Electronic structure and vertical transport in GaN/AlN/GaN single-barrier structures

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III-nitride semiconductors have experienced an astonishing evolution in the last decade, leading to the commercialization of nitride-based devices like UV-blue-green light emitters, UV photodetectors and high electron mobility transistors. The combination of the outstanding electronic, optoelectronic and piezoelectric properties of these materials renders them suitable for a broad variety of applications and provides unexplored tools for the device designer. For instance, nitride semiconductors, with their large conduction-band offset −about 1.8 eV for GaN/AlN−, are promising candidates to develop intersubband (ISB) devices operating in the near-infrared, and resonant tunneling diodes with high values of peak-to-valley ratio.

First reports of unipolar devices based on vertical electron transport (resonant tunneling diodes and quantum well infrared photodetectors) are controversial because of the scarcity and irreproducibility of the published data [1]. Current instabilities are admitted, and their assignation to resonant tunneling or trapping is under debate. Furthermore, the current densities and peak-to-valley ratios do not correspond to the values predicted by standard tunneling models. These anomalies are due to two critical factors in III-nitride technology:

- The presence of a strong internal electric field in heterostructures grown along the (0001) axis, due to the high piezoelectric constants of III-nitride materials and the difference in spontaneous polarization, which can lead to the presence of two-dimensional electron gases (2DEG) at the heterointerfaces when dimensions are reduced to the nanometer scale.
- The high density of dislocations in these materials, still in the 10^8 cm^{-2} range in high-quality substrates.

Understanding the contribution of these two factors to the vertical electron transport in III-nitride heterostructures is a priority in order to address the design of quantum devices, such as resonant tunneling diodes, quantum well infrared photodetectors or quantum cascade lasers.

In this work, we investigate the vertical electron transport through GaN/AlN/GaN single-barrier structures with different AlN barrier thickness, grown by plasma-assisted molecular-beam epitaxy. The barrier thickness was varied from 2 monolayers (ML) to 20 ML (0.5 nm to 5 nm). High-resolution and energy-filtered TEM measurements demonstrate that the GaN/AlN interfaces are chemically abrupt with a roughness of <1 ML [2]. The results of electrical characterization are interpreted by comparison with simulations of the electronic structure using a self-consistent Schrödinger-Poisson equation solver.

Capacitive measurements indicate that the internal electric field induces a partial or complete depletion of the GaN cap layer −depending on the layer thickness−, and the formation of a two-dimensional electron gas (2DEG) at the bottom interface of the AlN barrier, even for a barrier thickness as small as 0.5 nm (2 ML of AlN) [3]. This band distortion is further confirmed by low temperature photoluminescence, where the recombination from the 2DEG to the top of the valence band in the upper GaN/AlN interface was clearly identified. Conductive atomic force microscopy images of these samples display a density of leakage current spots in the 10^7 cm^{-2} range, i.e. a third of the dislocation density in these layers, which reveals that not all the dislocations contribute to the leakage current, which is significantly lower than the dislocation density ($\sim 5 \times 10^8$ cm^{-2}). For a barrier thickness of 5 nm, we observe a degradation of the electrical performance with presence of trap-induced phenomena and an enhancement of the leakage current, which is attributed to the relaxation of the AlN layer. These results are promising for the fabrication of nano-scale resonant tunneling diodes.

References:

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[2] E. Sarigiannidou, E. Monroy, N. Gogneau, G. Radtke, P. Bayle-Guillemaud, E. Bellet-Amalric, B. Daudin, and J. L. Rouvière, Semicond. Sci. Technol., **21**, (2006) 912.

[3] S. Leconte, F. Guillot, E. Sarigiannidou, and E. Monroy, submitted to Appl. Phys. Lett.

Figures:

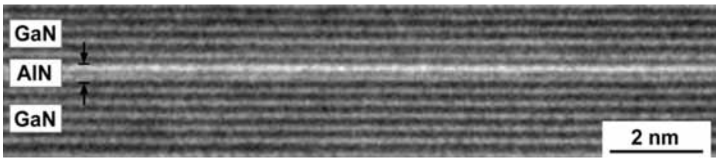

Fig. 1 : HRTEM image of a 0.5 nm barrier of AlN in GaN showing (0002) lattice fringes. The growth axis is directed upwards.

