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MBE growth of AlN/GaN-based photovoltaic intersubband photodetectors

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We report on the molecular-beam epitaxial growth, fabrication and characterization of AlN/GaN photovoltaic quantum well infrared photodetectors operating at 1.55 µm. Devices display a spectrally-narrow photovoltaic response to p-polarized light in the near infrared at room temperature. We have analysed the effect of the growth temperature, quantum well thickness, and number of periods in the active region, concluding that responsivity is enhanced by growing at relatively low temperature and by increasing the number of quantum wells.

1 Introduction Intersubband (ISB) transitions in semiconductor quantum wells (QWs) have proven their capability for optoelectronics the mid- and far-infrared spectral regions. The extension of ISB optoelectronics towards the near infrared spectral region is interesting for the development of ultrafast photonic devices for optical telecommunication networks. Material systems with large enough conduction band offsets to accommodate ISB transitions at these relatively short wavelengths (1.3 µm, 1.55 µm) include InGaAs/AlAsSb, (CdS/ZnSe)/BeTe, and GaN/Al(Ga)N QWs. In the case of III-nitride heterostructures, their conduction-band offset − about 1.75 eV for the GaN/AlN system [1] − is large enough to develop ISB devices operating in the fibre-optics transmission windows at 1.3 µm and 1.55 µm. A specific advantage of III-nitrides is their extremely short ISB absorption recovery times (~150−400 fs [2]) due to the strong electron−phonon interaction in these materials, which open 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. Finally, devices would profit from other advantages of nitride technology, such as high power handling capabilities and chemical and thermal robustness.

In the last few years, various groups have reported ISB absorption at 1.3−1.55 µm in GaN/Al(Ga)N nanostructures in the form of QWs [1−5] or quantum dots [6]. The first GaN/AlN photovoltaic quantum well infrared photodetectors (QWIPs) have been recently demonstrated [7, 8].

In this work, we investigate the effect of the QW thickness, the growth temperature, and the number of periods on the properties of Si-doped GaN/AlN QW superlattices and on the performance of photovoltaic QWIP devices fabricated on those samples.

2 Growth and experimental techniques Sample growth was performed in a plasma-assisted molecular-beam epitaxy (PAMBE) chamber equipped with standard effusion cells for Ga, Al and Si, and a radio-frequency plasma cell to provide active nitrogen. Substrates consisted of 1 µm thick AlN-on-sapphire templates. The growth rate was fixed at 0.3 ML/s (~270 nm/hour).

The samples under study consist of GaN/AlN multiple-quantum-wells (MQWs) grown directly on the AlN templates. We have varied the deposition temperature, the QW thickness, the number of periods, and the barrier thickness. The QWs were Si doped with a Si concentration of 5×10^{19} cm^{-2}. All the samples were capped with a 50 nm thick AlN layer.

The structural properties of the MQWs were analyzed by high-resolution X-ray diffraction (HRXRD) using a SEIFERT XRD 3003 PTS-HR diffractometer with a beam concentrator prior to the Ge(220) 4-bounce monochroma-

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tor and a Ge(220) 2-bounce analyzer in front of the detector. The surface morphology of the MQW structures was analyzed by atomic force microscopy (AFM) in the tapping mode, using a Dimension 3100 system.

Photoluminescence (PL) was measured by exciting with the 244 nm line of a frequency-doubled continuous-wave Ar^+ laser, and the luminescence was collected by a 0.46 m focal length spectrometer equipped with a charge-coupled device (CCD) camera. For infrared absorption measurements, samples were mechanically polished in a standard multi-pass geometry with a mirror-like backside and two parallel 45° wedges, which enables 4–5 total internal reflections. The infrared transmission for p- and s-polarized light was measured at room temperature using a Fourier transform infrared (FTIR) spectrometer and a deuterated triglycine sulfate photodetector.

To test the photovoltaic response, planar photodetector devices are fabricated on the 45°-waveguide-geometry structures by evaporation of two Ti/Au contacts on the sample surface. Optical response spectra are obtained by illumination of one of the contacts through a single 45° facet, while the other contact is kept in the dark. The resulting photovoltage is amplified and fed into the external detector port of a Fourier transform infrared spectrometer.

2 Results and discussion Best GaN structural quality is achieved by deposition under Ga-rich conditions with 2 monolayers (ML) of Ga-excess segregating at the growth front, at the Ga droplet formation threshold. In the case of AlN, the Al flux is fixed to the Al/N stoichiometric value and an additional Ga flux is introduced to stabilize the surface. Unless indicated, the growth temperature is kept around 720 °C, in order to prevent the irregular thinning of the QW observed at higher temperatures. The substrate temperature is identified by refractive high-energy electron diffraction (RHEED), measuring the length of the Ga desorption transient after growth of GaN in the regime of 2 ML of Ga excess. Under these conditions, the samples present a flat surface morphology with an rms surface roughness of 1.0–1.5 nm measured in an area of $5 \times 5\ \mu m^2$. High-resolution transmission electron microscopy (HRTEM) shows homogeneous QWs, with an interface roughness of ~1 ML [9].

