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Non-linear properties of nitride-based nanostructures for optically controlling the speed of light at 1.5 μm

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ABSTRACT

Future bandwidth demand in optical communications requires all-optical devices based on optical non-linear behavior of materials. InN, with a room temperature direct bandgap well below 0.82 eV (1.5 μm) is very attractive for these applications. In this work, we characterize the non-linear optical response and recombination lifetime of the interband transition of InN layers grown on GaN template and Si(1 1 1) by molecular beam epitaxy. Non-linear characterization shows a decrease of the third-order susceptibility, $\chi^{(3)}$, and an increase of recombination lifetime when decreasing the energy difference between the excitation and the apparent optical band-gap energy of the analysed samples. Taking into account the non-linear characterization, an optically controlled reduction of the speed of light by a factor $S = 4.2$ is obtained for bulk InN at 1.5 μm. The S factor of InN (5 nm)/$In_{0.7}Ga_{0.3}N$ (8 nm) multiple quantum well heterostructures at the same operation wavelength is analysed, predicting an increase of this factor of three orders of magnitude. This result would open the possibility of using InN-based heterostructures for all-optical devices applications.

1. Introduction

During the last years, there has been an increasing demand of higher optical bandwidth and transparency in optical networks. The main challenge to satisfy this demand lies in the network nodes themselves, since the electronic processing of information in these nodes is inherently bandwidth limited and not transparent to the data format. Therefore, these nodes should evolve towards an all-optical control of the information [1]. Thus, the active control of the timing of light pulses is attracting much attention for the development of fast-access memories and optically controlled delay lines compatible with fibre-optic communication systems. It is possible to achieve a control of the speed of light by creating spectrally narrow gain/loss bands in the medium through optical pumping. In this kind of steep transitions, the group index is strongly increased or reduced, giving as a result that the group velocity (i.e., the velocity at which a narrow-band signal propagates) is strongly modified [2]. This effect had only been observed in the resonances of certain ultra-cold atomic gases through a process called electromagnetically induced transparency (EIT) [3] and in certain crystalline solids using the process known as population oscillations (PO) [4]. However, these demonstrations were performed at wavelengths of little interest for fibre-based optical communications. Additionally, several techniques to achieve slow and fast light have been demonstrated in optical fibres, namely using stimulated Brillouin [5], Raman scattering [6] and parametric amplification [7]. All these embryonic studies show clearly the strong potential of this way of implementing optically controlled delay lines.

The demonstration of the slow-light effect in AlGaAs/GaAs multiple quantum wells (MQW) at 850 nm wavelength using the PO technique [8] has paved the way for achieving similar results in the wavelength band of interest for optical fibres (1.3–1.5 μm) by using suitably band-engineered materials. In particular, InN and ternary semiconductors based on GaN and InN are ideal candidates, since they exhibit direct bandgap and a highly stable behaviour. Also, quantum wells and quantum dots with high In content and InGaN or GaN barriers should allow meeting the required wavelengths. Furthermore, absorption saturation processes in InN have been reported [9,10], which is a requirement for slow light generation in solids.

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This paper presents a preliminary evaluation on the suitability of InN for the development of slow-light devices in the spectral region around 1.5 μm. To this aim, we have measured the third-order susceptibility, $\chi^{(3)}$, of thick InN samples with different apparent optical band-gap. With this data, we have calculated the slow-down factor that we can achieve in the material at reasonable pump fluencies, reaching values in the order of 4.2. Estimations of S factor for InN/InGaN shows that further work in these heterostructures may yield slow-down factors several orders of magnitude higher.

2. Experimental results

The InN samples investigated in this work were grown on 10-μm-thick non-intentionally doped (nid) GaN-on-sapphire templates and on Si(111) substrates by plasma-assisted molecular beam epitaxy (PAMBE). In situ growth monitoring was performed by reflection high energy electron diffraction (RHEED).

In the case of the InN grown on GaN-on-sapphire templates (sample S1), prior to the growth of the InN layer, a 10-nm-thick nid GaN buffer layer was deposited at 720 °C. InN growth was then carried out at a substrate temperature of 450 °C, with a N flux corresponding to a growth rate of 0.3 monolayers per second, and with an In/N ratio of 1.2. Periodic growth interruptions under N are performed to consume the In excess and prevent qthe accumulation of In droplets on the surface. The growth period (InN growth time/growth interruption time) for sample S1 was 5/1 min.

For InN sample grown on Si(111) (sample S2), the substrates were heated in the growth chamber at 800 °C for 30 min to remove the native oxide. The AlN buffered Si(111) was preceded by depositing a few monolayers of metallic Al at high temperature. Afterwards, the AlN buffer layer was grown at 780 °C at a rate of 200 nm/h to minimize surface roughness [11]. Once the buffer layer is grown, the growth is stopped to decrease the temperature down to 475 °C [12]. InN layers were grown under slightly indium-rich conditions at a rate of 0.8 μm/h. A streaky 1×1 RHEED pattern observed during all the growth indicates two-dimensional growth mode.

Linear optical properties of the samples in the wavelength range of 1100–2550 nm were studied at room temperature by normal-incidence transmission measurements, using a Perkin-Elmer Lambda 9 scanning spectrophotometer.

