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Vertical electron transport study in GaN/AlN/GaN heterostructures

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Abstract

In this work, we investigate the electronic structure and vertical electron transport through GaN/AlN/GaN single-barrier structures with different AlN thickness, grown by plasma-assisted molecular beam epitaxy. Conductive and capacitive characterization has been performed, and the experimental results are interpreted by comparison with 1D self-consistent simulations. Capacitive measurements reveal a complete depletion of the top GaN layer, and the formation of a two-dimensional electron gas at the bottom interface of the AlN barrier, even for barrier thicknesses of 0.5 nm (2 monolayers of AlN). Conductive atomic force microscopy reveals discrete leakage current locations with a density of $\sim 10^7$ cm^{-2}, more than one order of magnitude lower than the dislocation density in these samples. These results are promising for the fabrication of resonant tunnelling diodes using the GaN/AlN material system.

Keywords: GaN; Resonant tunneling diode; Two dimensional electron gas; Conductive atomic force microscopy

1. Introduction

III-nitride materials, with their large conduction-band offet – about 2 eV for the GaN/AlN system –, 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. However, we are still far from understanding unipolar vertical electric transport in nitride heterostructures. First reports of resonant tunnelling in Al(Ga)N/GaN double barriers [1–5] are controversial because

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of the scarcity and irreproducibility of the published data. Current instabilities are admitted [2,4,5], and their assignment to resonant tunnelling or trapping is under debate. Furthermore, the current densities and peak-to-valley ratios do not correspond to the values predicted by standard tunnelling models. Understanding the vertical transport and the electronic properties of AlN/GaN tunneling barriers is hence a priority in order to improve the design of multi-barrier quantum devices, such as resonant tunnelling diodes, quantum well infrared photodetectors or quantum cascade lasers.

In this work, we investigate the charge distribution and vertical electron transport through GaN/AlN/GaN structures with different AlN barrier and GaN capping thicknesses. Capacitive measurements of samples with barrier thickness between 0.5 and 3 nm reveal the presence of a depletion region in the top GaN layer, and the formation of a two-dimensional electron gas (2DEG) at the bottom interface of the barrier, even for barrier thicknesses as small as 0.5 nm (2 monolayers of AlN). In addition, conductive atomic force microscopy has been used to identify the leakage current distribution.

2. Experimental

Samples consisting of an AlN thin layer embedded in non-intentionally-doped (n.i.d.) GaN were grown by plasma-assisted molecular-beam epitaxy (PAMBE) in a MECA2000 chamber equipped with standard effusion cells for Al and Ga. Active nitrogen was supplied by a radio-frequency plasma cell. Substrates consisted of 10 μm-thick n.i.d. GaN-on-sapphire templates. A 600 nm-thick n.i.d. GaN buffer layer was deposited prior to the growth of the AlN barrier and the 50 nm-thick n.i.d. GaN cap layer. The barrier thickness varied between 0.5 and 3 nm. The substrate temperature was $T_S = 720\,^{\circ}\mathrm{C}$, and growth proceeded under Ga excess during the deposition of both GaN and AlN, i.e. the Ga shutter remained permanently opened during growth, and AlN was obtained by additional opening of the Al cell. No growth interruptions were performed at the interfaces. We have previously reported that under these growth conditions we obtain abrupt GaN/AlN interfaces at the atomic-layer scale [6], due to the preferential incorporation of Al compared to Ga [6,7].

The electronic structure of the GaN/AlN/GaN single barrier structures was calculated from 1D self-consistent simulations using WinGreen and Nextnano^3 software [8,9]. We assumed that the AlN barriers are strained on the GaN layer, and the GaN residual doping was 5×10^{17} cm^{-3}, as deduced from our capacitance measurements. Low-temperature (10 K) photoluminescence measurements were performed by exciting the samples with a power of 1 mW from a frequency-doubled Ar laser (244 nm). Capacitive characterization was carried out using an HP4274A LCR meter and a Keithley 4200 semiconductor characterization system. Conductive atomic force microscopy (C-AFM) experiments were performed in a Dimension 3100 microscope, and a Keithley 617 programable electrometer was used to detect the localized current between a Pt/Ir AFM tip and the sample when a dc bias was applied.

3. Results and discussion

Fig. 1 illustrates the simulation of the band diagram of the 2 nm-thick AlN barrier. The difference in piezoelectric and spontaneous polarization at the GaN/AlN interfaces, induces an electric field of about 12 MV/cm in the barrier, strong band bending in the GaN cap layer and the formation of a two-dimensional electron gas (2DEG) at the AlN/GaN-buffer interface. The energy gap through the barrier (E_{GB} in Fig. 1(a)), i.e. the energy difference between the bottom