Intersubband spectroscopy of electron tunneling in GaN/AlN coupled quantum wells

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Abstract—**We report on the observation at room-temperature of intersubband electro-absorption modulation in GaN/AlN coupled quantum wells at short infrared wavelengths covering the fibre-optics telecommunication range. The electro-modulation originates from electron tunneling between a wide well (reservoir) and a narrow well, separated by an ultrathin AlN barrier. Electro-absorption modulation with opposite sign is observed at λ=1.2-1.67 µm and λ=2.1-2.4 µm. Both intersubband absorption and modulation spectroscopic measurements are in good agreement with simulations. The modulation depth is ~44 % at λ=2.2 µm under maximum applied bias. The -3 dB cut-off frequency limited by the RC time constant is 11.5 MHz for 700x700 µm^2 mesa.**

Index Terms— **Electro-optical modulation, electron tunneling, intersubband absorption, GaN/AlN coupled quantum wells**

I. Introduction

Wide band gap III-nitride semiconductors are of great interest for intersubband (ISB) devices operating at telecommunication wavelengths, thanks to the large conduction band offset offered by their heterostructures (~1.75 eV for GaN/AlN) and to the very fast ISB absorption recovery time [1-3]. Ultrafast optical switches, high frequency ISB photodetectors at λ=1.55 µm as well as ISB light emitting devices have been recently demonstrated [4-6]. Electro-optical modulators are also key components for high data-rate fibre-optics telecommunication systems. Modulators based on the Stark shift of ISB absorption in GaN/AlGaN quantum wells (QWs) with frequency responses at -3 dB as high as 60 GHz have been proposed [7]. It was predicted that ISB modulators would provide better handling of chirp issues during the commutation process with respect to current technologies based on interband electro-absorption. Experimentally, nitride ISB modulators relying on the charge transfer between a 2D electron gas and a superlattice have been demonstrated [8]. The recent observation of strong electronic coupling between GaN/AlN QWs opens new prospects for ISB modulators relying on charge transfer between the wells [9]. Such principle of operation has proved to be effective at long infrared wavelengths in GaAs/AlGaAs coupled quantum wells (CQWs) [10-11].

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II. Experimental Results

Here we report on an ISB electro-absorption modulation device operating at room temperature, which relies on electron tunneling in GaN/AlN CQWs. The active structure consists of a wide well (electron reservoir) showing ISB absorption at 2.2 µm, and of a narrow well designed to exhibit ISB absorption at $\lambda\approx$1.3 µm. Under positive bias, charge is transferred into the narrow well, which gives rise to an electro-modulated absorption covering the telecommunication wavelength band.

The sample was grown by plasma-assisted molecular beam epitaxy on an AlN/*c*-sapphire template. The active region, sandwiched between two $Al_{0.6}Ga_{0.4}N$ layers n-doped at 1×10^{19} cm^{-3}, contains 20 periods of CQWs separated by 29 nm thick AlN spacer layers. In growth order, the CQWs consist of a 2.9 nm thick GaN reservoir well, a 1 nm thick AlN coupling barrier and a 1 nm thick GaN well n-doped with silicon at 5×10^{19} cm^{-3} (layer thickness deduced from transmission electron microscopic measurements). The samples are processed in the form of square mesas of 700×700 µm^2 using reactive ion etching with chlorine gas. A Ti/Al/Ti/Au metallization followed by annealing at 750°C during 30 sec is then performed to form the top and bottom contacts. The center area of the mesas (500×500 µm^2) is not metallized in order to allow testing of the devices at Brewster's angle of incidence.

The infrared transmission for p- and s- polarized light was measured at room temperature using a Fourier Transform Infrared (FTIR) spectrometer. The p-polarized absorption spectrum (Fig. 1) shows a peak at 0.56 eV with a full width at half maximum (FWHM) of 85 meV and a magnitude of 40% as well as a broader structured peak at 0.9 eV with FWHM of 105 meV and absorption magnitude of 16%. No absorption is observed within experimental accuracy for s-polarized light.

The quantum confinement in the CQWs was modeled using the envelope function approximation by self-consistently solving the Schrödinger and Poisson equations. A detailed description of the model can be found in Ref. [12]. The inset of Fig.1 shows the calculated CB profile of the CQW. The two lower states, e_1 and e_2 are close in energy (e_2-e_1= 28 meV). Based on the measured absorption efficiency, we have estimated the populations at room temperature of the e_1 and e_2 subband to be 3.4×10^{12} cm^{-2} and 1.7×10^{12} cm^{-2}, respectively. Fig. 1 compares the calculated and measured absorption spectra. The absorption at 0.56 eV is ascribed to the e_1e_3 ISB transition originating from the reservoir well, while the broad absorption at 0.9 eV mainly arises from the e_2e_4 and e_2e_5 ISB transitions with a smaller contribution from the low oscillator strength e_1e_5 transition. The multiple transitions involved in the absorption peak at 0.9 eV explain the larger broadening with respect to the absorption at 0.56 eV.

