Resonant tunneling barriers in nitrides

The widening of the application base for nitride semiconductors from light-emitting diodes, through laser diodes to high-power-density high-electron-mobility transistors has encouraged researchers to look at more advanced structures. Dr Mike Cooke reports on recent work on GaN/AlN quantum-well-based resonant tunneling diode structures.

There are a number of reasons why resonant tunneling diodes (RTDs) are of interest to the semiconductor community. First, they can be used to test and modify models of semiconductor behavior that take into account quantum effects, such as the envelope approximation based on using effective masses of carriers. Further, the simple vertical transport structure that is used is the basis for more complicated, multilayer devices using quantum interference effects to create new intersubband structures and devices (e.g. quantum cascade lasers and quantum well infrared photodetectors). Finally, RTDs have a number of interesting device applications of their own.

For example, they are among the limited number of electronic devices that can reach towards terahertz frequencies, offering possibilities for signal generation, switching, analog-to-digital conversion and detection. RTDs maintain their position as the fastest large signal semiconductor switching device with slew rates as fast as 300mV/ps [1].

In addition, RTDs can also be used as 'functional' logic devices, combining in one object a number of functions and creating simpler structures. Possibilities include: (i) one-transistor static random access memory (present-day SRAM generally uses either six transistors or four transistors and two resistors; the RTD version typically needs in addition just a field-effect transistor and a resistor) and (ii) multi-valued memory cells.

The same properties can also be used in combination with other semiconductor structures for improved performance, such as in the unipolar resonant tunneling transistor, which has a resonant tunneling double barrier between the emitter and base layers of the device. One unipolar resonant tunneling transistor can replace eight MESFETs in providing exclusive-NOR logic functions. Resonant tunneling bipolar and FETs can also be created. Resonant tunneling is also being considered for devices that are being developed to supersede standard CMOS technology, which is due to run out of steam towards the end of the next decade [2].

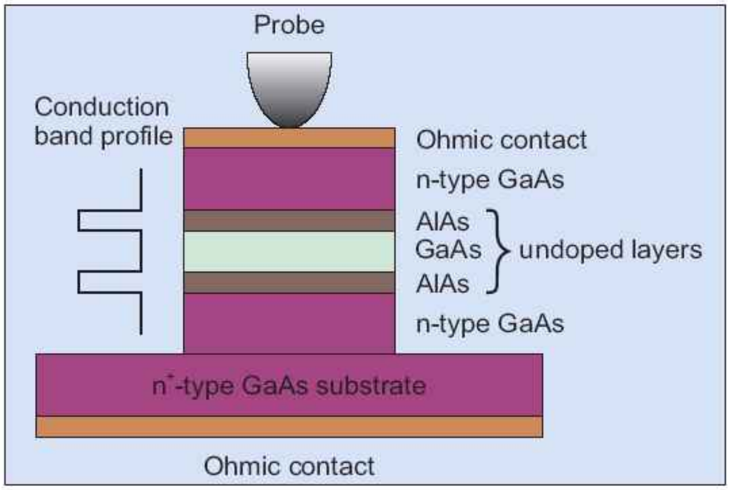

Figure 1: Schematic of a mesa-type AlAs/GaAs/AlAs double-barrier resonant tunnelling diode.

Formation of resonant tunneling diodes

Resonant tunneling diodes are commonly formed from heterostructures consisting of layers of GaAs and AlAs (Figure 1). For example, the sequence from a GaAs substrate of GaAs/AlAs/GaAs/AlAs/GaAs presents a structure where free electrons in the GaAs layers can exist at energies below the bottom of the AlAs conduction band. Hence, the AlAs layers act as barriers to electron transport.

For thin layers, electrons trapped between the barriers can be considered to be approximately confined to discrete energy levels, as described by a simplistic quantum-mechanical model of a square-well potential. Since the barriers are of finite width, these electrons would tend to leak out via quantum tunneling. Electrons from outside the well that hit the barrier structures will largely be reflected, except those within a very narrow range around the discrete energy levels of the well, which acts as an electron energy filter. The thicker the barriers on each side of the well, the narrower the range of electron energies that the structure transmits.

