Study of Absorption Saturation in InN Thin Films through the Z-Scan Technique at 1.55 µm

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Abstract: We investigate the nonlinear absorption saturation effect of thin InN films at 1.55 µm through the z-scan technique, varying the pumping peak intensity. Over 30 % nonlinear change in sample transmittance has been estimated.

OCIS codes: (160.4330) Nonlinear optical materials; (160.6000) Semiconductor materials; (260.3060) Infrared

1. Introduction

Materials exhibiting nonlinear absorption processes are required for many applications, such as nonlinear optical filtering or fabrication of all-optical switches in photonic integrated circuits. Particularly, saturable absorbers are the cornerstone for mode-locking and Q-switching applications in laser resonators. These types of materials experiment an increase of their transmittance as a function of the pumping intensity. The z-scan technique is one of the most accepted ways to determine not only the nonlinear absorption, but also the nonlinear refraction of any material, mainly due to the huge information it reveals and its simplicity. This technique was first proposed by M. Sheik-Bahae *et.* al. in 1990 [1], consisting on pumping a material with low and high intensities. This is carried out by placing the material in a stage that can travel around the focus of a lens, thus increasing the intensity when the sample is approaching the focus.

III-nitride semiconductors have attracted large attention due to their unique properties, such as high thermal and chemical stability, high radiation hardness, and a direct and widely tunable band gap [2]. Among them, InN has been typically used for visible applications. However, due to its band gap energy (0.65 - 0.90 eV), this material seems appropriate for operation in the near infrared, since it can be resonant at different wavelengths in this range. Moreover, InN has previously demonstrated large saturable absorption effect in the C-Band (1.55 µm) [3]. However, its saturation intensity has never been explored using the z-scan technique, as far as we know.

In this work, we investigate the absorption saturation effect of two different 1-µm-thick InN thin films, presenting a different band gap energy, through the z-scan technique for different values of the peak intensity.

2. Nonlinear measurements of thin InN films

The samples studied in this work comprise a 1-µm-thick InN layer grown by molecular beam epitaxy at 450 ºC with a nitrogen-limited growth rate of 280 nm/h. In both samples, a 10-µm-thick GaN-on-sapphire template has been used as substrate. The main difference between them is that one of the samples has been directly grown on the substrate (S1), while in the other 11 periods of $InN/In_{0.3}Ga_{0.7}N$ (4.5 nm / 7 nm) have been deposited as a buffer layer before growing the InN film (S2). The introduction of this buffer layer has led to an improvement of the structural quality on one hand [4], and on the other to a reduction of the free carrier concentration, and thus, to the reduction of the Burstein-Moss effect, which increases the absorption band gap energy with the carrier concentration [5]. The band gap energy for each sample has been estimated from linear transmittance measurements by using a Tauc plot, finding values of E_g (S1) ~ 0.80 eV (1549 nm) and E_g (S2) ~ 0.77 eV (1610 nm). This shift is attributed to the reduction of the carrier concentration, which has been estimated in 10^{19} cm^{-3} for S1, and 5×10^{18} cm^{-3} for S2, using reference [5].

The complete study of the nonlinear absorption has been carried out through the z-scan method. The pump source used for this purpose delivers 250 fs pulses, with a repetition rate of 5.2 MHz, and 32.5 mW average power. Using a 3-cm lens, the maximum peak intensity has been estimated in $I_P = 14.5$ GW/cm^2, being the beam waist ω_0 ~ 15 µm. Measurements at different peak intensities have been carried out for each sample, as depicted in Fig. 1(a) and (c) for S1 and S2 respectively. It can be observed that S2 exhibits a huge nonlinear change, with over 300% change in its transmittance level for the maximum peak intensity, which is closed to the full bleaching limit of the structure. A similar situation is obtained for sample S1, but with a total change in transmittance of ~60 %, lower than for S2. With the linear transmittance value estimated at 1.55 µm, T_{lin} = 26.1 % for S1, and T_{lin} = 11.7 % for S2 and the net change in transmittance, the total transmittance as a function of the peak intensity has been estimated, as

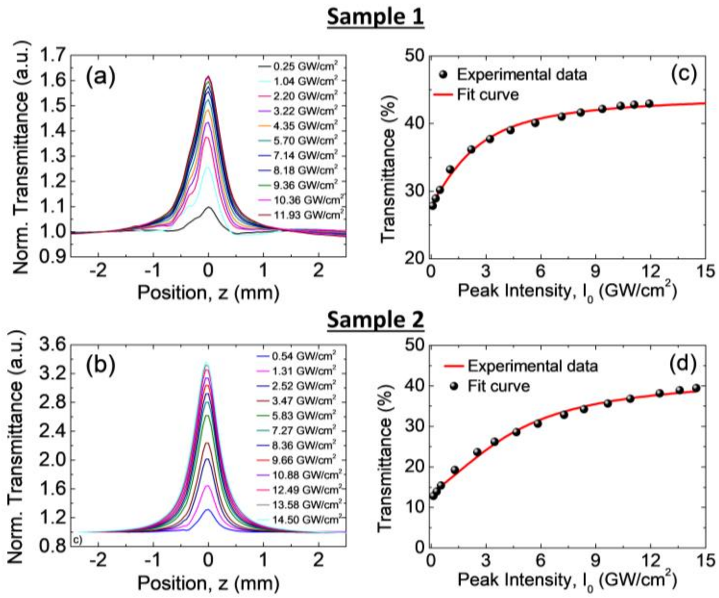

Fig. 1: (a) Experimental z-scan measurements varying the excitation peak intensity for (a) S1 and (b) S2. The peak intensity is shown for each measurement. Estimated transmittance obtained as a function of the peak intensity for (c) S1 and (d) S2. Line corresponds to fit to equation (1) in each case.

plotted in Figs. 1(b) and (d) for S1 and S2 respectively. The curves have been fit to equation (1), originally proposed by M. Haiml *et*. al [6], but modified for transmission configuration, where T_{sat} is the transmittance at which the sample totally bleached, and I_{sat} corresponds to the saturation intensity:

$$T = T_{sat} \frac{\ln\left(1 + T_{lin} \big/ T_{sat} \left(e^{I_P/I_{sat}} - 1\right)\right)}{I_P \big/ I_{sat}} \tag{1}$$

From the fitting, values of T_{sat} = 44.5 % and I_{sat} = 1.08 GW/cm^2 have been estimated for S1, and T_{sat} = 43.8 % and I_{sat} = 1.45 GW/cm^2 for S2.

3. Conclusions

In conclusion, the saturation absorption effects at 1.55 μm of two 1-μm-thick InN thin films have been investigated through the z-scan technique. The sample with an estimated band-gap energy closer to the excitation wavelength shows a lower nonlinear behavior, with a net nonlinear change of $\Delta T(S1) \sim 18.5$ % and $\Delta T(S2) \sim 32$ %. This can be explained since the bleaching level in both samples is very similar, but S2 attains a higher linear absorption coefficient than S1. Moreover, the saturation intensity in the two samples is close to 1 GW/cm^2. From the measurements that we have presented, we conclude that both samples have exhibited a large nonlinear effect and seem promising for mode-locked lasers at 1.5 μm, with shorter pulses expected for S2.

Partial supported by: Spanish Government, TEC2015-71127-C2-2-R, Community of Madrid S2013/MIT 2790.

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