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Nonlinear all-optical GaN/AlGaN multi-quantum-well devices for 100 Gb/s applications at $\lambda = 1.55\ \mu m$

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Using quantum-mechanical analysis, a strain-balanced stack of coupled GaN/AlGaN quantum wells has been engineered for bandwidth-optimized all-optical switching at low switching powers. Intersubband transitions between three conduction subbands provide the basis for the large, fast, nonlinear optical response. Optimized performance for a given symbol rate is obtained by engineering the response time and nonlinear phase shift. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2132084]

This letter focuses on waveguided nonlinear optical components that are key enables for the ultrafast optical networks of the future. These third-order nonlinear components would be part of a chip-scale network that would in turn be part of a fiber-and-chips telecom system. At present, the need for on-chip optical-to-electrical conversion is hindering the speed and complexity of the optical communication system; thus, the optimum network will be "all optical." The desired all-optical devices are investigated in this letter. We show that GaN/AlGaN multi-quantum-well (MQW) heterostructures are capable of realizing all-optical switches, wavelength converters, and optical signal regenerators that operate at data rates from 40 to 160 Gb/s.

Currently, the nonlinear devices used in optical communications are based upon the optical fiber nonlinearity[1–3] or the nonlinearity of semiconductor optical amplifiers (SOAs).[4–9] Because the fiber nonlinearity is based on generation of virtual carriers, its response time is only a few femtoseconds corresponding to potential operation at a few Tb/s, however the magnitude of the nonlinear refractive index is very small, less than 10^{16} cm^2/W. The SOA nonlinearity is much stronger, but the response time is relatively slow, about 100 ps, which makes it inapplicable to data rates above a few tens of Gb/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 density required to produce 180° of nonlinear phase shift in one absorption length, $I_\pi = \alpha\lambda/2n_2$, where α is the absorption coefficient, λ is the wavelength in vacuum and n_2 is nonlinear refractive index. For the homogeneously broadened transition characterized by the Lorentzian full width at half maximum (FWHM) linewidth Γ, maximum index change occurs at a photon energy that is detuned from the resonance by one half of Γ, and the switching power density is

$$I_\pi = \frac{n}{2\alpha_0}\frac{\Gamma}{z^2\tau},$$

where n is the refractive index, $\alpha_0 = 1/137$ 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 40–160 GB/s that means response times in the range of 5–20 ps.

Unfortunately, there are not many nonlinear media wherein the relaxation rates can be adjusted easily in this range, with the exception of intersubband transitions (ISTs) in quantum wells (QWs) where the intersubband relaxation rates are determined by the LO phonon scattering and depend strongly upon the overlap of wave functions that can be engineered within wide limits. For the past two decades, IST could be observed only in the far infrared, but more recently we have witnessed the development of III-nitride QW structures with large band offsets (deep QWs) in which IST within the 1.55 μm telecom window has been attained.[10–13] Iizuka *et al.*[12,13] have measured intersubband absorption in GaN/AlN QWs in the 1.3–2.2 μm range, with relaxation time ~100 fs; but this time is too short for 40–160 Gb/s rates. One way to increase this relaxation time is to construct a series of identical wells and "narrow" barriers offering interwell coupling that gives a reduced overlap of the wave functions involved in the IST transition. Unfortunately, the reduction in overlap also decreases the transition matrix element and thus does not improve the figure of merit. As was originally suggested in Ref. 14 and implemented in Ref. 15 for the far IR transitions, z and τ can be optimized separately if one introduces a metastable state (trapping level) whose position would determine the effective relaxation time without significantly affecting the transition dipole. In this work we show how one can use trapped states in nitride structures to engineer high figure-of-merit switches in the telecommunication region of the optical spectrum.