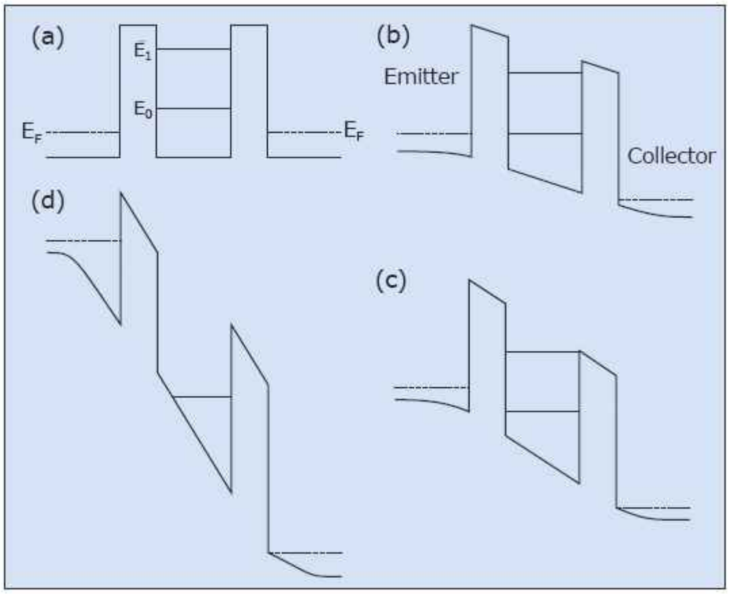

Figure 2: Variations in conduction band energy levels under (a) zero bias; (b) towards the peak current where the energy level of the well lines up with electron states in the emitter; (c) towards the valley current where the energy level falls below the edge of the conduction band into the gap; and (d) where thermionic emission over the barrier begins.

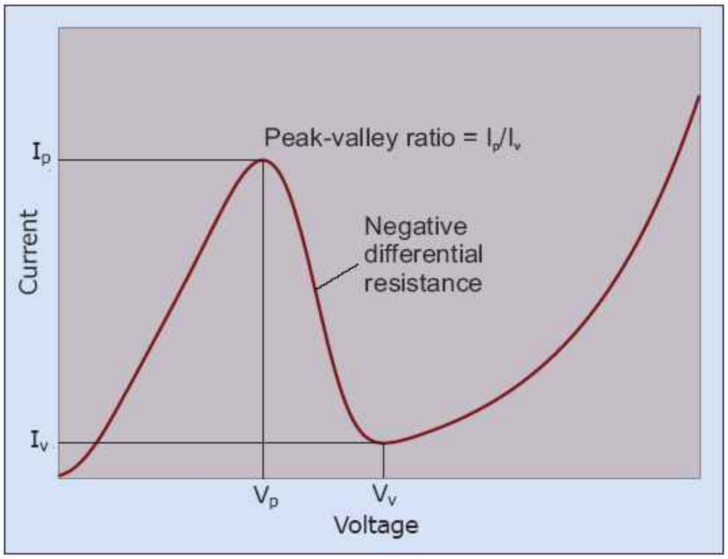

Figure 3: Sketch showing features sought in I–V behavior of RTDs.

In real electronic applications, electrons have a thermally distributed range of energies. Applying an electric potential difference shifts the well's energy levels. As this energy level passes through the peak of the thermal electron distribution, the current peaks, giving a distinctive peak and valley appearance to the current–voltage (I–V) curve (Figures 2 and 3). In the region where the current I decreases with increasing voltage V, one has a negative differential resistance (NDR). Advantages of RTDs include low junction capacitance due to the relatively low doping levels compared with other NDR devices such as ordinary (Esaki) tunnel and transferred-electron devices (TEDs). This enables cut-off frequencies for RTDs to encroach on the terahertz range (10^{12}Hz). Standard applications of the NDR effect include use in ultra-fast pulse forming, radiation detection and signal generation systems.