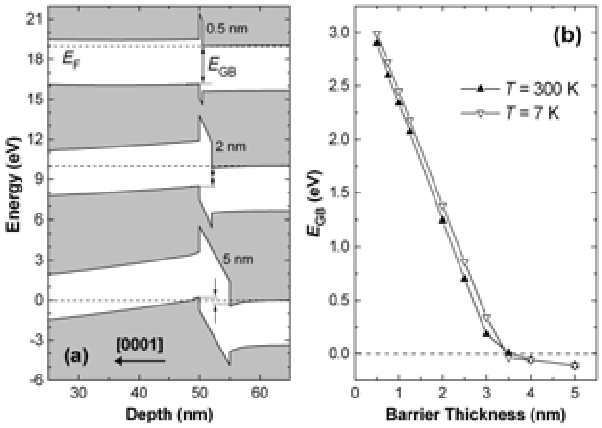

Fig. 2 : (a) Band diagram of single barrier structures with different AlN barrier thickness. The arrows indicate the energy band gap through the barrier, E_{GB}. (b) Evolution of E_{GB} with the barrier thickness, calculated at a temperature $T = 7$ K and $T = 300$ K.

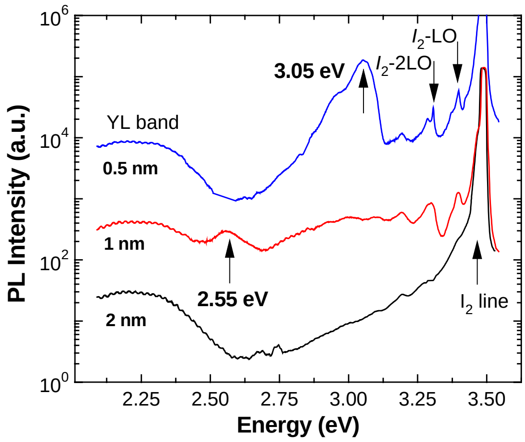

Fig. 3 : Low temperature ($T = 10$ K) photoluminescence spectra of GaN/AlN/GaN single barrier structures with different barrier width located 50 nm deep in the GaN matrix. The spectra are vertically shifted for clarity.

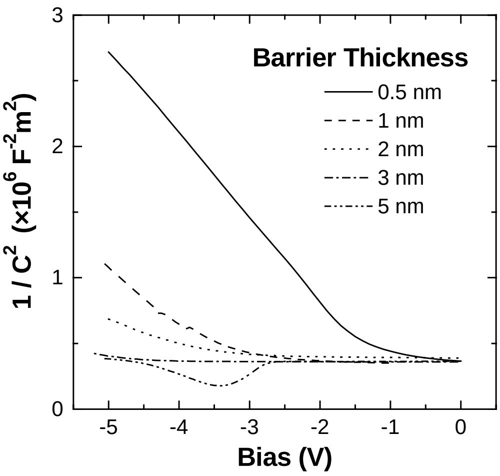

Fig. 4 : $1/C^2$-V measurements of Ø = 400 μm mesas in samples with a GaN cap of 50 nm and an AlN barrier thickness from 0.5 nm to 5 nm.

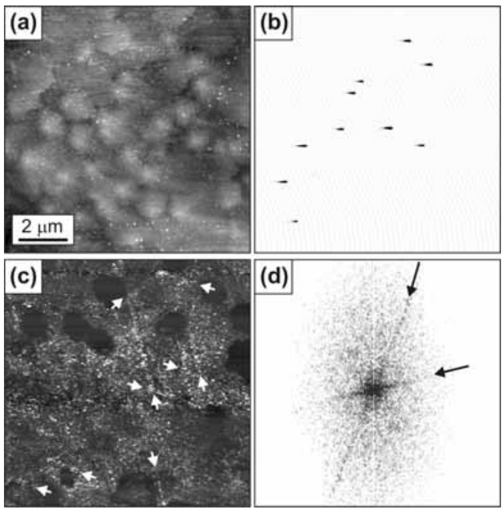

Fig. 5 : (a) AFM topographic image of the GaN(50 nm)/AlN(5 nm)/GaN structure. (b) C-AFM image under +4 V bias. (c) C-AFM image under -3 V bias. (d) 2D FFT of image (c) showing preferential orientations with a 6-fold symmetry.