})$ cap. The growth temperature for the Ge islands was 600 °C, resulting in low density and large Ge islands with diameters of about 80 nm.[4] Single embedded layers of such islands emit at 0.77 eV. Neglecting strain induced electron localization this yields a VB offset of about 400 meV. The sample is processed into mesas. We use optical lithography and wet-chemical etching with HNO_3:HF. A typical pillar is given in Fig. 2(a). Pronounced underetching is evident. Small dips in the sidewall indicate different etching rates for the Si and SiGe epilayers. The presented mesa is 400 nm wide. For such diameters we expect only a few island stacks in the mesa. Large area Ti/Au contacts are then evaporated onto a polymide passivated surface [see Fig. 2(b)]. Electrical measurements are carried out in a ^{3}He evaporation cryostat equipped with a 12 T magnet. The direction of the current flow through the RTD is indicated in the inset of Fig. 3.

The $I-V$ curve of the RTD for positive bias is presented in Fig. 3 (solid curve) and shows two resonances, one at 0.49 V, which exhibits negative differential resistance and a sec-

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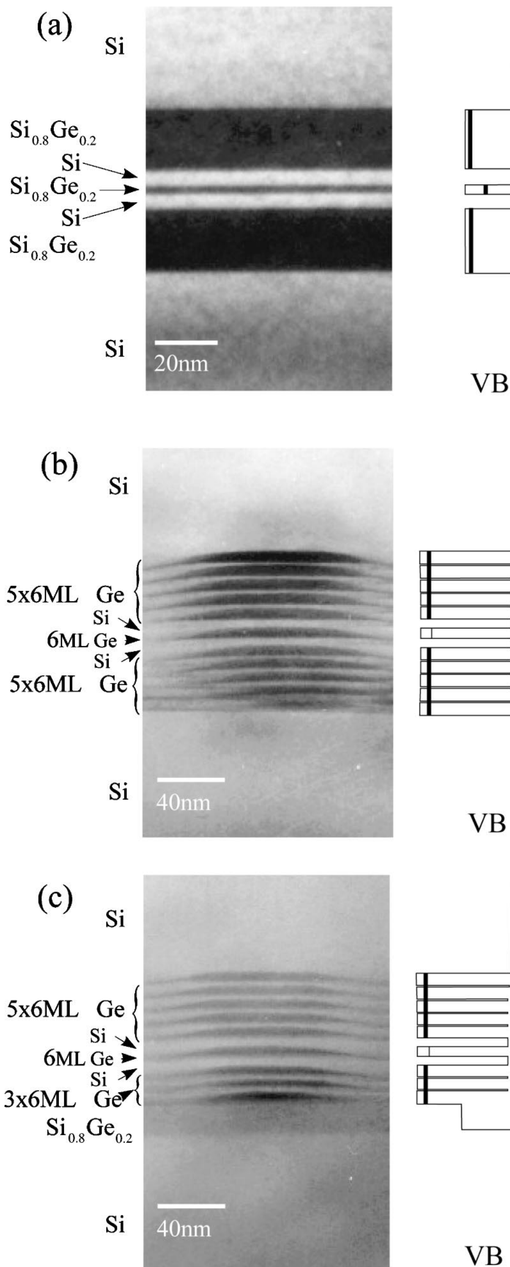

FIG. 1. Cross-section TEM images illustrating three different approaches to realize resonant tunneling diodes based on the SiGe material system. Schematic band alignment without doping and bias is shown next to the TEM images. (a) Shows the conventional quantum well case, whereas in (b) and (c) Ge islands are used for the thermalization layers and the resonant tunneling structure.

ond shoulder at about 0.34 V. The two features can be explained by resonant tunneling of hhs through the hh and lh subbands of the middle Ge island. The $I-V$ characteristic agrees with those observed for conventional RTDs using Si/

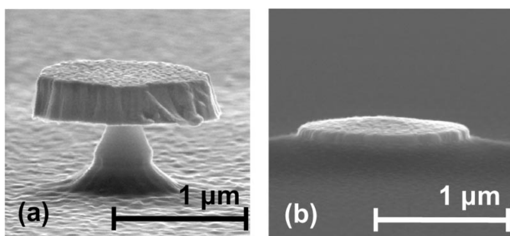

FIG. 2. (a) Wet-chemically etched mesa, (b) buried by polymid.