The classic RTDs are built using GaAs/AlAs, InAs/AlSb or InAs/GaSb on GaAs or InP substrates, depending on criteria such as lattice matching. At room temperature, GaAs/AlAs RTDs typically have peak-to-valley ratios (PVRs) of around 3, while for InAs/AlSb the PVR can reach 8. However, alternative material systems are possible, including silicon/germanium and nitride semiconductors. The attraction of silicon is possible cost reductions and device integration, while the GaN/AlN combination offers a large conduction band offset of 1.8eV, creating the potential for even larger PVRs and quantum behavior at much higher temperatures than in other III-V systems. Such devices, if practical, could offer higher power at a given frequency or higher frequency at given power, compared with devices built in alternative systems. Lateral transport high-electron-mobility transistor devices are already using the nitride system to produce high-power-density amplifiers for use in mobile phone base-station transmitters.

However, the GaN route for vertical transport devices such as RTDs is beset with some of the usual barriers in the nitride material system, in particular dislocations and strong internal spontaneous and strain-related (piezo) electric fields. The result is that RTDs with AlN/GaN double barriers have yet to demonstrate the predicted benefits in terms of peak-to-valley ratios and current densities. Other vertical devices, such as quantum well infrared photodetectors (QWIPs) built using the same techniques, suffer from similar problems, although paradoxically these more complex architectures often produce more promising results than the basic RTD structure. This suggests that much work needs to be done in comprehending and modeling quantum phenomena in the nitride semiconductor system. For this, understanding the behavior of simpler structures is vital.

Data from fabricated AlN/GaN RTDs tend to be non-reproducible. Some propose that the effects that are seen could also be due to charge trapping rather than resonant tunneling. Current instabilities are also evident. Early GaN RTDs were reported by Kikuchi et al [3], suggesting a massive maximum PVR of 32 in the latter article. A 3ML (monolayer) GaN quantum well was sandwiched between 4ML AlN barriers. The contact layers consisted of n-type silicon-doped GaN. The layers were grown using plasma-assisted molecular beam epitaxy (PAMBE) on sapphire (Al_2O_3). NDR was reported at 2.4V with a current of 2.9mA (a density of 180A/cm^2).

