High peak-current-density strained-layer $In_{0.3}Ga_{0.7}As/Al_{0.8}Ga_{0.2}As$ resonant tunneling diodes grown by metal-organic chemical vapor deposition

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Peak current densities two times higher than the best values reported for GaAs-based resonant tunneling diode (RTD) structures have been obtained from metal-organic chemical-vapor deposition (MOCVD)-grown deep-quantum-well strained-layer $In_{0.3}Ga_{0.7}As/Al_{0.8}Ga_{0.2}As$ RTDs. By growing on nominally exact (100) $+/-0.1°$ GaAs substrates, we have been able to obtain smooth interfaces between the strained-layer $In_{0.3}Ga_{0.7}As$ quantum well and $Al_{0.8}Ga_{0.2}As$ barriers, which, in turn, enabled us to benefit from resonant tunneling through the *second* resonant energy level of $In_{0.3}Ga_{0.7}As/Al_{0.8}Ga_{0.2}As$ structures. Peak current densities in excess of $300\,kA/cm^2$, and peak-to-valley current ratios as high as 3:1, at 300 K, have been obtained from structures with 14-Å-thick barriers and a 57-Å-thick well. © *1997 American Institute of Physics.*
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Currently, resonant tunneling diodes (RTDs) are the widest bandwidth semiconductor devices with gain, which have been used to build microwave oscillators with oscillation frequencies in excess of 700 GHz,[1] trigger circuits operating up to 110 GHz,[2] and a wide range of high-speed logic and switching circuits.[3–5] For the above applications the peak current density (PCD) and the current peak-to-valley ratio (PVR) are the two major figures of merit.[2,6] Also, the choice of material system is of great importance. GaAs-based RTDs are favored over GaSb- and InP-based structures for practical applications due to the maturity of growth and material processing techniques as well as the possibility of integration with other high-speed devices.[7] The best reported PCD value for GaAs-based RTDs[8] is 140 kA/cm^2, achieved from a Schottky-collector AlAs/GaAs structure having a PVR of 2:1. As for RTDs grown by the metal-organic-chemical-vapor deposition (MOCVD) technique, the PCD values reported[9] are at best 96 kA/cm^2. Here we report on MOCVD-grown GaAs-based RTDs operating at room temperature with PCDs in excess of 300 kA/cm^2 and PVRs as high as 3:1, made possible by resonant tunneling through the second energy level of a deep quantum well in a strained-layer structure with smooth quantum-well interfaces.

The initial measurements done by Broekaert *et al.*,[10] show that, in an $In_{0.53}Ga_{0.47}As/AlAs/InAs$ structure grown on InP substrate, the PCD for the resonant tunneling through the second energy level is almost ten times greater than the PCD associated with the first energy level for the same structure. However, the peak voltage for the second resonant energy level is so high ($\sim$4.1 V) that it makes the use of tunneling through the second level highly impractical for any application. A later report by Mehdi *et al.*[6] shows that by using a deep quantum well and adjusting the second resonant energy level to the bottom of conduction band, it is possible to obtain higher PCD values at low peak voltages compared to the conventionally designed RTDs. However, PVRs measured for such structures did not exceed 2:1 at room temperature. Reports on GaAs-based strained-layer InGaAs quantum-well RTDs[11,12] display either low PVRs: $\leq 2:1$, at 100 K for structures based on resonant tunneling through the second energy level,[11] or low PCD values ($\sim 50\,kA/cm^2$) for conventional ones based on tunneling through the first energy level.[12] Researchers were able to obtain relatively high (i.e., 125 kA/cm^2) PCD values for strained-layer GaAs-based RTDs only by using molecular beam epitaxy (MBE) to grow complex structures based on highly strained $(InAs)_M/(GaAs)_N$ short-period multiple-quantum-well regions.[13]

In order to take advantage of resonant tunneling through the second energy level in GaAs-based RTDs, our RTD structure consists of two $Al_{0.8}Ga_{0.2}As$ barriers and a strained-layer $In_{0.3}Ga_{0.7}As$ quantum well (Fig. 1). The RTD structure is separated from doped layers by a 100-Å-thick intrinsic spacer layer on the emitter side and a 300-Å-thick intrinsic spacer layer on the collector side, which reduce the intrinsic capacitance of the device. The thickness of barriers is 14.5 Å to obtain a high peak current density. Figures 1(a) and 1(b) show a schematic of the device epitaxial structure and the corresponding band diagram in unbiased condition, respectively. In order to determine the thickness of the well required to adjust the second resonant energy level close to the edge of the conduction band at the emitter side, a global-transfer-matrix method is used, assuming ''unpopulated'' quantum-well levels. That is, we do not consider the perturbation of the second energy level due to band bending in the quantum well when the ground level is partly populated, because, for the *extreme* case of the Fermi level being aligned with the second level (which means maximum charge accumulation in the $n=1$ level), we calculate that the second level displacement with respect to the unpopulated case is at most 10%. Figure 2 shows the peak current density and peak voltage of the above structure as a function of well width. It can be seen that for a 57-Å-thick well a peak current density in excess of 300 kA/cm^2 at a peak voltage of $\sim$1.4 V can be obtained. Also, the well thickness should be below the criti-