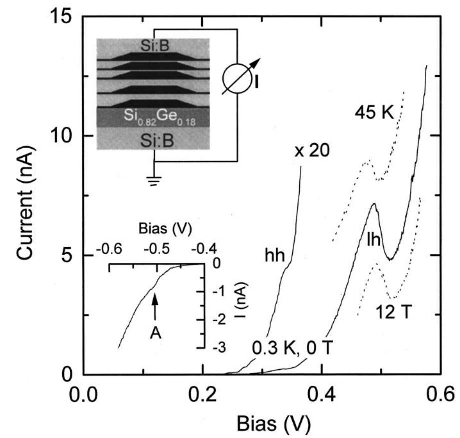

FIG. 3. Three $I-V$ curves of the RTD for different temperatures and magnetic fields. The solid line shows the measurement at 0.3 K without magnetic field. The lower dotted curve is taken at 0.3 K and 12 T and the upper dotted curve was recorded at 45 K without magnetic field. The lower left inset shows the $I-V$ characteristic for negative bias (0.3 K without magnetic field). The upper left inset is a schematic illustration of the RTD.

SiGe quantum wells.[12] Figure 3 also shows (upper dotted curve) that NDR persists for temperatures larger than 45 K. The peak to valley current ratio (PVCR) as a function of temperature is given in Fig. 4(a). At 0.3 K the PVCR is 1.5, whereas at 60 K only a shoulder is resolved in the $I-V$ characteristic.

The $I-V$ curve around the hh–lh resonance for a magnetic field $B=12\,\mathrm{T}$ is given in Fig. 3 (lower dotted curve). The magnetic field is applied parallel to the current. There is a slight shift to higher voltages with increasing B as illustrated in Fig. 4(b). The magnetic field constrains the electronic states into Landau levels, which split as $\Delta E \sim B/m_{\mathrm{eff}}$, where m_{eff} is the effective mass. Since the effective masses are different in the emitter (heavy holes) and in the middle island (light holes) the whole resonance is expected to shift linearly with increasing B.[12] We find a shift of 12 mV for $B=12\,\mathrm{T}$, which is similar to values reported for quantum well based RTDs. In Ref. 12 for example a shift of 10 mV at 12 T was found. A slightly nonlinear dependence

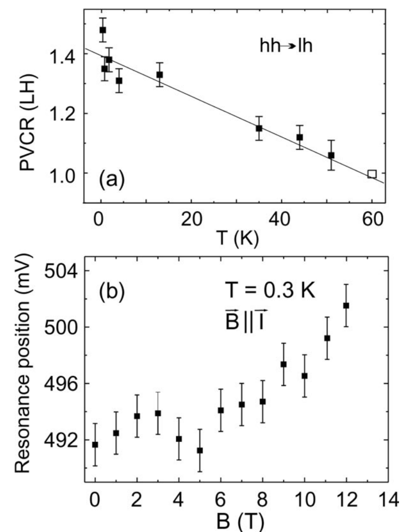

FIG. 4. (a) Peak to valley current ratio (PVCR) as a function of temperature. (b) Resonance position of the hh–lh resonance as a function of magnetic field applied parallel to the current.

for magnetic fields smaller than 5 T is observed in our structure as well as in the QW RTD in Ref. 12. The similarity between our island and the QW RTDs suggests a two-dimensional density of states in the Ge islands. This is a reasonable assumption since the lateral extension of the islands is much larger than the de Broglie wavelength of charge carriers in the semiconductor.

It is noteworthy that our $I-V$ curve is not symmetric around zero bias and only shows a very weak resonance at -0.5 V (marked as A in the lower-left inset of Fig. 3). We attribute this asymmetry to the pronounced nonsymmetric shape and alloy profile of the Ge islands (see Fig. 1). This leads to differently thick Si barriers on the emitter and collector side and destroys the symmetric behavior of the resonances in the $I-V$ curve.