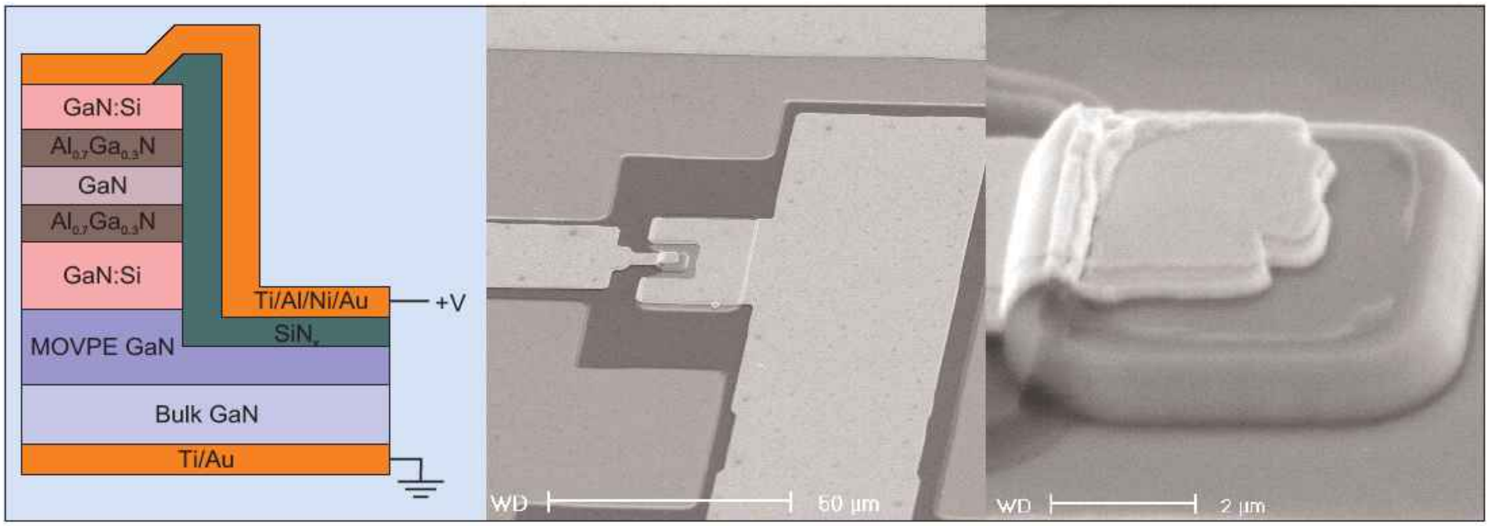

Figure 4: Schematic (left) and scanning electron micrographs (centre and, magnified, right) of GaN RTD device investigated by Golka et al [Appl. Phys. Lett., vol. 88, p. 172106, 2006]. The diagram is not to scale. The MOVPE GaN is 1µm thick and doped n-type to achieve a carrier concentration of $5x10^{18}cm^{-3}$. The silicon-doped GaN layers also have carrier concentrations of $5x10^{18}cm^{-3}$. The layer thicknesses of the wells and barriers (not intentionally doped) are 2nm, while the GaN:Si layer above the MOVPE GaN is 150nm thick and that next to the top contact is 100nm. The SiN_x insulator is 300nm thick. The GaN substrate is doped n+ with a carrier concentration of $5x10^{19}cm^{-3}$.

This article provoked a comment from Belyaev et al [4], reporting the finding that peaks found in similar devices are highly sensitive to the way in which the I–V measurements are made. In particular, the I–V curve varied in a series of up–down voltage sweeps. This behavior prompted Belyaev et al to question the interpretation of Kukushi et al's I–V curves and a simple resonant tunneling explanation. Belyaev et al's experiments showed a peak from sweeping in the down direction at around –6V, but no peak in the subsequent up direction. Moving beyond 0V, a very weak peak is seen at +5V. The peaks that are seen degraded on further sweeps through the voltage range. The behavior was attributed to the strong hysteresis and the degradation to bias-dependent electron trapping, possibly assisted by strong polarization fields in the AlGaN system. This multinational group (UK, Ukraine, Russia, Germany) reported further results in [5].

For their part, Kikuchi et al [6] believed that they had been misunderstood and stressed that they did not claim that a simple RTD model could explain their results due to the presence of a large piezoelectric field in the system. The next year, Hermann et al [7] reported a maximum PVR of 8.3.

Further work by Belyaev et al [8] suggests that the structural quality of GaN heterojunctions and impurity scattering from doping destroys the momentum conservation needed for the successful application of resonant tunneling. Another factor to be considered is the higher effective electron mass — some three times that in GaAs — requiring barriers and wells of about half the thickness, i.e. ~1–4nm for GaN wells and ~1–3nm for AlGaN barriers. Using these values, Belyaev et al produced RTDs on Si-doped GaN/sapphire substrates, again using PAMBE. The resulting device has a peak in the I–V curve in the reverse bias direction. However, sweeping through the I–V curve again causes the peak to degrade, and is only seen in sweeping down and not up. The team's numerical simulations suggest that the double well becomes asymmetrical due to the internal electric fields. The resulting charge structure inhibits resonant tunneling into the ground quasi-bound state of the well. Tunneling is only able to occur successfully (in the model) into excited quasi-bound states. The researchers conclude that the hysteresis and degradation of the peak is due to bias-dependent trapping of electrons, possibly in the quantum well after having made one tunneling transition from the emitter. The resulting charging and discharging creates nonlinear and unstable current behavior.