Samples have been analysed by HRXRD in order to confirm the layer thickness and get information on the structural quality and the strain state of the structure. Figure 1 presents the $\omega-2\theta$ scan of the (0002) reflection of a 40-period Si-doped GaN/AlN (1.5 nm/1.5 nm) QW superlattice, together with a simulation using X'pert Epitaxy software. To assess the layer strain, this measurement has been complemented with a reciprocal space mapping around the $(10\bar{1}5)$ reflection, also presented in the figure. From the analysis of these data, we can confirm the nominal layer thickness and we deduce a relaxation of the QWs of about 20%. Analysis as a function of the number of periods indicates that this relaxation takes place very fast, within the first 5 QWs.

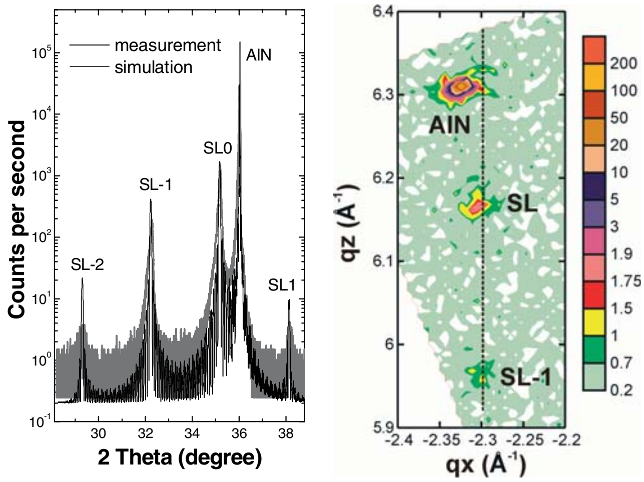

Figure 1 (online colour at: www.pss-a.com) Left: $\omega-2\theta$ scan of the (0002) reflection of a 40-period Si-doped GaN/AlN (1.5 nm/1.5 nm) QW superlattice, together with a simulation using X'pert Epitaxy software. Right: Reciprocal space map around the $(10\bar{1}5)$ reflection of the same sample.

The ISB absorption of a series of 40-period Si-doped AlN/GaN MQW structures with 5 nm AlN barriers and various GaN QW thicknesses was investigated, with the result displayed in Fig. 2. The samples show a pronounced p-polarized absorption, attributed to transition from the first to the second electronic levels in the QW ($e_1 \rightarrow e_2$), while no absorption was found for s-polarized light within experimental accuracy. For large QWs (>2.5 nm), the $e_1 \rightarrow e_3$ transition is clearly observed. This transition is allowed in nitride QWs because of the presence of strong internal electric field, which breaks the symmetry of the potential.

The samples presented in Fig. 2 were grown at a substrate temperature of 720 °C. In order to evaluate the effect of the substrate temperature on the optical properties of the structures, we have synthesized a series of three samples

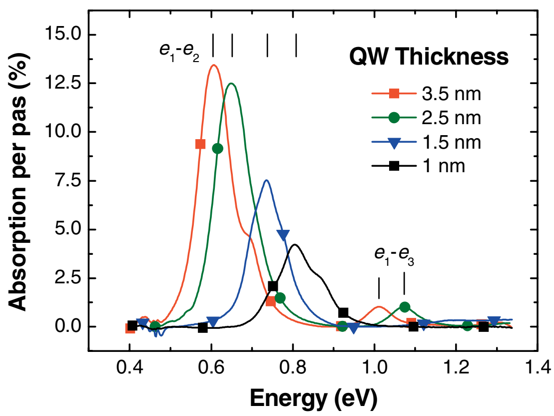

Figure 2 (online colour at: www.pss-a.com) Room-temperature p-polarized ISB absorption spectra from Si-doped GaN/AlN MQW structures with 5 nm thick AlN barriers and different GaN QW thickness.

