III-N nanostructures for Intersubband optoelectronics

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Intersubband (ISB) technology achieved a major milestone when the first InAlAs/InGaAs quantum cascade (QC) laser was demonstrated. Unlike the interband devices whose operating wavelength depends on the band gap, ISB offers possibilities of wavelength control by design, since it involves transitions between the confined states of quantum wells (QW). Owing to many advantages of the ISB technology, much effort was focussed trying to push the operation wavelength towards telecommunication spectral range. Using the GaN/AlN system, we can easily reach this technologically important wavelength thanks to the large conduction band offset of 1.75 eV. Other advantage of these semiconductors is the prospects for ultrafast ISB devices operating at multi-Tbit/s data rates due to short recovery times (~ 200fs), possible by strong Frohlich interaction in III-N. In this abstract we will discuss the various material issues, followed by a description of devices in near-IR (NIR) region. The advantage of using polar or semipolar materials for our application, and the current status of nitride-based ISB technology for the mid-IR (MIR) will also be addressed.

The growth of the structures was performed on AlN-on-sapphire templates using plasma-assisted molecular beam epitaxy with in-situ monitoring by reflection high energy electron diffraction. The large lattice mismatch of 2.4% between GaN/AlN demands critical tuning of growth conditions. Thus, to reduce relaxation through channels like threading dislocations and periodic stacking faults, we have adopted methods like supplying Ga excess during the deposition of GaN and AlN, which reduces the surface energy and increases the mobility of the adsorbed species [1]. Taking advantage of sapphire transparency in the NIR, we have demonstrated charge transfer electro-optical modulators with modulation depth of 14dB -enough to achieve 10-12 bit error rate-, polarization induced phonon ladder QC detectors [2] with a responsivity of 10 mA/W and RC limited -3dB bandwidth greater than 10 GHz, and intraband quantum dot photodetectors. Fig (2) clearly shows the energy levels placed in resonance with the phonon energy of ~ 90 meV, allowing rapid relaxation.

Although polar structures offer many advantages, like a polarization-induced enhancement of the conduction-band offset, there are some potential disadvantages - for example, the wavelength shift and the corresponding reduction in oscillatory strength when operated under bias- which can be overcome by using semipolar-oriented structures. As a step in this direction we recently reported the first observation of ISB absorption from semipolar GaN/AlN SLs.

The III-N ISB technology not only finds application in the NIR wavelengths, as described above, but it also offers the flexibility to fabricate devices in the MIR range and even further, upto possibly the Terahertz range. Using an 8 band k.p Schrödinger poisson solver we have theoretically predicted the suitable structural parameters required for ISB transition at MIR region. The red shift of transition energy can be achieved on reduction of electric field and quantum confinement in the well, by decreasing the Al content in the barrier and increasing the well width. We have performed the growth of the structures absorbing at MIR on semi-insulating Si(111), to avoid the absorption by the substrate. Experimental measurements of the ISB transition energy show good agreement with our calculatins. The observed experimental ISB absorption can be tuned up to 10 µm, with the spectral width falling between 15-20% -comparable to Arsenic system with values between 10-15% [4].

References:

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[2] A. Vardi, et al., Appl. Phys. Lett. 93, 193509 (2008).
[3] Nextnano3 http://www.nextnano.de/nextnano3/
[4] P. K. Kandaswamy, et al., J. Appl. Phys. 106, 013526 (2009)

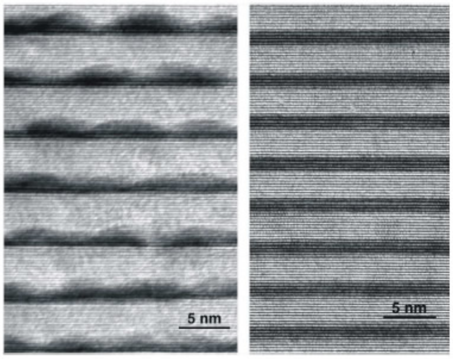

Fig. 1. High-resolution TEM images of (0001)-oriented GaN/AlN QD (left) and QW (right) superlattices.

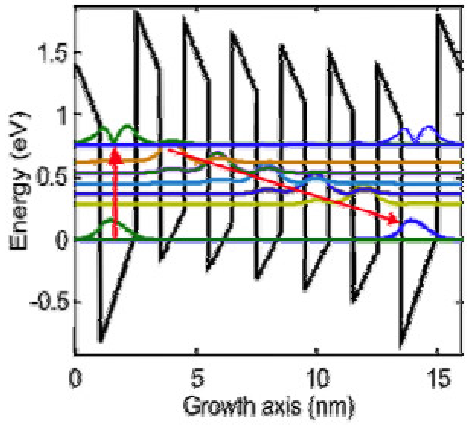

Fig 2. Band diagram and energy levels in one stage of the structure. (Red arrow) direction of electron relaxation (Bold lines) denote states involved in optical transitions.

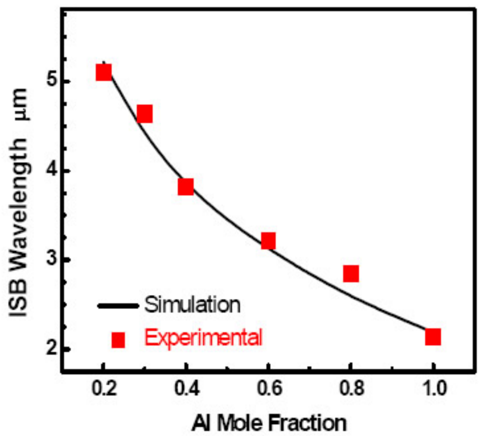

Fig 3. Variation of ISB transition energy with Al mole fraction on the barrier

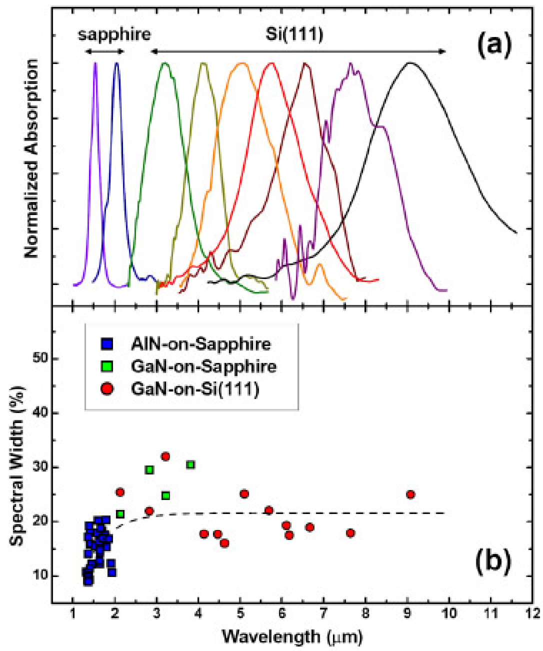

Fig 4 (a). IR absorption spectra for TM-polarized light measured in GaN/Al(Ga)N superlattices grown either on sapphire or on Si(111) templates. (b) spectral width of the samples absorbing from NIR to MIR range.