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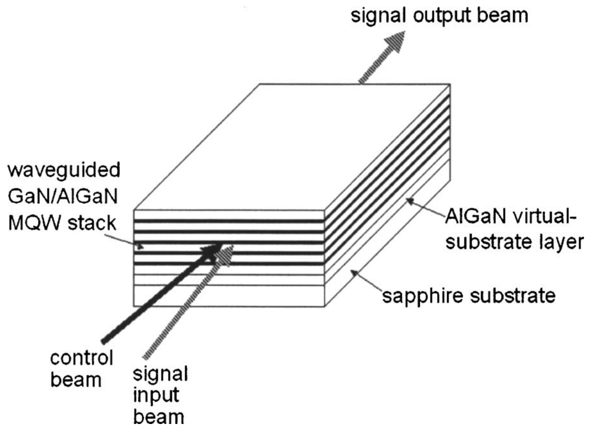

FIG. 1. Perspective view of nonlinear optical waveguided component (rib etching not shown) for all-optical switching, regeneration, and wavelength conversion applications. To improve switching two components can be arranged into a waveguided Mach–Zehnder interferometer.

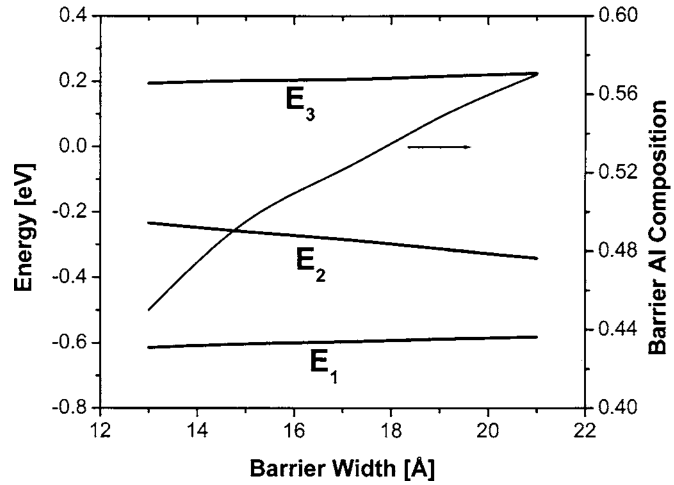

FIG. 3. Subband energy levels as a function of barrier width with small change of Al content in the barrier to ensure energy separation $E_3 - E_1$ maintained at 1.55 μm.

Figure 1 illustrates our proposed waveguided multiple quantum well (MQW) stack with two infrared input beams (polarized for TM mode propagation) and the corresponding signal output beam. We assume here the new paradigm of a strain-balanced nitride MQW, which means that a relaxed buffer layer of $Al_{1-x}Ga_xN$, known as a virtual substrate (VS), is grown upon a sapphire substrate (the lower-index cladding for the rib waveguide) while the barrier material within the MQW has the composition $Al_{1-y}Ga_yN$.[16] The VS composition is chosen with $x < y$, such that the GaN wells have compressive in-plane strain while the y barriers have tensile strain of strength that produces net zero strain over the "strain-compensated" stack. For the nonlinear absorption experiments, the GaN wells are doped N-type to populate the ground subband E_1 with electrons.

Each period of the MQW stack is a three-level coupled-QW system that consists of four layers: a tensile barrier layer (50 Å) with the $Al_{0.7}Ga_{0.3}N$ composition, and two compressive GaN layers separated by a tensile barrier with the composition $Al_yGa_{1-y}N$. The band diagram of a telecom-engineered period of this MQW is shown in Fig. 2, where the incoming $\hbar\omega = 800$ meV photon energy is nearly resonant with the subband separation $E_3 - E_1$; that is, the IST takes place between the ground state E_1 and excited state E_3 while the state E_2 serves as a trap, delaying relaxation to the ground state. Selection of the barrier width provides a means for optimizing the relaxation time τ and IST strength z independently. The choice of lower Al content y in the coupling barrier ($y < 0.7$) is made to produce the energy of the excited state E_3 above the coupling $Al_yGa_{1-y}N$ barrier, while still confined by the $Al_{0.7}Ga_{0.3}N$ layers that separate the neighboring periods, so that the envelope wave function associated with E_3 overlaps with those of both E_1 and E_2. The built-in electric fields of the c-axis wurtzite stack were taken into account when engineering the subband energy separations.

