Ultrafast All-optical Switches Based on Intersubband Transitions in GaN/AlN Multiple Quantum Wells for Tb/s Operation

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ABSTRACT

Theoretical and experimental results on ultra-fast all-optical switches based on intersubband transitions for Tb/s operation are presented. Designs for engineering intersubband transitions (ISBT) in GaN/AlN quantum wells near communication wavelengths (~1.55 μm) and for realizing all-optical switches requiring small pulse energies are discussed. Optimized designs show all-optical switching at Tb/s data rates with pulse energies as small as 200 fJ. Experimental realization of narrow line-width ISBT in GaN/AlN superlattices is also demonstrated.

INTRODUCTION

Ultrafast all-optical switches are expected to play an important role in high capacity optical time division multiplexed (TDM) networks. Two important figures of merit for all-optical switches are their operating energy and their speed. All-optical switching devices based on non-resonant optical non-linearities are fast, but require large pulse energies [1] (greater than 100 pJ.) Resonant non-linearities, such as those associated with interband transitions in semiconductors, require smaller pulse energies for all-optical switching (typically less than 500 fJ) but are generally slow. For example, all-optical switches based on interband saturable absorbers and using cross-loss modulation (XLM) scheme are limited by slow carrier relaxation times to speeds not much greater than few tens of Gb/s. All-optical switching devices for operation at data rates close to 1 Tb/s need to be able to restore their state in time periods less than 1 ps. It is well known that electron intersubband relaxation times in semiconductor quantum wells are around 1 ps or less. These fast relaxation times can be used to realize ultrafast all-optical switches. Semiconductor heterostructures with large conduction band offsets, such as GaN/AlN, are required for realizing intersubband transitions at communication wavelengths (~1.55 μm). Here, results on all-optical waveguide switches based on cross-loss modulation in GaN/AlN quantum wells are presented.

DESIGN, GROWTH AND CHARACTERIZATION

The intersubband transition energies and their corresponding envelope wave functions are calculated based on self-consistent solutions of Schrodinger and Poisson equations. The quantum wells are assumed to be n-doped with a density of $10^{18}\mathrm{cm}^{-3}$. Figure 1.a. shows the electron wave-functions for the first two subbands and the conduction band profile for a superlattice of 1 nm wide quantum wells. A TEM image of a GaN/AlN superlattice (figure 1.b) demonstrates control in material growth to monolayer precision. Polarization selective absorption, which is a signature of intersubband transitions, is measured by Fourier Transform Near-IR spectrsocpy (figure 1.c.) with a peak at 0.9 eV (1.4 μm) and a line width of 0.1 eV.

ALL-OPTICAL SWITCHING CHARACTERISTICS

The cross-loss modulation (XLM) scheme for all-optical switching is shown in figure 2a. Both the data pulse and the control pulse are coupled into a saturable absorber made of GaN/AlN multiple quantum wells. In the absence of the control pulse, the data pulse is absorbed in the device. The control pulse, when present, saturates the loss of the absorber and allows the data pulse, traveling with the control pulse, to be transmitted through the device.

The pulse energy required to saturate the absorber is directly proportional to the homogeneous linewidth of the absorption and inversely proportional to the optical confinement factor in the GaN/AlN quantum wells waveguide[2]. Also, it scales inversely with the dipole matrix element between the lower and upper wave functions. These parameters allow for designing material and waveguide properties for minimum saturation energy. Simulations show that intersubband-transition-based devices can be optimized to operate at pulse energies as low as 200 fJ.

Device performance at high data rate was simulated by numerically solving pulse propagation equations[3]. Figure 2.b. shows that extinction ratios between logical 1 and logical 0 higher than 10 dB can be achieved at data rates faster than R = 1 Tb/s and control pulse energies of 600 fJ.

