

Engineering Intersubband Nonlinearities in GaN/AlGaIn Coupled Quantum Wells for Optimised Performance in Wide Bandwidth Applications

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Abstract: We investigate nonlinear optical properties of coupled GaN/AlGaIn quantum wells and show that one can engineer the response time and nonlinear phase shift within wide limits and thus achieve optimised performance for a given symbol rate.

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The progress in optical communications in the last decade was nothing short of spectacular – the data rates have increased from hundreds of MB/s to tens of GB/s and the number of channels has grown to hundreds. Further progress in the speed and complexity of optical networks is impeded by the necessity of optical-to-electrical conversion for switching and regeneration, thus the future networks must be all-optical ones. The crucial enabling elements of all-optical networking are the nonlinear optical devices used in switching, wavelength conversion, regeneration, etc.

Currently, all the nonlinear devices used in optical communications are based either on fiber nonlinearity [1] or nonlinearity of semiconductor optical amplifiers (SOA) [2]. Fiber nonlinearity is based on generation of virtual carriers and has a response time of less than a few fs, but the magnitude of the nonlinear refractive index is also very small ($<10^{16} \text{cm}^2/\text{W}$). The nonlinearity in the SOA is much stronger, but the response time is relatively slow ($\sim 100\text{ps}$) which makes it inapplicable to rates faster than 10GB/s. The relation between the strength and the speed of the nonlinearity is rather obvious for the materials in which the nonlinearity has absorption saturation as its origin. For this type of nonlinear medium material, one can define a figure of merit as the power intensity required to produce 180 degrees of nonlinear phase shift in one absorption length,

$I_{\pi} = \frac{\alpha\lambda}{2} n_2^{-1}$, where α is the absorption coefficient, λ is the wavelength in vacuum and n_2

is nonlinear refractive index. If the transition is broadened by Γ , the power intensity at a photon energy that is detuned from resonance by Γ , is given as $I_{\pi} = \frac{n}{\alpha_0} \frac{\Gamma}{z^2\tau}$, where n is the

refractive index, α_0 is the fine structure constant, z is the matrix element of the transition dipole, and τ is the response time that determines the maximum operational bandwidth. In this relation, τ can be used to minimize I_{π} . To maximize the nonlinearity for a given signal bandwidth B_{sig} , one should ideally set the response time in such a way that $\tau \sim B_{sig}^{-1}$. For the data rates of 40-160GB/s that means response times in the range of 5-20ps.

Unfortunately, there do not exist many nonlinear media wherein the relaxation rates can be easily adjusted in this range with the exception of intersubband transitions (IST) in quantum wells (QWs) where the intersubband relaxation rates are determined by the LO phonon scattering and strongly depend on the overlap of the wavefunctions that can be engineered within wide limits. For the last two decades, the IST could be observed only in the far-IR range, but more recently we have seen development of nitride-based semiconductors with large band offsets (deep wells) in which IST within the telecommunication window (1550nm) has been attained. Recently Iizuka et al [3] have measured intersubband absorption in GaN/AlN QWs in the 1.3-2.2 μ m range with relaxation times of 400fs, but this time is too short for the 40-160GB/s rates. An obvious way to increase the relaxation time is to use coupled QWs with reduced overlap of wavefunctions involved in the transition. Unfortunately the reduction in overlap also decreases the transition matrix element and thus does not improve figure of merit.

