Room-temperature intersubband emission of GaN/AlN quantum wells at $\lambda = 2.3\ \mu m$

L. Nevou, F.H. Julien, R. Colombelli, F. Guillot and E. Monroy

Optically-pumped intersubband emission of GaN/AlN quantum wells at room temperature has been experimentally demonstrated for the first time. The peak emission wavelength is at $\lambda = 2.3\ \mu m$. It is the shortest value ever reported for an intersubband device.

Introduction: Unipolar light emitting devices, i.e. devices based on intersubband (ISB) transitions in semiconductor quantum wells, such as the quantum cascade (QC) or the optically-pumped quantum fountain (QF) laser, have already been successfully demonstrated in the mid- and far-infrared wavelength ranges using the GaAs/AlGaAs or the InGaAs/AlInAs-on-InP material systems [1, 2]. On the other hand, nitride heterostructures offer new prospects for unipolar lasers operating at room temperature in the near-IR spectral range, thanks to their large conduction-band offset (~1.75 eV for GaN/AlN). Intersubband absorptions at fibre-optic telecommunication wavelengths have been observed by several groups using GaN/AlGaN quantum wells (QW) or quantum dots (QD) [3]. However, despite a number of theoretical proposals for nitride-based QC or QF light emitting devices, the observation of ISB emission in this material system has proven elusive. One difficulty is the extremely low luminescence efficiency. This is a characteristic of all ISB emitters and it stems from the very short non-radiative electron-LO phonon scattering times. In nitrides, the excited electron lifetime has been measured to be in the range 150–300 fs [4]. It should be noted, however, that a weak luminescence efficiency does not prevent the realisation of high-performance QC or QF lasers, since the oscillator strength associated with ISB transitions is very large.

In this Letter, we report the first observation of room-temperature ISB emission in GaN/AlN quantum wells at a record short wavelength of $\lambda = 2.3\ \mu m$. The QWs are designed to exhibit three bound states in the conduction band, as shown in Fig. 1. Optical pumping resonant with the $e_1 - e_3$ ISB transition is used to populate the e_3 excited state. The emission is ascribed ISB radiative recombination between state e_3 and state e_2.

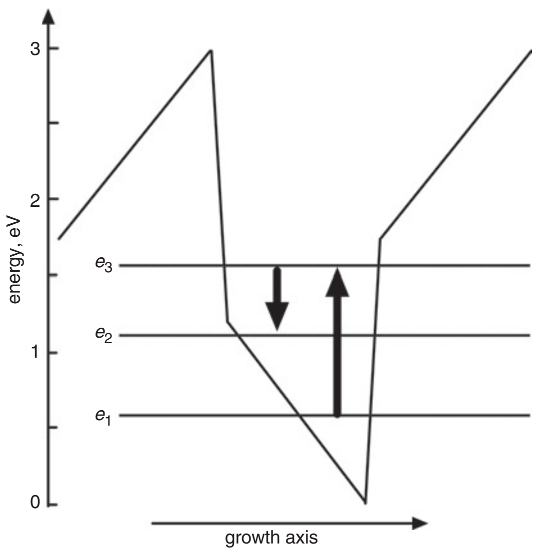

Fig. 1 *Conduction band profile and energy levels of GaN/AlN quantum wells*

Sample growth: The sample was grown by plasma-assisted molecular-beam epitaxy on a 1 μm-thick AlN buffer on *c*-sapphire. It contains 250 periods of GaN QW layers separated by 3 nm-thick AlN barriers. The nominal thickness of the wells is 8 monolayers (ML), i.e. 2.07 nm. The wells are doped with silicon at a concentration of $5 \times 10^{19}\ cm^{-3}$ in order to populate the ground state with electrons. For spectroscopic measurements, two opposite facets of the sample were mechanically polished at 45° angle to form a multipass waveguide with 10 total internal reflections. For the luminescence measurements, only one facet of the sample is polished at 45° angle.

Measurements: Fourier transform infrared spectroscopy (FTIR) was performed at room temperature using either the multipass waveguide configuration or light irradiation at Brewster's angle incidence in order to determine the ISB transition energies. For the luminescence measurements, optical excitation is provided by a tunable Ti:sapphire near-infrared laser operated in continuous wave under optical pumping by a 20 W Ar^{++} laser. The laser beam is focused onto the 45° angle facet using a quartz lens with 5 cm focal length and the pump beam experiences multipass reflections in the sample. The emission from the opposite facet of the sample is collected by an achromatic spherical mirror with 2 cm focal length and 5 cm diameter. A 5 mm-thick Ge plate is used to reject the residual pump light. The emission beam is then directed onto the emission port of the FTIR spectrometer operated in the step-scan mode. Detection is performed by a liquid nitrogen cooled InAs detector. For high-sensitivity lock-in detection purposes, the pump beam is mechanically chopped at 5 kHz frequency. All experiments were performed at room temperature. The spectral response of the optics, filter and detector was carefully calibrated.

