Extended Abstracts of the 2016 International Conference on Solid State Devices and Materials, Tsukuba, 2016, pp573-574

N-3-01(Invited)

III-Nitride-based Negative Differential Resistance and Resonant Tunneling Devices With up to THz Operation Capability

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Abstract

The design, characteristics and performance of Negative Differential Resistance, Resonant Tunneling and Superlattice devices using III-Nitride materials are reviewed. High power and THz operation are expected. Defects leading to self-charging and incoherent transport, thermal effects, scattering and spontaneous and piezoelectric polarization resulting in QW changes need to be addressed for the successful implementation of the technology. Recent results suggest Room Temperature operation.

1. Introduction and General Design Considerations

Negative Differential Resistance (NDR) is manifested by devices of various designs and is of importance for signal generation at frequencies extending to THz. It is observed in bulk layers due to electron transfer from the light-mass valley to heavy-mass satellite valleys in traditional III-Vs such as GaAs and InP and has also been observed by the authors in GaN [1], [2]. Resonant Tunneling Diodes (RTDs) and Superlattices (SLs) as proposed by Esaki-Tsu have also been shown to exhibit negative differential conductance (NDC) through the bias dependent resonance between the quasi-bound levels and adjacent reservoir of electrons in designs consisting of a combination of Quantum-Wells (QWs) and barriers. Bragg reflection of miniband electrons in SLs may also induce traveling dipole domains and self-sustained current oscillation. III-Nitrides are suitable for millimeter wave generation by NDR, RTD and SL designs due to their potential for very high-frequency, high-power operation. Nitride SLs have been explored by the author both in the AlGaN/GaN and GaN/InGaN system [3]. Their NDC I-V characteristics were found to be dependent on the charge state of the device as determined by the bias voltage and carrier trapping and emission effects in the well and the heterostructure interface. Material defects, thermal and electromigration effects have also been found to limit the performance of bulk III-Nitride NDR.

This paper reviews bulk NDR. RTD and SL devices and related effects based on III-Nitride materials and designs.

2. Bulk NDR

NDR (Gunn) diodes realized on n+GaN substrates presented a wide NDR region for electric fields E larger than a threshold field E_{th} of 150 kV/cm [1], [4], which when exceeded led to electromigration. The measured drift velocity was estimated to be 1.9×10^7 cm/s. The devices were found to be very stable for pulse widths up to 70 ns. The theoretically predicted fundamental frequency of operation may exceed 0.5THz.

3. III-Nitride Resonant Tunneling Diodes

The interface roughness geometry in GaN RTDs impacts their current and peak-to-valley (PVR) current ratios eliminating in certain cases NDR. A parasitic current caused by dislocations is observed [5].

GaN/AlN double barrier RTDs revealed NDR at Room temperature (RT) under forward bias with a peak current density of ~6.4 kA/cm^2 and a peak to valley current ratio of ~1.3 [6]. The layers used were grown by MBE on the (0001) plane of bulk GaN substrates. Reverse bias operation presented a characteristic turn-on threshold voltage related to the polarization fields of the heterostructures.

The strong internal electric fields in QWs grown along the c axis in III-Nitrides due to spontaneous and piezoelectric polarization leads to a trapezoidal E_c and E_v lineup that blueshifts the Intersubband (ISB) transition energies and carrier extraction from the subbands into unbound states becomes difficult [7]. Interwell tunneling transport among the lower-energy states of QWs is also challenging. Step-QW structures with two or more layers of different (Al)GaN compositions may be used in each well to create a more rectangular potential energy profile. Design considerations of this type although directly applicable to ISB photodetectors may inspire work for ensuring controlled NDR signal generation.

Reproducible NDR (R of -67 Ω) with PVR of 1.08 and P_{MAX} of 0.52 mW has also been demonstrated in III-Nitrides and in both reverse and forward direction [8]. Low dislocation density and minimization of the polarization charges at the double-barrier hetero-interface are a key for reproducible NDR in GaN-based RTDs.

