Carrier lifetime in erbium-doped GaN waveguide emitting in 1540 nm wavelength

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We report the characteristics of an erbium-doped GaN semiconductor waveguide amplifier grown by metal-organic chemical vapor deposition. We demonstrated that both 980 and 1480 nm optical pumping were efficient to create population inversion between the $^4I_{13/2}$ and $^4I_{15/2}$ energy levels. The carrier lifetime in the $^4I_{13/2}$ energy band was measured to be approximately 1.5 ms in room temperature, which is slightly shorter than that in erbium-doped silica due to the interaction between the erbium ions and the semiconductor lattice structure. But it is significantly longer than the carrier lifetime in a typical semiconductor optical amplifier which is in the nanosecond regime. © *2010 American Institute of Physics*. [doi:10.1063/1.3527089]

Erbium (Er)-doped materials have attracted much attention for their applications in photonics, especially in the area of optical communications.[1–3] Doped in a solid host, Er^{3+} ion has allowable intra-$4f$ shell transition from its first excited state ($^4I_{13/2}$) to the ground state ($^4I_{15/2}$) and the transition corresponds to a wavelength of minimum optical loss in silica based optic fibers (1.55 μm).[1–4] Thus, Er-doped materials are ideal candidates to make amplifiers for optical communications. Today, Er-doped fiber amplifiers (EDFAs) are widely used in long-haul fiber-optic communications.[1–4] On the other hand, InGaAsP-based traveling-wave semiconductor optical amplifier (SOA) is electrically pumped and monolithically integratable with other components such as laser sources. However, due to the short carrier lifetime of a SOA, cross-saturation may cause significant interchannel crosstalk between different wavelength channels, which is a major problem preventing its practical applications in wavelength division multiplexing (WDM) systems.[4] In fact, short lifetime is intrinsic to free carriers involved in the band-edge recombination in most semiconductors.[4,5]

III-nitride semiconductors are excellent host materials for Er-ions due to their structural and thermal stabilities. III-nitride wide bandgap semiconductors have recently attracted much attention because of their applications in blue/UV optoelectronic devices as well as high power, high temperature electronic devices. Optical emission in 1.55 μm wavelength window in Er-doped GaN films has been observed.[6–9] In particular, GaN and AlGaN epilayers doped with Er-ions have demonstrated a highly reduced thermal quenching of the Er luminescence intensity from cryogenic to elevated temperatures as compared to other semiconductor host materials such as Si and GaAs. Optical amplification in Er-doped GaN waveguide has also been demonstrated using a 365 nm light emitting diode optical pumping source.[10] UV pumping above the GaN bandgap excited free electrons and holes and subsequently the electrons and holes transfer their energy to the doped erbium ions and produce sufficient carrier population on the $^4I_{13/2}$ band which is responsible for emission in the 1550 nm wavelength window. This above bandgap excitation

was demonstrated to be more efficient than below bandgap excitation.[11]

Although EDFA in fiber-optic systems uses 980 or 1480 nm optical pumping,[1] investigations in Er-doped GaN so far were limited by using either green pump in 530 nm wavelength window[12,13] or UV pumping at 350 nm.[10,11] In fact, pumping at near infrared wavelengths to populate carriers in $^4I_{13/2}$ energy band has an advantage of providing higher photon conversion efficiency than using higher energy photons such as in UV and green wavelengths, which avoided transitions through intermediate energy levels and the associated energy loss during these transitions.

The Er-doped GaN epilayers were synthesized by metal-organic chemical vapor deposition (CVD) in a horizontal reactor. Trimethylgallium was used for the Ga source, and blue NH_3 was used as the N source. The metal-organic precursor used for the *in situ* Er doping was tris(2,2,6,6-tetramethyl-3,5-heptanedionato) erbium, which was transported to the reactor by H_2. All samples were grown on (0001) sapphire substrates. The growth of these epilayers began with a thin (~30 nm) GaN buffer layer, followed by a 1.4 μm GaN epilayer template and a 0.5 μm Er-doped GaN layer. The growth temperature of the GaN template and Er-doped GaN layer was 1040 °C. The waveguides were fabricated using
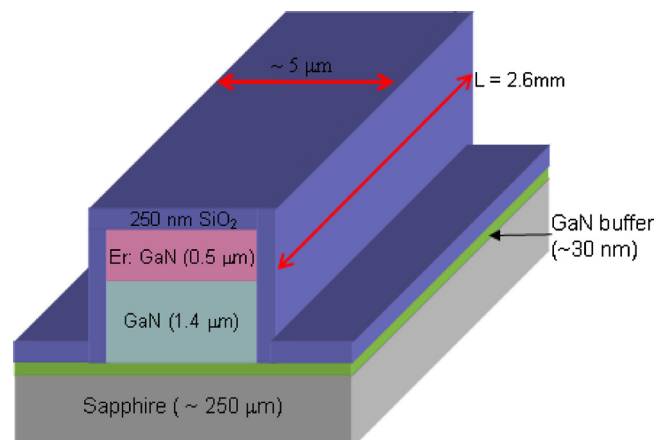