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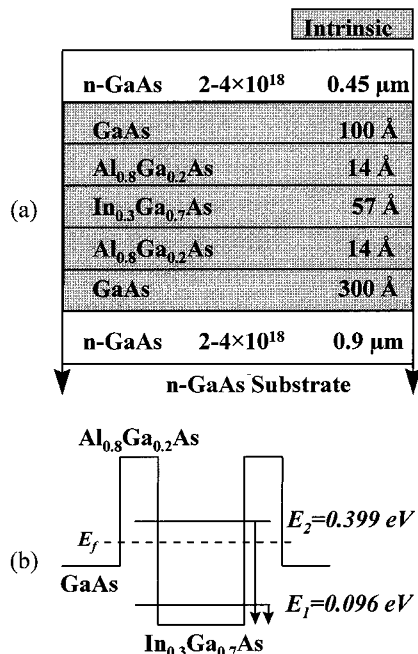

FIG. 1. (a) Schematic view of the grown RTD structure; (b) energy band diagram of the RTD structure, E_f is the Fermi level (assuming unpopulated energy levels at zero bias).

cal value for $In_{0.3}Ga_{0.7}As$ grown on GaAs substrate (<100 Å).

The RTD structure is grown using low-pressure (50 mbar) metal-organic-chemical-vapor deposition (LP-MOCVD) in an Aixtron A-200 system at a growth temperature of 700 °C and a V/III ratio of 100. The group III sources are trimethylgallium and trimethylaluminum. The group V source is arsine with silane used as an n-type dopant. Prior to growth of the RTD structure, the solid composition (x) of $Al_xGa_{1-x}As$ was measured using x-ray diffraction, as a function of the aluminum gas-phase mole fraction. Growth rates were obtained from film-thickness measurements using scanning electron microscopy. Similarly, the solid composition (y) of $In_yGa_{1-y}As$ was determined from x-ray diffraction rocking curve measurements on thick (relaxed) layers. To improve the quantum-well interfacial morphology, RTD structures were grown on nominally exact $(100)+/-0.1°$ GaAs substrates.[14] The reason for selecting such a substrate orientation was that studies at UW-Madison of strained-layer InGaAs quantum-well structures, via atomic force microscopy (AFM),[14] indicate that growth using on-orientation substrates significantly improves the interfacial structure by eliminating step-bunching. In turn, scattering of injected electrons by rough interfaces is avoided,[15] thereby allowing high PVRs at room temperature.

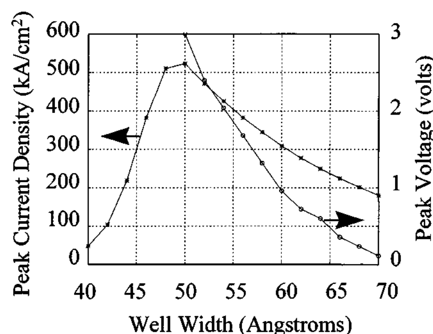

FIG. 2. Calculated peak current density (stars) and peak voltage (blank circles) as a function of well width for the structure shown in Fig. 1.

After the growth of the RTD structure, the layers thicknesses were confirmed by using high-resolution TEM lattice imaging (Fig. 3); it is clear that abrupt interfaces can be obtained by LP-MOCVD in the A-200 system. The device fabrication starts with the deposition of the top metal contact by e-beam metal deposition. For ohmic contact, Ge/AuGe/Ni/Au is deposited. Then, the metal film is patterned to $3\times3\ \mu m^2$ dot contacts by liftoff. By using wet chemical etching, $6\times6\ \mu m^2$ mesas are etched around the contacts. After covering the whole wafer with 1000-Å-thick SiO_2 film as an isolation layer, $3\times3\ \mu m^2$ windows are opened on top of the buried contacts. Then, a second metalization, composed of Ti/Pt/Au layers, is deposited on the wafer. After lapping and bottom-side metalization, the wafer is diced into devices.

Figure 4 shows the current density versus voltage characteristic of a $6\times6\ \mu m^2$ device measured by a Tektronix 571 curve tracer at room temperature. As the current-voltage ($I-V$) curve shows, the device turns on at zero voltage and the current increases linearly to the peak which basically indicates that the resonant energy level is properly aligned with the edge of GaAs conduction band. The peak current density of the device exceeds 300 kA/cm² which, to the best of our knowledge, is more than two times higher than the PCD values reported for GaAs-based RTDs,[8,13] and more than three times higher than the PCDs obtained for any type of MOCVD-grown RTDs.[9] Since, the peak current density obtained here is much higher than the peak current density of conventional GaAs-based structures with barriers and a well of the same thicknesses (e.g., the structure reported by Ozbay *et al.*[2]) it appears obvious to us that, in agreement with our calculations, tunneling occurs through the second energy level. Also, notice that the PCD for a similar InGaAs well structure,[12] but based on tunneling through the first energy level, is six times lower than the value obtained here.