Coaxial nanowire RTDs from non-polar AlN/GaN on silicon were also explored using AlN/GaN core-shell nanowire (NW) heterostructures grown by plasma assisted MBE and take advantage of non-polar (m-plane) nanowire sidewalls [9]. Non-polar orientation is expected to enhance resonant tunneling compared to polar structures, while AlN double barriers will lead to higher PVR compared to AlGaN barriers. NWs showed NDR at RT with peak current density of 5×10^5 A/cm^2.

4. Negative Differential Conductance in Nitride Superlattices

$Al_xGa_{1-x}N$/GaN Superlattices exhibit a traveling dipole domain oscillation frequency in the THz [10]. The short-period condition was satisfied with an Al composition (x) between 18% and 40% and a value for the sum of the barrier and quantum well thickness of less than 50 Å. $Al_xG_{1-x}N$/GaN SL layers were grown by MOCVD with 50 periods of AlGaN/GaN layers and 15 Å thick AlGaN layer (x~34%) and a 15Å thick GaN layer. NDC was observed at ~1 V with a PVR of 1.3 at RT but the stability of the I-V characteristics was affected by carrier trapping.

5. Other NDR Designs

Heavily doped (homojunction) n++/p++ interband Tunnel Junctions (TJs) showed repeatable hysteresis-free RT NDR and low resistance which is significant for new LED topologies such as p-contact less LEDs [11]. Interband tunneling could be used for increasing the efficiency of visible light emitting diodes (LEDs) and UV LEDs but also for high frequency signal generation. J_c values of 150 kA/cm^2 were found suggesting use in bipolar III-nitride devices such as lasers for operation at very high current densities with low conduction losses and low charging time for light modulation applications.

The combination of 2D Transition Metal Dichalcogenides (TMDs) with bulk (3D) GaN allows the development of novel devices without any constraints of lattice matching. Using Nb-doped p-MoS_2/n-GaN heterojunctions, interband tunnel diodes were demonstrated with peak J_c of 446 A/cm^2 and repeatable RT NDR with PVR of 1.2, and minimal hysteresis. [12].The 2D/3D interface plays a key role in the experimentally observed device characteristics.

Unipolar GaN-based tunneling hot electron transistors showed reproducible RT NDR with PVR of 7.2 [13] by employing tunnel-injected electrons to vary the electron energy and change the fraction of reflected electrons. High frequency oscillators based on quasi-ballistic transport could be envisaged with such structures.

6. Conclusions

RTDs and bulk NDR device show great promise for high-frequency signal generation up to the THz regime. Other applications such as ISB photodetectors and lasers, LEDs can profit from developments in this area. Reproducibility and RT operation are impacted among other by dislocation, interface roughness and design.

Acknowledgements

The author would like to thank his students and researchers that contributed to the reported work as well as his colleagues E. Brown, D. Jena, O. Malis, R. C. Myers, R. Paiella, S. Rajan, M. Razeghi, M. Shur and H. G. Xing, for their assistance in presenting the latest developments in the III-Nitride RTD and NDR device area.

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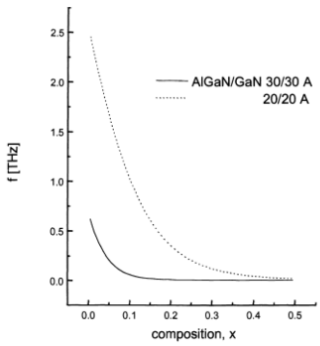

Fig. 1 THz Signal Generation by short III-N SLs [10]

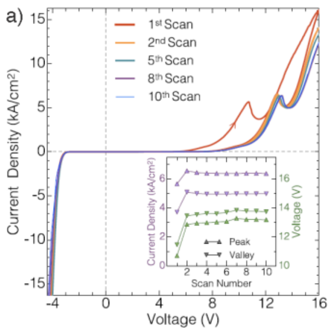

Fig. 2 Bias scans of III-N NDC and stability of peak J_c [6]

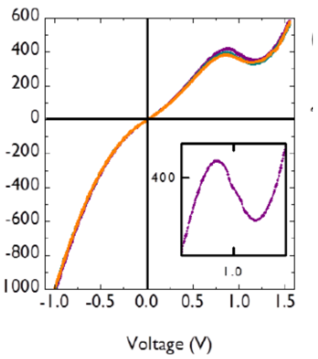

Fig. 3 I-V in p+ MoS_2/n+ GaN tunnel diode [12]