Optical non-linear characterization has been performed by forward degenerate four-wave mixing (DFWM) technique in boxcars configuration [13]. For this technique, the excitation source used was an optical parametric amplifier (OPA) providing 100 fs pulses, tunable in the 300–3000 nm interval, at a repetition rate of 1 kHz. The relaxation time of the excited carrier population grating (τ) has been determined by introducing a delay line in one of the arms of the experimental setup.

Fig. 1 shows the measured transmission data (straight line) of the investigated InN samples. Substrate limits the maximum transmittance to 0.86 and 0.53 for sapphire and silicon, respectively. Experimental transmission spectra were compared with theoretical calculations using a three-layer model (substrate/buffer layer/InN) [14] to obtain values of thickness, ordinary refractive index $n_0(\lambda)$, and absorption coefficient $\alpha(\lambda)$ of the InN layer. A sigmoidal approximation was used for $\alpha(\lambda)$ [15], meanwhile $n_0(\lambda)$ was obtained in the transparency region considering a first-order Sellmeier dispersion formulas [16]. Scattering from rough surface is included in the calculations that follow the model proposed by Filinski [17]. The optical absorption band edge of the samples is estimated at 1550 nm (sample S1) and 1650 nm (sample S2). High resolution X-ray diffraction measurements

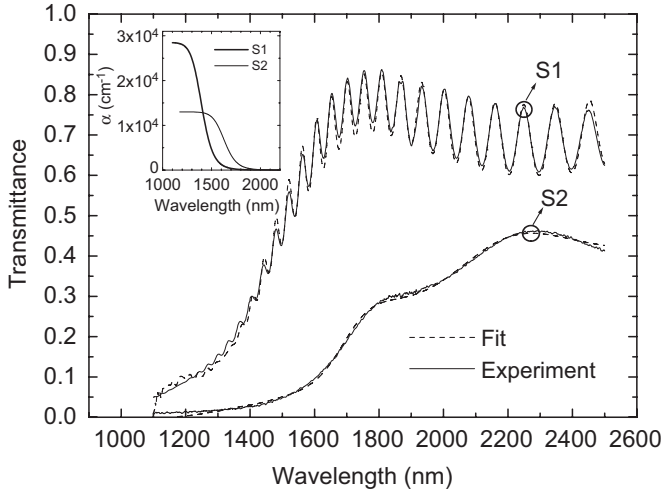

Fig. 1. Transmission spectra of the InN analysed samples. Inset: calculated absorption coefficient.

Table 1
Summary of results obtained from linear and non-linear optical measurements at 1500 nm

Sample	Substrate	Thickness (nm)	α (cm^{-1})	n	αL	$\lvert\chi^{(3)}\rvert$ (esu)
S1	GaN template	650	4.7×10^3	2.85	0.3	$(5.4\pm0.5)\times10^{-10}$
S2	Si(111)	1000	1.2×10^4	2.95	1.3	$(8.0\pm0.8)\times10^{-10}$

(not shown) lead to values of c-lattice parameter of 5.690 Å (S1) and 5.700 Å (S2), within the range of values measured in high quality single crystalline InN films (scattered in the range of $c = 5.69$–5.705 Å [18]). Thus, the difference in the obtained optical bandgap is attributed to the Burstein–Moss effect induced by a slightly different residual electron concentration in the samples, both in the range of 10^{19} cm^{-3} [19].

Table 1 summarizes the linear optical estimations performed for 1500 nm applied to the later $|\chi^{(3)}|$ calculation. Absorption by the GaN and AlN buffer layers (sample S1 and S2, respectively) was considered negligible at 1500 nm, while refractive index of GaN and AlN was estimated about 2.23 and 1.75 at 1500 nm, respectively.

Regarding the DFWM measurements, the coefficient c of the relationship $I_C = cI_P^3$ has been obtained by plotting the conjugated beam intensity I_C versus the pump intensity I_P. A fused silica (SiO_2) plate with $|\chi^{(3)}| = 1.28\times10^{-14}$ esu and $n_0 = 1.45$ [13] was used as reference. Details about $|\chi^{(3)}|$ calculations can be found in Ref. [20]. $|\chi^{(3)}|$ values of $(5.4\pm0.6)\times10^{-10}$ esu and $(8.0\pm0.8)\times10^{-10}$ esu were measured at 1500 nm for samples S1 and S2, respectively. The obtained $|\chi^{(3)}|$ value increases with the linear absorption of the samples being higher for the sample with the lowest optical bandgap (S2). This behavior is consistent with a resonant excitation, as observed when analysing the change in $|\chi^{(3)}|$ with the excitation wavelength for a given sample [20].

The resonant character of the involved mechanism for InN leads to values of $|\chi^{(3)}|$ close to two orders of magnitude above the measured one for GaN $(4.4\pm0.4)\times10^{-12}$ esu [20] and Si 2.8×10^{-11} esu [21] at 1500 nm. Furthermore, contribution of substrate to the measured $|\chi^{(3)}|$ was neglected performing the DFWM experiments with a pump power below the limit to obtain a measurable non-linear response for the substrate [20].

Fig. 2 shows the DFWM signal intensity as a function of the induced delay time for the analysed samples. Lifetime estimated