Polar and semipolar GaN/AlN nanostructures for optoelectronic applications

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III-nitride semiconductors are currently the materials of choice for optoelectronic devices in the green to UV spectral region. GaN and AlN are binary compound semiconductors with wurtzite crystallographic structure and direct band gap of 3.4 eV and 6.2 eV, respectively. The huge carrier confinement in GaN/AlN nanostructures, with a conduction band offset ~1.8 eV, makes them particularly interesting for the study of quantum phenomena at high temperatures. Furthermore, their thermal and chemical stability open the way to applications in harsh environments or under extreme operation conditions.

Due to the strong carrier confinement, GaN quantum dots (QDs) embedded in an AlN matrix can act as efficient ultraviolet/visible light sources at room temperature and above. The promise of low-threshold lasers, high-temperature generation of entangled photons for quantum cryptography, or coherent manipulation of a quantum bit for quantum information processing has launched the research on GaN/AlN QDs. Moreover, such nanostructures present interesting features for the development of novel opto-chemical transducers [1], taking advantage of the transparency of the substrate, the material stability in harsh atmospheres and the spontaneous sensitivity of the surface Fermi level to the ambient chemistry – which can be additionally enhanced or functionalized. In these devices gas interaction with a catalytic metal or by direct contact to an electrolyte solution results in a chemically-induced external electric field generated by.

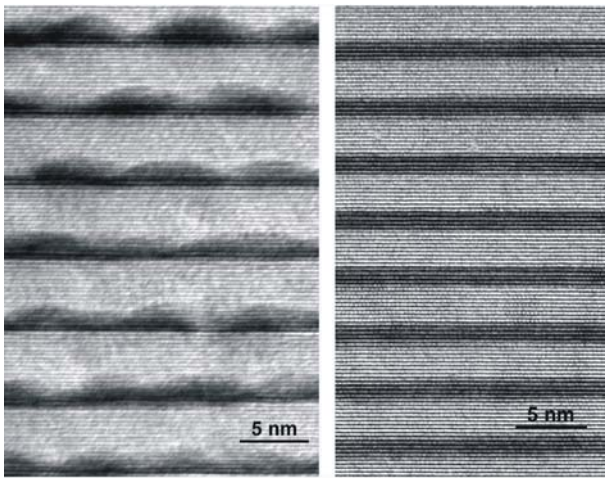

Fig. 1: High-resolution transmission electron microscopy images of (0001)-oriented GaN/AlN QD (left) and QW (right) superlattices.

On the other hand, thanks to their large conduction band offset, GaN/AlN heterostructures in the form of quantum wells (QWs) [2] or QDs [3] are excellent candidates for high-speed unipolar devices operating at optical-fiber telecommunication wavelengths, and relying on the quantum confinement of electrons. A specific advantage of III-nitrides is their extremely short intersubband (ISB) absorption recovery times (~200 fs) due to the strong Frölich interaction in these materials, which opens the way for devices operating in the 0.1-1 Tbit/s bit-rate regime. Furthermore, the remote lateral valleys lie very high in energy (>2 eV above the Γ valley), which is a key feature to achieve ISB lasing. Additionally, devices would profit from other advantages of nitride echnology, such as high power handling capabilities and chemical and thermal robustness. However, due to the rather large electron effective mass of GaN ($m^* = 0.2m_0$), QWs as thin as 1-1.5 nm are required to achieve ISB absorption at 1.3-1.55 µm.

In order to understand the electronic properties of the GaN/AlN system, it is crucial to keep in mind the presence of spontaneous polarization, which arises from the lack of symmetry of the wurtzite crystalline structure. The high piezoelectric constants, combined with a lattice mismatch of 2.5%, result in an additional polarization contribution, apart from setting a strain-engineering challenge for the grower and device designer. Therefore, GaN/AlN heterostructures grown along the *c* axis present a polarization-induced internal electric field of several MV/cm, which red shifts the luminescence lines and reduces the radiative recombination efficiency. An approach to palliate polarization effects is the use of nonpolar crystallographic orientations, with the *c*-axis

perpendicular to the growth direction (*a*- or *m*-planes). However, nitride growth along nonpolar axis is hard to control because of the strong anisotropy of the surface properties. An alternative to decrease the quantum confined Stark effect is the use of semipolar planes, with the c-axis forming an angle different from 0° or 90° with the growth direction.

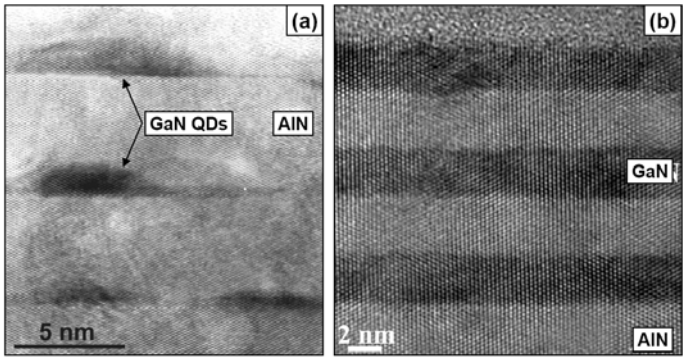

Fig. 2: High-resolution transmission electron microscopy images of (11-22)-oriented semipolar GaN/AlN QD (left) and QW (right) superlattices.

Plasma-assisted molecular-beam epitaxy (PAMBE) is the most suitable growth technique for the synthesis of GaN/AlN nanostructures due to the low growth temperature, which hinders GaN-AlN interdiffusion. Furthermore, *in situ* monitoring of the surface morphology by reflection high energy electron diffraction (RHEED) makes it possible to control the growth at the atomic layer scale. As a function of the substrate (either *c*- or *m*-sapphire), it is possible to activate the growth of (0001)- or (11-22)-oriented nitride materials. Moreover, PAMBE deposition of GaN on AlN can follow the Frank-Van der Merwe or the Stranski-Krastanow growth mode by the proper tuning of the growth parameters. Therefore, PAMBE growth of polar and semipolar GaN/AlN QWs [2,4] and QDs [3,5] with controlled nanometer dimensions and atomically abrupt interfaces has been demonstrated.

In this talk, we will summarize the latest achievements in terms of PAMBE growth and characterization of polar and (11-22)-oriented semipolar GaN/AlN QW and QD superlattices for the fabrication of opto-chemical transducers as well as unipolar devices such as QW or QD infrared photodetectors (QWIPs or QDIPs). We will discuss the structural and optical properties of these nanostructures, as well as the effect of 1-dimensional or 3-dimensional confinement, the internal electric field and various growth and design parameters on the device performance.

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