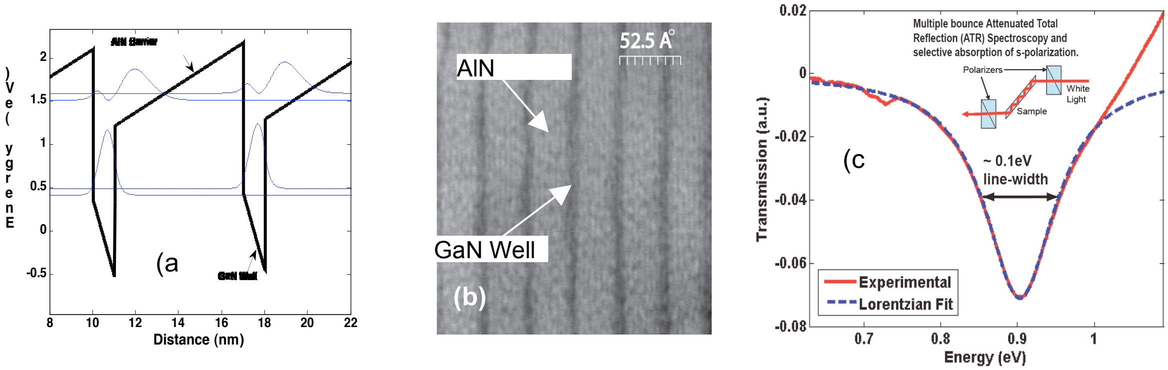

Figure 1: (a) **Material Design**: The conduction band profile of GaN/AlN quantum wells and the numerically computed wavefunctions of the confined electrons in lower and upper subbands. (b) **Material Growth:** Transmission Electron Microscopy (TEM) of the designed quantum wells grown by MBE showing growth control at monolayer scale. (c) **Characterization:** Intersubband absorption in the quantum wells near the telecommunication wavelengths emerges solely due to the sub-nanometer structure of the material.

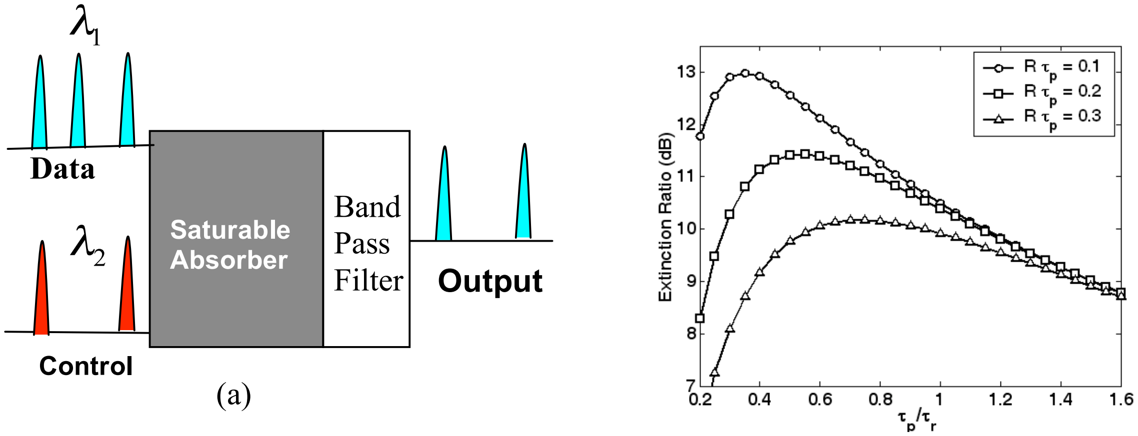

Figure 2: (a) Cross loss modulation with a saturable absorber. The data pulse is transmitted only if a concurrent control pulse is present to saturate the absorption of the sample. (b) Extinction ratio for the output signal pulses as a function of the ratio between the control pulse width τ_p and relaxation time τ_r for different values of the product of data rate R (bits/s) and τ_p. Relaxation time of τ_r = 200 fs, control pulse energy of 600 fJ, data pulse energy of 50 fJ and saturation energy 200 fJ were assumed.

REFERENCES

1. J. P. Skoloff, P. R. Prucnal, I. Glesk, M. Kane, *IEEE Photonics Tech. Letts.*, **5**, 787-790, 1993.
2. F. Rana, R. J. Ram, *Phys. Rev. B*, **65**, 125313, 2002.
3. G.P. Agrawal, *IEEE J. Quantum Electon*. **27**, 1843-1849 (1991)