FIG. 1. (Color online) Layered structure of the Er-doped GaN waveguide.
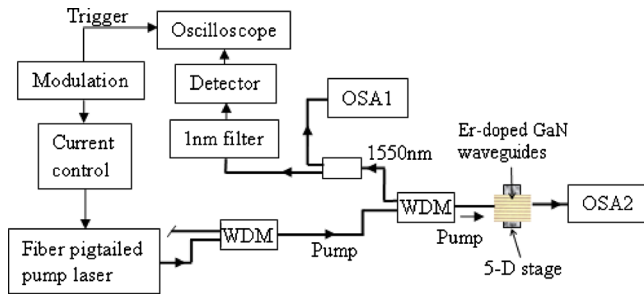
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FIG. 2. (Color online) Experimental setup.

optical lithography and inductively coupled plasma dry etching. A 250 nm SiO$_2$ passivation layer was deposited on top of the waveguides by plasma enhanced CVD to reduce the optical scattering. The layered structure of the waveguide is shown in Fig. 1 which is about 5 μm wide and 2.6 mm long. The 0.5 μm thick Er-doped GaN layer has an Er concentration of approximately 5×10^{20} cm^{-3}. A numerical calculation using beam propagation method (BPM) software indicates that the overlap between the fundamental optical mode and the Er-doped layer is $\Gamma = 19.8\%$, which is commonly referred to as the field confinement factor.

The experimental setup is shown in Fig. 2. A fiber pigtailed laser diode, either at 980 or at 1480 nm, is coupled into the Er-doped GaN waveguide through two WDM fiber couplers which provide >40 dB isolation between the 1480 (or 980) and 1550 nm wavelength bands. A single mode fiber with a tapered tip was used to guide and focus the 1480 nm (or 980 nm) optical pump into the Er-doped GaN waveguide. The same fiber tip also collects the counterpropagating 1540 nm spontaneous emission generated from the waveguide and sends it to an optical spectrum analyzer (OSA1) for measurement. The spontaneous emission at 1537 nm was also selected by a bandpass optical filter for power measurement and the time-domain modulation response.

Figure 3 shows the measured spontaneous emission spectra when the waveguide was excited by 1480 and 980 nm optical pumping. The shape of the emission spectra did not change with different pump wavelengths, and in both cases, the emission covers approximately 30 nm optical bandwidth, which is comparable to that in Er-doped silica. When the pump power is high enough to achieve the highest carrier inversion between $^4I_{13/2}$ and $^4I_{15/2}$ energy levels, the peak emission density at 1537 nm reached to approximately -60 dBm for the resolution bandwidth of 2 nm with either pumping source. Considering an approximately -4 dB optical loss including the coupling loss from the waveguide to the fiber (3 dB) and the loss of the WDM coupler (1 dB), the
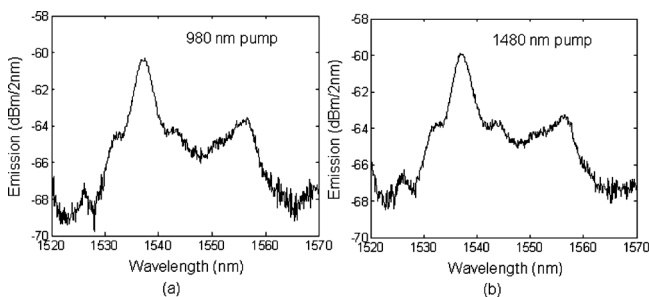

