GaN/AlN Double Barrier Nanowire Resonant Tunneling Diodes

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Resonant tunneling devices (RTDs) have attracted many interests because of their extremely high switching speeds and potential applications in multi-logic circuits. Due to the large conduction band offset and strong piezoelectric and spontaneous polarization, III-nitride (III-N) wide band gap semiconductors are promising materials for resonant tunneling devices. However, III-nitride thin film structures suffer from a large density of threading dislocations (typically 10^8-10^9 cm^{-2}) as they are grown on non-native largely lattice-mismatched substrates. Recently, III-nitride nanowires (NWs) have emerged as an alternative choice. [1-2] This is because the large surface-to-volume ratio and small cross sections allows NWs accommodate much higher lattice mismatch with an efficient elastic strain relaxation thereby inhibiting the formation of dislocations during the epitaxial growth of III-N thin film structures.

In this work, we demonstrate III-nitride NW RTDs with high tunneling current density and peak-to-valley current ratio. We started with growth of 500 nm-long n-GaN/ 2.5nm AlN/ 2.5nm i-GaN/2.5nm AlN/ 500nm n-GaN NWs by plasma assisted molecular beam epitaxy. The NWs were then transferred to thermally grown SiO_2 substrate and followed by e-beam lithography and metallization for Ti/Al/Mo/Au metal contacts with a spacing of 0.45 µm (Fig.1). The I-V characteristics show clear negative differential resistance (NDR) features. However, a 2.5nm-thick AlN double barrier can block most of current and give a low tunneling coefficient. As a result, the devices show a low resonant current density (~10^4 A/cm^2) after completely turning on (Fig. 4).

To improve the resonant peak current density, a 1.5nm-thick AlN double barrier structure was grown. Based on simulation results, such thin AlN barrier can dramatically increase tunneling coefficient by almost two orders and lower down the NDR onset voltage (Figs 2&3). The I-V characteristics show clear NDR features at both room temperature and cryogenic temperatures for thin AlN barrier device (Fig. 5). The most significant discovery is that NDR is observed with both forward and backward voltage sweep at the same bias (Fig. 4(b)). This is a strong evidence that such NDR really comes from GaN/AlN double barrier as designed and is not trap-assisted tunneling related, which is typically the case for reported III-N thin film heterostructures. The maximum peak to valley current ratio (PVCR) on a device is 5.09 and the maximum resonant peak current density is 10^6 A/cm^2 on another device.

Moreover, we show that PVCR can be further enhanced using a Ni/Au Schottky metal contact at one end of the nanowire RTD. The Schottky barrier suppresses the thermionic emission current before the onset voltage of NDR to capture the pure current resulting from resonant tunneling. As a result, an extremely high PVCR of 41 is demonstrated (Fig. 6). To our best knowledge, this is higher than any reported PVCR values in AlN/GaN RTDs.

1. Carnevale, S. D.; Marginean, C.; Phillips, P. J.; Kent, T. F.; Sarwar, A. T. M. G.; Mills, M. J.; Myers, R. C. *Applied Physics Letters* **2012,** 100, (14), 142115-4.
2. Songmuang, R.; Katsaros, G.; Monroy, E.; Spathis, P.; Bougerol, C.; Mongillo, M.; De Franceschi, S. *Nano Letters* **2010,** 10, (9), 3545-3550.

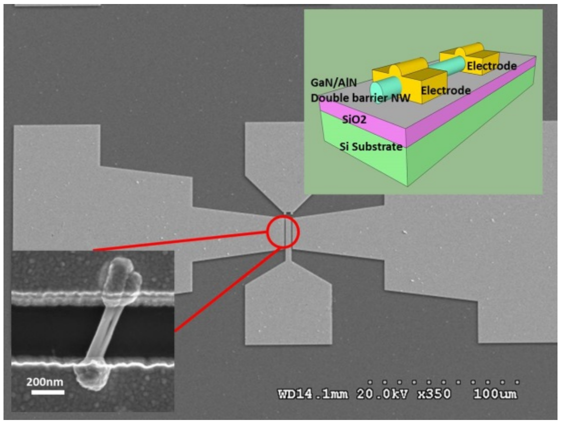

Fig. 1 SEM micrographs of GaN/AlN NW RTD device. Inset shows the cross section view of RTD device structure.

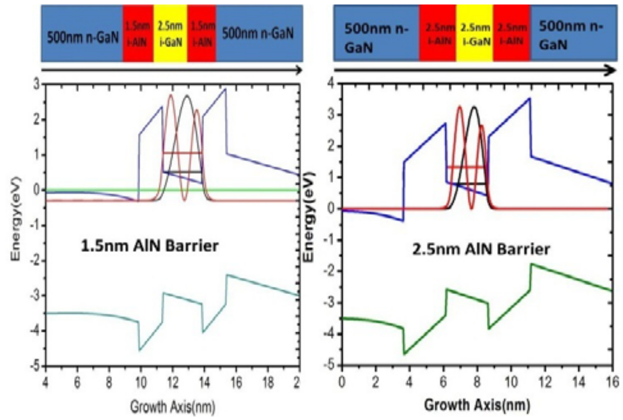

Fig. 2 Simulated band diagrams of the AlN/GaN hereostructure including two quasi-bound states and wavefuctions within the quantum well: 1.5nm barrier (left) and 2.5nm barrier (right).