Leconte et al [9] studied GaN/AlN/GaN single-barrier structures (grown using PAMBE) with a view to intersubband and RTD devices. Vertical transport through varying AlN thicknesses (2–20ML, 0.5–5nm) were compared with simulation results from a self-consistent Schrödinger–Poisson equation solver. Capacitive measurements suggest that a depletion layer is formed in the top GaN layer, while a two-dimensional electron gas forms at the bottom GaN/AlN interface, even for the 2ML barrier. Photoluminescence experiments support this interpretation, since a signal from recombination of electrons from the two-dimensional electron gas (2DEG) into the valence band of the top GaN layer is identified. Conductive atomic force microscopy is used to investigate leakage currents. The density of leakage current dislocations is

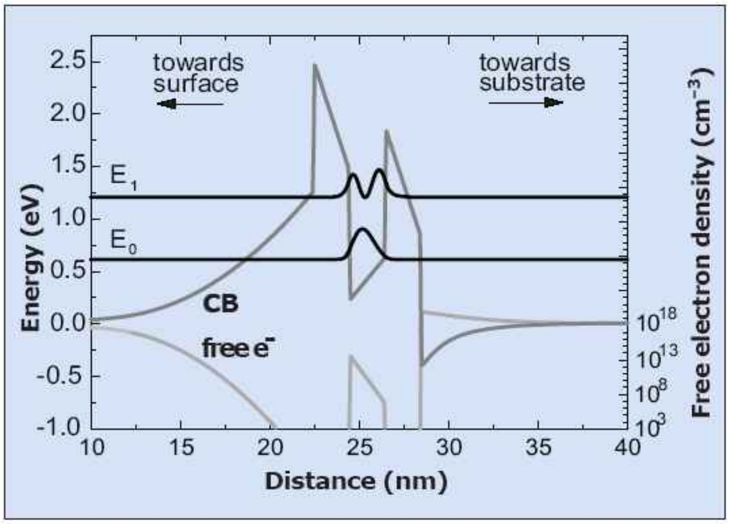

Figure 5: Conduction band diagram resulting from a self-consistent Schrödinger–Poisson equation solver without external bias. The ground-state energy is E_0 = 0.613eV and the excited state, E_1, is at 1.206eV. (From the 2006 Wide Bandgap Semiconductor Quantum Structures summer school, Switzerland presentation by Gottfried Strasser.)

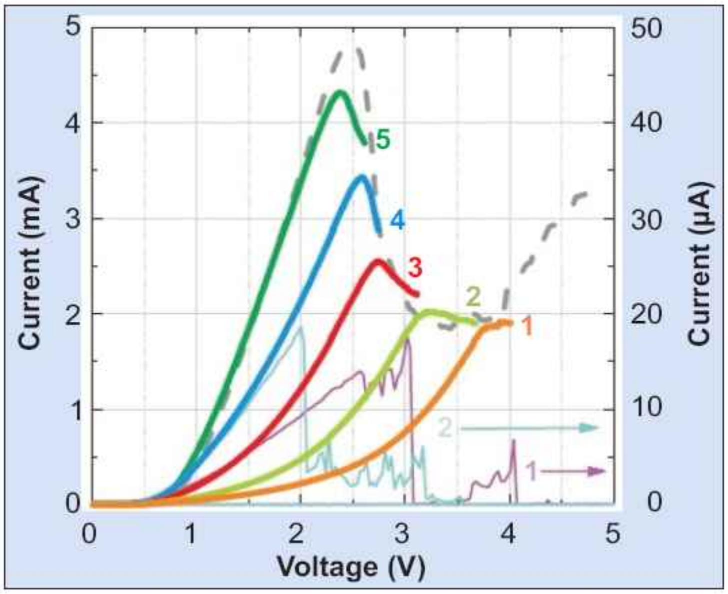

Figure 6: Sequence of traces of two GaN RTDs showing decay of the peak/discontinuity currents. (From the 2006 Wide Bandgap Semiconductor Quantum Structures summer school presentation by Gottfried Strasser.)

$\sim 10^7 cm^{-2}$, about an order of magnitude smaller than the level of dislocations ($5x10^8 cm^{-2}$). Thicker barriers result in degradation in behavior that is assigned to trap-induced phenomena and relaxation of the AlN barrier layer. Leconte et al see these results as promising for micron-scale RTD device applications.