Although our first results look very promising we point out some problems faced during the fabrication of such RTDs: An ideal RTD would be based on a single island stack. For postepitaxial processing the position of this specific island stack must be precisely known. Consequently, controlled lateral ordering of self-assembling islands is an important prerequisite for further improvement of the RTD's $I-V$ characteristic. Recently, we showed that the degree of materials intermixing in upper island layers is more pronounced.[9,19] Additionally, penetrating strain fields and different shapes and sizes of buried islands[16–18] are likely to modify the electronic band structure in the island stacks and in the sandwiched Si barriers. These effects make it difficult to produce vertically homogeneous islands and hence to evaluate the exact band edge alignment. On the other hand, it is well known from QW RTDs that a careful tuning of the band edge alignment is essential to obtain good device performance. Hence, the fundamental electronic properties of Ge/Si island stacks need to be investigated further to improve the RTD results presented in this letter.

In conclusion, we have introduced a concept to fabricate RTDs based on stacked Ge/Si islands. The concept exploits the effect of vertical self-alignment and creates vertical Ge channels with larger valence band offsets than in conventional Si/SiGe quantum well RTDs. Our RTD sample shows pronounced resonance peaks in the $I-V$ curve, which are attributed to the hh and lh resonant tunneling currents. The lh resonance is distinct and exhibits negative differential resistance for temperatures up to 50 K. Magnetic field dependent measurements suggest a 2D density of states in the Ge islands. Problems in the fabrication of homogeneous islands are addressed.

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[1] G. Medeiros-Ribeiro, A. M. Bratkovski, T. I. Kamins, D. A. A. Ohlberg, and R. S. Williams, Science **279**, 353 (1998), and references therein.
[2] S. Christiansen, M. Albrecht, and H. P. Strunk, Appl. Phys. Lett. **64**, 3617 (1994).
[3] M. Goryll, L. Vescan, K. Schmidt, S. Mesters, H. Lüth, and K. Szot, Appl. Phys. Lett. **71**, 410 (1997).
[4] O. G. Schmidt, C. Lange, and K. Eberl, Appl. Phys. Lett. **75**, 1905 (1999).
[5] J. L. Liu, G. Jin, Y. S. Tang, Y. H. Luo, and K. L. Wang, Appl. Phys. Lett. **76**, 586 (2000).
[6] H. Sunamura, N. Usami, Y. Shiraki, and S. Fukatsu, Appl. Phys. Lett. **66**, 3024 (1995).
[7] L. Vescan and T. Stoica, J. Lumin. **80**, 485 (1999).
[8] V. Le Thanh, P. Boucaud, D. Debarre, Y. Zheng, D. Bouchier, and J.-M. Lourtioz, Phys. Rev. B **58**, 13115 (1998).
[9] O. G. Schmidt and K. Eberl, Phys. Rev. B **61**, 13721 (2000).
[10] T. Meyer, M. Klemec, and H. von Känel, Phys. Rev. B **60**, R8493 (1999).
[11] H. C. Liu, D. Landheer, M. Buchanan, and D. C. Houghton, Appl. Phys. Lett. **52**, 1809 (1988).
[12] G. Schuberth, G. Abstreiter, E. Gornik, F. Schäffler, and J. F. Luy, Phys. Rev. B **43**, 2280 (1991).
[13] A. Zaslavsky, D. A. Grützmacher, S. Y. Lin, T. P. Smith III, R. A. Kiehl, and T. O. Sedgwick, Phys. Rev. B **47**, 16036 (1993).
[14] V. Rahmati, W. Jäger, H. Trinkaus, R. Loo, L. Vescan, and H. Lüth, Appl. Phys. A: Mater. Sci. Process. **62**, 575 (1996).
[15] A. A. Darhuber, P. Schittenhelm, V. Hol, J. Stangl, G. Bauer, and G. Abstreiter, Phys. Rev. B **55**, 15652 (1997).
[16] E. Mateeva, P. Sutter, J. C. Bean, and M. G. Lagally, Appl. Phys. Lett. **71**, 3233 (1997).
[17] O. Kienzle, F. Ernst, M. Rühle, O. G. Schmidt, and K. Eberl, Appl. Phys. Lett. **74**, 269 (1999).
[18] O. G. Schmidt, O. Kienzle, Y. Hao, K. Eberl, and F. Ernst, Appl. Phys. Lett. **74**, 1272 (1999).
[19] O. G. Schmidt, K. Eberl, O. Kienzle, F. Ernst, S. Christiansen, and H. P. Strunk, Mater. Sci. Eng., B **74**, 248 (2000).