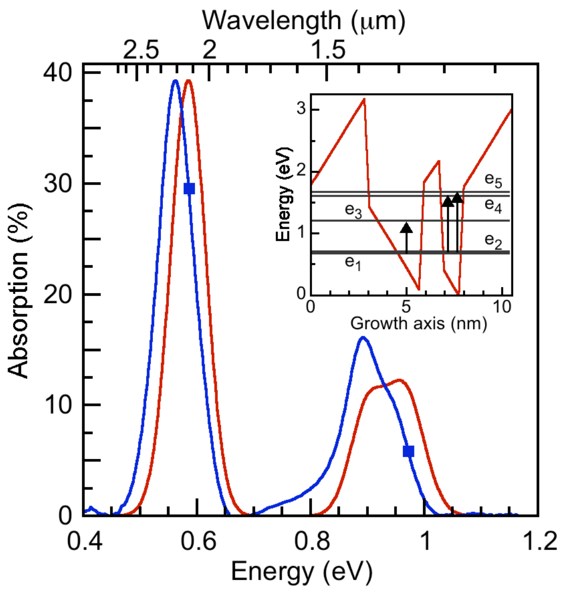

Fig. 1. Room-temperature absorption spectrum for p-polarized light (squares) and calculated ISB absorption (red curve). The inset shows the CB profile and energy levels for one period of CQWs.

The electron tunneling between the wells was probed at room temperature by measuring the ISB absorption at Brewster's angle of incidence versus applied bias. The sign and magnitude of the transmission change, ΔT/T, was calibrated at a wavelength of 1.34 μm using irradiation by a continuous-wave Nd:YVO4 laser. Fig.2 shows the transmission change for various positive and negative bias pulses. As illustrated in the inset to Fig.2, with increasing positive bias, electrons are transferred from the reservoir well to the active well and the ISB e_1e_3 absorption at λ=2.2 μm decreases, while the absorption in the wavelength range of 1.2-1.67 μm increases. An opposite behavior is observed for negative bias. This is a clear signature that the absorption modulation arises from the charge transfer between the two wells and that it is not due to the depletion of the active region as in Ref 8. Fig.2 also shows the calculated differential transmission of the sample at an applied bias of 0.8 V across the active region (according to the measured access and shunt resistances, this value corresponds to ≈30V applied to the contacts). The calculated spectrum well reproduces the main features of the modulation measurements, i.e. a decrease of the low-energy absorption accompanied by an increase of the high-energy absorptions related to the ISB transitions in the narrow well. The model also predicts a Stark shift of the e_1e_3 transition, which manifests as an increase of the absorption at 0.6 eV but which is not clearly observed experimentally. The absorption change at λ=2.2 μm under 30 V applied bias is 0.29 %, which is to be compared with the value of 0.68 % for the absorption at Brewster's angle of incidence. The modulation depth is then estimated to be 44 % (2.4 dB).

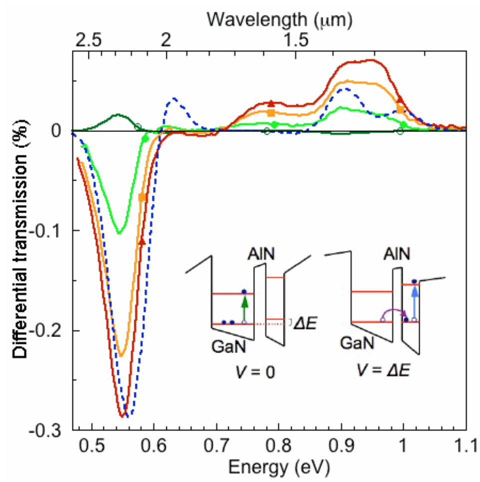

Fig. 2. Differential transmission ΔT/T versus photon energy for applied bias pulses of +30V (triangle), +20V (squares), +10V (full circles), and -5V (open circles). The dashed line shows the calculated transmission change. The inset illustrates the principle of operation.

The cut-off frequency of the modulator at -3 dB is measured to be 11.5 MHz, limited by the RC time constant of the 700×700 μm^2 mesas. In order to increase the modulation depth and frequency response, clear efforts must be devoted to reduce the access resistance and capacitance of the device, which can be achieved through higher doping and lower Al content of the AlGaN contact layers and through the device miniaturization. Frequency response exceeding 10 GHz can be expected in 10×50 μm^2 micro devices.

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