Results: Fig. 2 shows the absorption spectrum of the sample at Brewster's angle incidence for *p*-polarised light. The peak at $\lambda \sim 1.7\ \mu m$ (0.73 eV) is ascribed to the $e_1 - e_2$ ISB absorption. The ripple visible in the spectrum is not due to optical interferences. Indeed, in agreement with the theoretical and experimental investigations of [3], the peaks at $\lambda \sim 1.53$, 1.67 and 1.8 μm correspond to the ISB absorption of QWs with a thickness of 7, 8 and 9 ML, respectively. The full width at half maximum (FWHM) is around 41 meV for each peak. In the waveguide configuration, the $e_1 - e_2$ absorption is much stronger because of the multiple passes in the active layer, and a new peak appears at $\lambda \sim 0.98\ \mu m$ with a FWHM of 110 meV. This absorption is ascribed to the $e_1 - e_3$ ISB absorption of 8–9 ML-thick QWs, in agreement with [3].

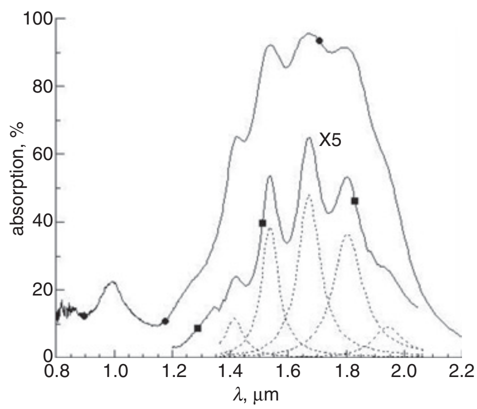

Fig. 2 *Transmission spectrum of sample*

–◆– multipass waveguide
–■– Brewster's angle incidence
– – – Lorentzian fit

Fig. 3 shows the uncorrected emission spectrum of the sample under *p*-polarised selective excitation at $\lambda \sim 0.98\ \mu m$ in resonance with the $e_1 - e_3$ transition in addition to the spectral response of the optics and detector. The pump power is 1 W. As seen in Fig. 3, the emission is peaked at $\lambda = 2.3\ \mu m$ (0.54 eV) with a FWHM of 160 meV. The peak position is very close to the expected energy (0.535 eV) of the $e_3 - e_2$ ISB transition deduced from transmission measurements. The emission is mainly *p*-polarised, as expected from ISB polarisation selection rules, with a ratio between *p*- and *s*-polarisation exceeding a factor of 3. The residual *s*-polarised signal is probably due to depolarisation effects because of multiple reflections inside the sample. The emission signal vanishes when the pump beam polarisation is rotated from *p*- to *s*-polarisation. This is proof that the luminescence originates from ISB transitions in the quantum wells. In addition, when tuning the pump wavelength, the luminescence signal closely follows the $e_1 - e_3$ absorption lineshape. The efficiency of the collected $e_3 - e_2$ ISB luminescence is measured to be in the range 10–11 nW per Watt of pump power. The internal ISB luminescence efficiency for one QW is calculated to be 38 pW per Watt, based on estimates of the radiative and non-radiative lifetimes.

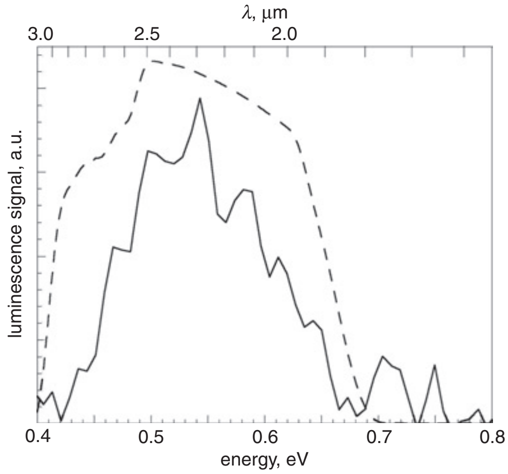

Fig. 3 *Luminescence spectrum of sample, and spectral response of optical system*

—— luminescence spectrum
– – – spectral response

Conclusion: We report the observation of room-temperature intersubband emission between excited states of GaN/AlN quantum wells under optical pumping of the $e_1 - e_3$ ISB absorption. The peak emission wavelength is $\lambda = 2.3$ μm. It is the shortest value reported so far for any ISB light emitting device.

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