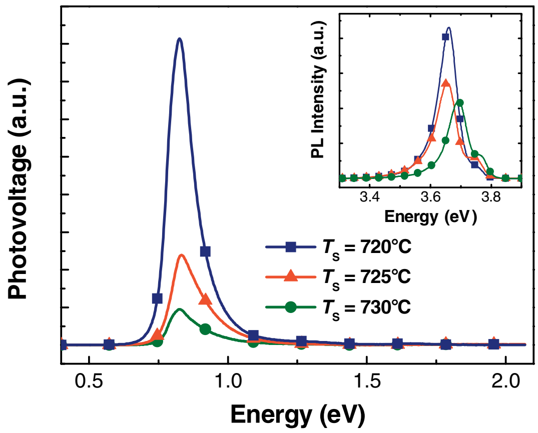

Figure 3 (online colour at: www.pss-a.com) Low-temperature ($T = 10$ K) photovoltaic response of QWIPs fabricated on GaN/AlN MQW structures grown at different substrate temperatures. In the inset, low-temperature ($T = 10$ K) photoluminescence spectra from the same GaN/AlN MQW structures.

grown at different substrate temperature and consisting of 40-period GaN/AlN (1.5 nm/1.5 nm) QWs in the active region. The samples have been characterized by low-temperature PL, as presented in the inset of Fig. 3. For increasing growth temperatures, we observe a decrease of the PL intensity together with a blue shift, which is explained by the QW thinning induced by AlN overgrowth at high temperature [10]. The improved optical performance for low growth temperature is further confirmed by the photovoltaic response of QWIPs fabricated on these samples. The low temperature (10 K) spectral response displayed in Fig. 3 shows a decrease of the responsivity by almost one order of magnitude when increasing the growth temperature from 720 °C to 730 °C.

We have fabricated a series of GaN/AlN (1.5 nm/ 1.5 nm) superlattices to evaluate the effect of the number

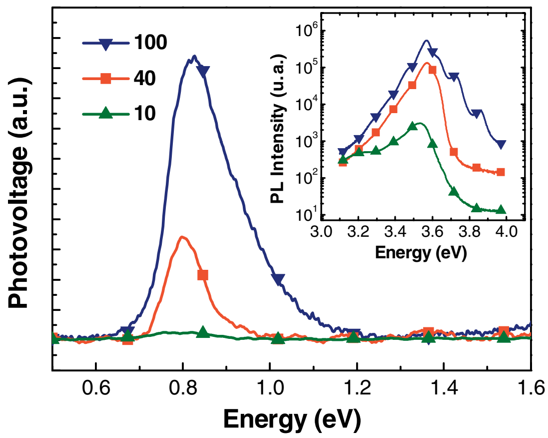

Figure 4 (online colour at: www.pss-a.com) Room-temperature photovoltaic response of QWIPs fabricated on GaN/AlN MQW structures with different number of periods. In the inset, low-temperature ($T = 10$ K) photoluminescence spectra from the same GaN/AlN MQW structures.

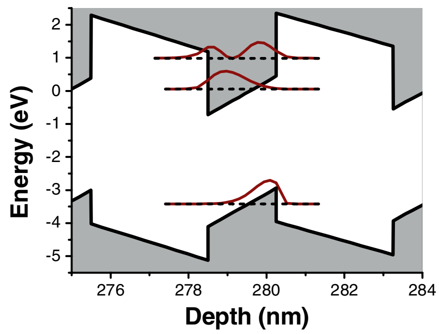

Figure 5 (online colour at: www.pss-a.com) Band diagram of a GaN QW in an AlN/GaN superlattice.

of periods on the performance of the devices. Low temperature ($T = 10$ K) PL measurements are shown in the inset of Fig. 4. All the structures present about the same PL peak energy (about 3.55 eV), which is a good indication of sample reproducibility. We observe however a broadening and structuration of the emission for increasing number of periods. This might be explained by a thermal drift during the growth of thick structures.

The ISB absorption of these samples was characterized by FTIR spectroscopy obtaining an increase of the absorption proportional to the number of periods (not shown). Photovoltaic QWIP devices fabricated on these structures present a clear signal at room temperature, as illustrated in Fig. 4. We observe that the peak photovoltaic signal increases with the number of periods, which indicates that all the QWs participate in the photodetection process.

These results are consistent with the interpretation of the photovoltage as due to optical rectification [11]. The strong piezo- and pyroelectric effects in these material family lead to intrinsic asymmetries of the electronic potential in the QWs, as illustrated in Fig. 5. Since in a GaN/AlN superlattice, the transition of an electron to an excited energy level implies a small displacement of the wave function in the growth direction, which results in an electrical dipole moment. For high electron density and in a multiple QW structure, these dipole moments add up and can be detected as an external photovoltage.

4 Conclusion

We have investigated the effect of the growth temperature, QW thickness, and number on period on the performance of GaN/AlN photovoltaic quantum well infrared photodetectors. Devices display a spectrally-narrow photovoltaic response to p-polarized light in the near infrared at room temperature. Best results are obtained for growth at relatively low temperature. The responsivity scales with the number of QWs in the active region.

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