RTDs are not the only devices to be affected by dislocations resulting from the 18% lattice mismatch between GaN and sapphire. Laser diodes (LDs) built in the GaN material system on sapphire tend to have very short reliability lifetimes, on the order of 20 minutes. And yet, GaN blue LDs are now entering the market in optical disk storage video playback and data devices. Indeed, Sony released its Playstation3 (containing a Blu-ray laser disk reader) on 11 November in Japan and 17 November in the USA, and early this year in the rest of the world. LD commercialization has depended on abandoning the less expensive GaN on sapphire or even silicon carbide and using pure GaN crystal substrates to drastically reduce dislocation densities and thus create realistic LD lifetimes.

Golka et al [10] have performed experiments on GaN-based RTDs grown on bulk (0001) single-crystal GaN substrates in order to remove as many dislocation-related effects as possible, such as traps, leakage and carrier scattering. The latter effect destroys the quantum coherence needed for the resonant tunneling mechanism.

In addition to changing the substrate, Golka et al reduced the diode lateral dimensions from the typical 40–100µm to around 6µm. Another change is to move from AlN barriers to AlGaN with a 70% Al content (Figure 4). This is designed to reduce lattice mismatches between the GaN and barrier layers. The GaN substrates used were about 60µm thick and about 5mm in diameter. They were grown using a high-pressure process developed at the Polish Academy of Science UNIPRESS high-pressure research centre. The RTDs were deposited on the Ga polarity side of the substrate using PAMBE. The deposition was performed under Ga-rich conditions using adlayer enhanced lateral mobility (AELD) at 710°C to achieve high-quality 2D growth at lower temperatures than normal. The contacts were Schottky rather than Ohmic, although efforts were made to reduce the resulting rectifying behavior. The I–V curve shows a resonance peak at about 2.2V in the direction of the rectifying contacts and none under reverse bias. A simulation of the structure using a Schrödinger/Poisson solver (Figure 5) suggested a lower bound for the resonance of about 1.2V, which is in reasonable agreement with the measured value, taking into account potential drops away from the double-barrier structure such as at the non-ideal contacts. Further, screening of the barrier occurs due to charge layers that build up in front of the barriers as a result of the strong polarization fields in nitride semiconductors.

The measured peak-to-valley ratio (PVR) is around 2, which is much smaller than the value of 32 reported for the device of Kikuchi et al [3]. In the devices that demonstrated negative differential resistance (about 20% of the total), the width of the NDR region was about 0.3V. Another 20% of the devices showed a sharp discontinuity in the I–V curve, while the remainder showed no more than an exponential background in their I–V characteristic. The diodes are destroyed if they are taken beyond 6V bias in either direction.

In the diodes with NDR, Golka et al see the same degradation of the peak after the first sweep, as reported by other groups. By stopping the sweep close to the peak, one sees a gradual decay that follows an envelope representing a full sweep on a virgin device (Figure 6); i.e. the peak decreases and shifts to higher energy.

Golka et al discuss and dismiss non-resonant tunneling explanations of the NDR such as physical degradation and trap filling. However, traps are seen as having a role in increasing the barrier screening and hence shifting the peak to higher voltages. To test this idea, a 350°C thermal process under a nitrogen atmosphere was applied to the devices, with a view to releasing carriers from traps. The NDR behavior was restored, but with an order-of-magnitude reduction in the current density.

Gottfried Strasser of TU Wien, and part of the research team that includes UNIPRESS, comments: "These are, to the best of our knowledge, the only RTD structures on bulk GaN material. Although this is not an RTD, it is the first measurement that shows reproducible results. This is, as reported in the paper, most probably due to the reduced defect density (bulk substrates and smaller mesa sizes). While this is not yet a workable device, we can now start looking deeper into material properties and separate intrinsic from extrinsic behavior. It is too early to make final statements but, given the remarkable progress in the control of GaN-based materials within the last few years, and assuming continuous progress in improving substrates as well as growth and processing, there is a good chance of succeeding in developing usable RTDs."

The work of Golka, Strasser et al is part of a European project called NITWAVE, carried out between TU Wien and the company TopGaN (Poland). Further work is being carried out to produce RTDs on GaN crystals with a non-polar orientation as developed by UNIPRESS/TOPGaN. Also, lower Al concentration layers are being investigated further to understand vertical transport mechanisms.

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