The peak voltage is around 1.2 V, which could be reduced to less than 1 V by increasing the well width to 62 Å. The relatively good peak-to-valley ratio of the device (3:1) at room temperature may be attributed to the following factors:

(a) the use of a deep, narrow quantum well with widely separated levels,
(b) the use of smooth interfaces between the strained-layer quantum well and barriers. As explained above, in order to improve the quantum well interfacial morphology, RTD structures were grown on a nominally exact $(100)\pm0.1°$ GaAs substrate.

It is well known that the interface roughness scattering process is one of the major mechanisms contributing to the valley current,[16] and hence, smooth interfaces are quite essential to ensuring high PVR values.[15]

The thermal stability of the device can be improved by reducing the size of the device or by increasing the width of well. For example, for a structure with 63-Å-wide well the

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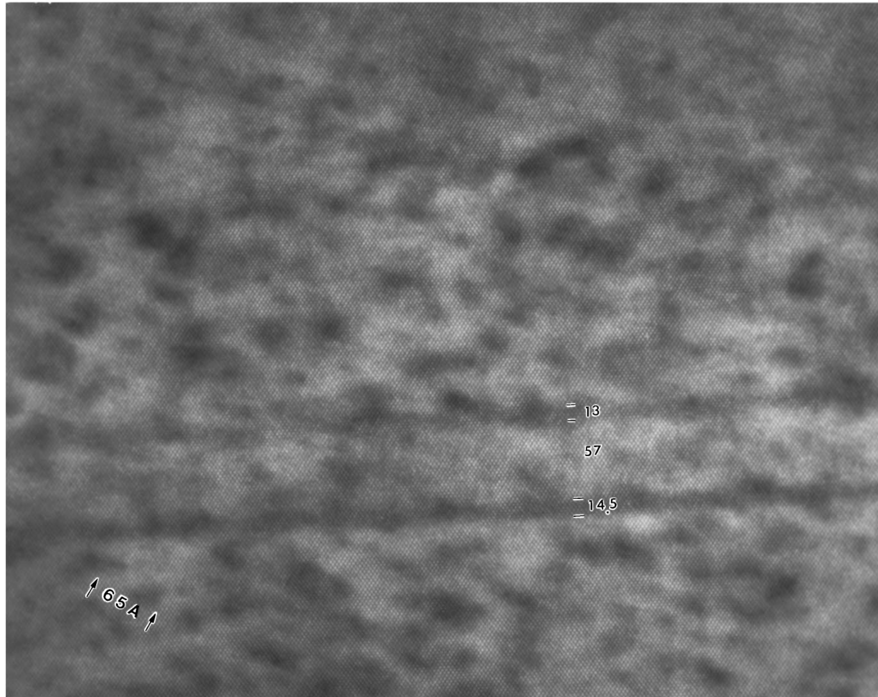

FIG. 3. High resolution TEM lattice image showing the layer morphology. The arrows show 20 (111) GaAs lattice spacings of 3.26 Å each. The total spacing between the arrows is 65 Å.

peak voltage reduces to less than 1 V and the peak current density is also reduced by a factor of 1.5; in turn, the power dissipation in the device is reduced by a factor of 2.

Based on the peak current density and peak voltage of this device (spacer layer = 300 Å), and assuming that the associated parasitic capacitance is negligible, the device could switch 1 V in less than 3 ps.[17] Furthermore, by using a pulsed-doping layer sandwiched between two undoped layers,[7] the intrinsic capacitance of the device can be reduced, which in turn will reduce the switching time by a factor of 2 or more, thus allowing for subpicosecond switching speeds.

In summary, we have successfully implemented very high peak-current-density GaAs-substrate strained-layer $In_{0.3}Ga_{0.7}As/Al_{0.8}Ga_{0.2}As$ RTDs based on resonant tunneling through the second energy level at room temperature.

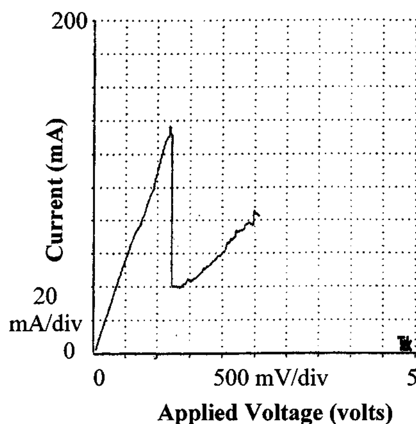

FIG. 4. $I-V$ characteristic of a 6×6 μm^2 device based on resonant tunneling through the second energy level.

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