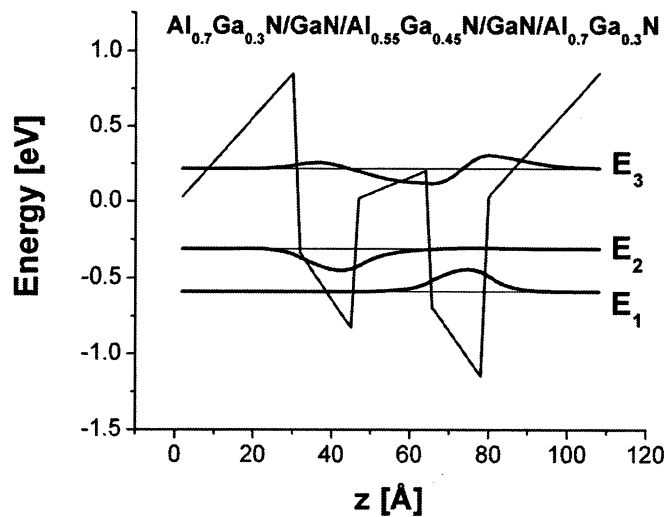


Fig.1. A three-level system consisting of Al_{0.7}Ga_{0.3}N barriers confining two coupled GaN QWs (15Å) separated by a Al_{0.55}Ga_{0.45}N barrier (20Å). The three levels are located at E₁=-0.588eV, E₂=-0.313eV, and E₃=0.216eV.

In order to optimize the relaxation rate and the IST strength separately we propose to use a three-level coupled QW system as shown in Fig.1. IST takes place between the ground state 1 and excited state 3 while the state 2 serves as a trap delaying relaxation to the ground state. Solving balance equations one can obtain the expression for the effective relaxation time, $\tau = \frac{\tau_{31}(2\tau_{32} + \tau_{21})}{\tau_{31} + \tau_{32}}$. For $\tau_{31} \approx \tau_{32} \ll \tau_{21}$ we obtain $\tau \approx 0.5\tau_{21}$. The

effective relaxation time can be varied within wide limits by changing the central coupling AlGa_{0.55}N barrier width, while the IST strength and wavelength are maintained by small changes in the barrier Al composition. In Fig.2 we show the results of calculations of the response time and nonlinear switching power. As the barrier width changes in the range of 1-2 nm, one can see that the effective relaxation time changes from 0.4 to 5 ps. For a typical RZ signal these values correspond to the bit rates range of 40-640 GB/s. The nonlinear switching power densities of $<10^8$ W/cm² correspond to switching instant powers in the <1 W range in a typical waveguide - substantially less than in a fiber loop. With the doping density of 5×10^{17} /cm³ the switching length would be only $\sim 100\mu$ m compared to the meters required in a fiber loop.

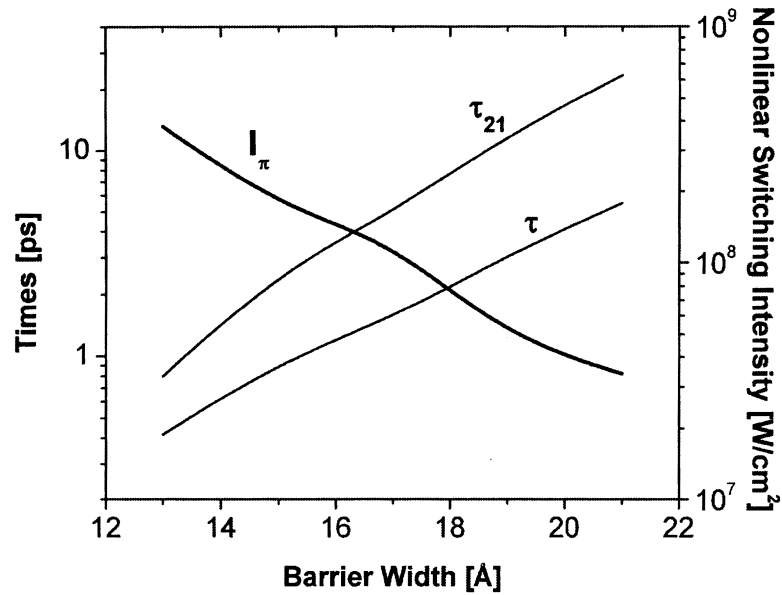


Fig.2. 2→1 Scattering lifetime (τ_{21}), effective relaxation time (τ), and nonlinear switching intensity as a function of coupling barrier width

In conclusion, we have shown that GaN/AlGaIn coupled QWs with a trap state provide unique opportunity for engineering bandwidth-optimized all optical devices with low switching power.

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