In the three-level system, absorption saturation takes place due to depletion of the ground level. Solving a standard set of 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 $\tau \approx 0.5\tau_{21}$—indicating that only about one half of the absorbed photons contribute to the saturation and ensuring index change. The effective relaxation time can be varied within wide limits by changing the central coupling $Al_yGa_{1-y}N$ barrier width. Figure 3 shows that the wavelength (1.55 μm) in resonance with the energy separation $E_3 - E_1$ is maintained by small changes of the Al content y in the barrier as its width varies. The IST strength z is also maintained within the range of 4.1–4.6 Å.

In Fig. 4, we show the calculated results of the response time and nonlinear switching power (assuming FWHM $\Gamma = 20$ meV). As the $Al_yGa_{1-y}N$ barrier width changes in the range of 10–20 Å, one can see that the effective relaxation time changes from 0.4 to 5 ps. For a typical RZ signal, these time values correspond to bit rates of 40–640 Gb/s. The nonlinear switching power densities of $< 10^8$ W/cm^2 correspond to switching instant powers of < 1 W in a typical waveguide—substantially less power than in a fiber loop. With the QW doping density of $N \sim 2 \times 10^{17}$ cm^{-3}, the switching length

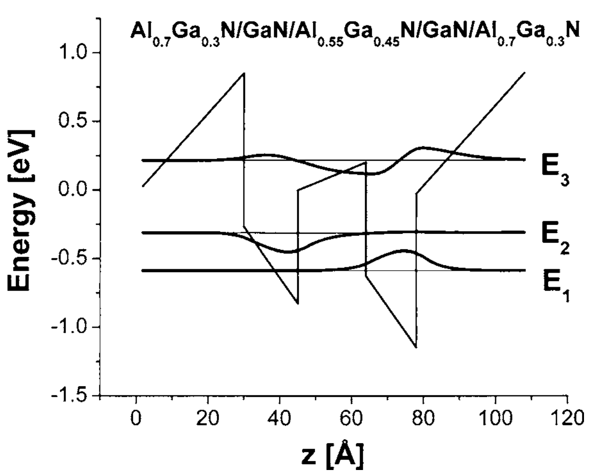

FIG. 2. One period of the multiple coupled-quantum-well stack consisting of $Al_{0.7}Ga_{0.3}N$ barriers (50 Å) confining two coupled GaN QWs (15 Å) separated by an $Al_{0.55}Ga_{0.45}N$ barrier (20 Å). The three conduction subband levels are located at $E_1 = -588$ meV, $E_2 = -313$ meV, and $E_3 = 216$ meV.

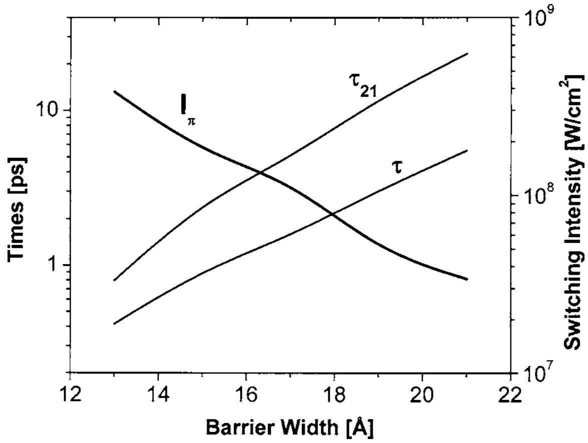

FIG. 4. A $2 \rightarrow 1$ scattering lifetime (τ_{21}), effective relaxation time (τ), and nonlinear switching intensity as a function of coupling barrier width.

$$L_{sw} = \frac{n}{4\pi\alpha_0}\frac{\Gamma}{\hbar\omega}\frac{1}{z^2N}$$

would be only about 25 μm compared to the meters required in a fiber loop.

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

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