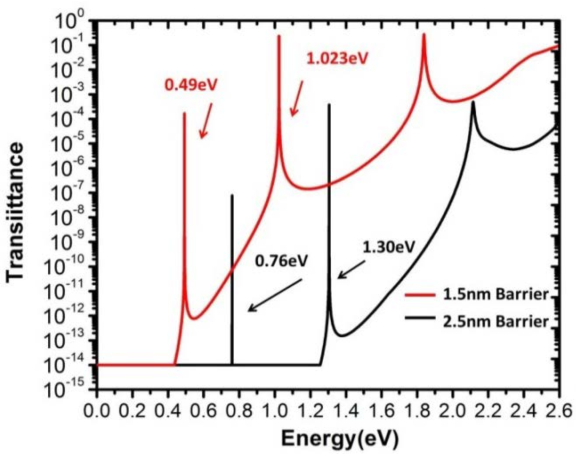

Fig 3. Simulated transmittance of resonant tunneling as a function of energy for: 1.5nm barrier (in red with two peaks at 0.49eV and 1.023eV); 2.5nm barrier (in black with two peaks at 0.76eV and 1.30eV).

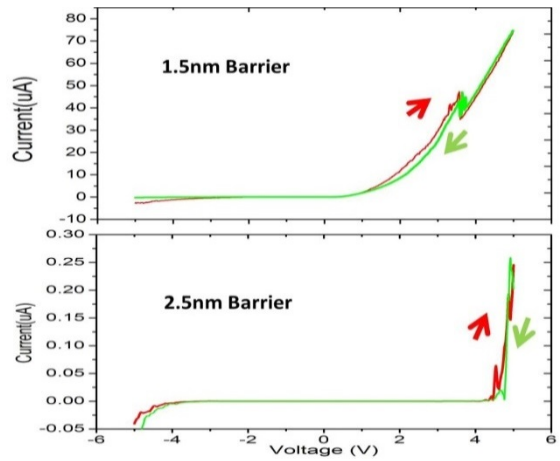

Fig. 4 Room temperature I-V characteristics with double sweeps. NDR features are shows at both forward and backward voltage scans for: 1.5nm barrier (top) and 2.5nm barrier (bottom).

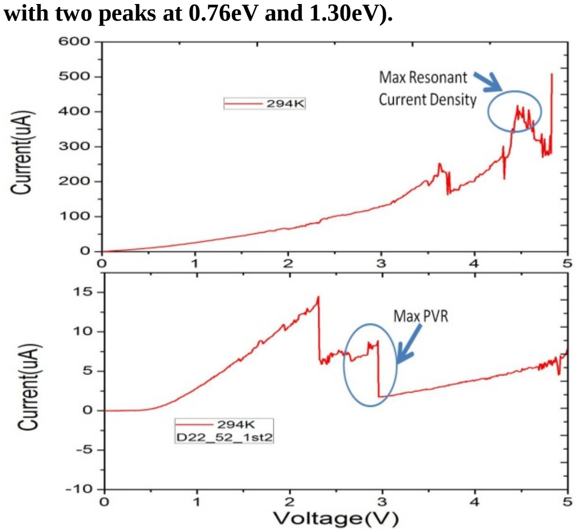

Fig. 5 Room temperature I-V characteristics of RTD devices. One device (top) shows a resonant tunneling current density of 106 A/cm^2. Another one shows a PVR of 5.09.

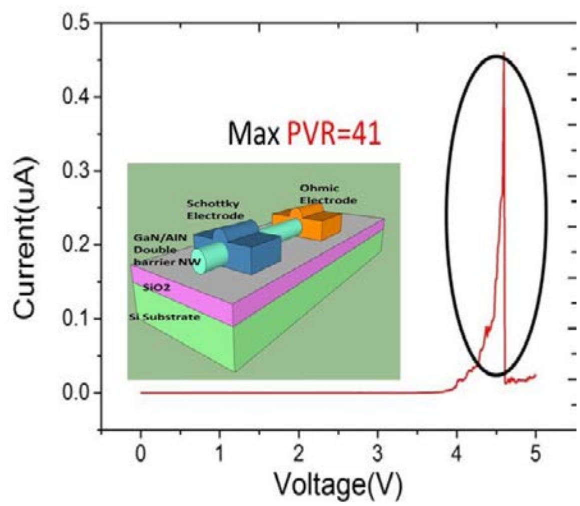

Fig. 6 Room temperature I-V characteristics of a Schottky contacted RTD device with a PVR of 41 at a bias of 4.5 V. Inset shows the cross section view of Schottky contacted RTD device.