FIG. 3. Measured spontaneous emission spectra in 1540 nm window with 50 mW pump at 980 nm (a) and 80 mW pump at 1480 nm (b).
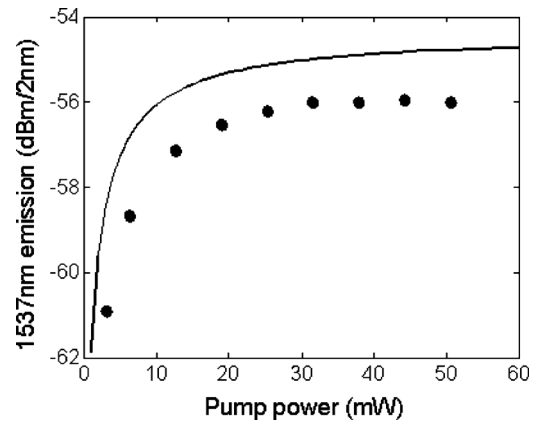

FIG. 4. Calculated (continuous line) and measured (dots) spontaneous emission power spectral densities at 1537 nm wavelength as functions of injected power of 1480 nm pump laser.

actual power spectral density emitted from the waveguide should be approximately -56 dBm/2 nm. This spontaneous emission power spectral density can be calculated by[1]

$$\rho_{ASE} = 2\Gamma\sigma_e(\lambda_s)h v_s \int_0^L \frac{N_T P_p e^{-2\alpha z}\sigma_a(\lambda_p)}{P_p e^{-\alpha z}[\sigma_a(\lambda_p) + \sigma_e(\lambda_p)] + h v_p A/\tau}dz,$$

(1)

where σ_e and σ_a are emission and absorption cross sections and N_T is the doping density of erbium ions. λ_p and λ_s are emission and pump wavelengths, respectively, τ is the carrier lifetime, Γ is the field confinement factor, L is the length of the waveguide, $h v_s$ and $h v_p$ are photon energies at emission and pumping wavelengths, A is the waveguide cross section, α is the attenuation coefficient, and P_p is the pump optical power. For such a short waveguide, we have neglected the saturation effect caused by spontaneous emission in the 1540 nm wavelength to simplify the calculation. Using the cross section values of erbium doped in silica glass and the pump wavelength at 1480 nm,[14] $\sigma_a(\lambda_p) = 1 \times 10^{-21}$ cm^2, $\sigma_e(\lambda_p) = 0.5 \times 10^{-21}$ cm^2, and $\sigma_e(\lambda_s) = 5 \times 10^{-21}$ cm^2, and assuming the doping density of $N_T = 5 \times 10^{20}$ cm^3, carrier lifetime $\tau = 1.5$ ms, and waveguide length $L = 2.6$ mm, the emission power spectral density can be calculated at 1537 nm wavelength, as shown in Fig. 4. We have also assumed the attenuation of the waveguide of 1.5 dB/mm.[10] With 50 mW pump power, the theoretical power spectral density emitted from the waveguide is -55 dBm/2 nm, which is about 1 dB higher than the measured value. This reduced efficiency is attributed to the nonradiative recombination and Auger recombination for the transition from the metastable level ($^4I_{13/2}$) to the ground level ($^4I_{15/2}$). Noting that although σ_a and σ_e values borrowed from erbium-doped silica may not be quantitatively accurate for GaN, the calculated result shown in Fig. 4 qualitatively agrees with the measurement, which provides a reasonable estimation of the pump efficiency.

In order to evaluate the dynamic response we passed the spontaneous emission through a 1 nm bandpass optical filter at 1537 nm and used an InGaAs photodiode to detect the optical power, and the waveforms were recorded by a real-time oscilloscope. By suddenly switching off the 1480 nm pump laser, the decay rate of the photoluminescence in 1537 nm is determined by the carrier lifetime on the $^4I_{13/2}$ energy
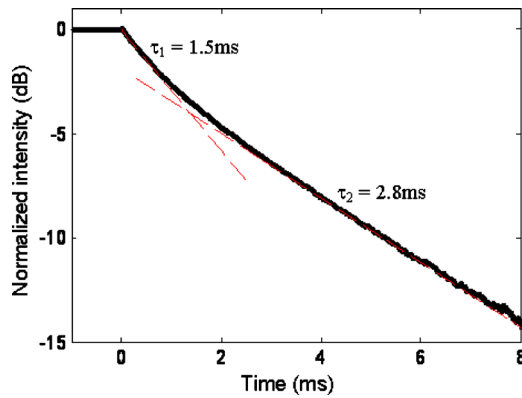
FIG. 5. (Color online) Falling edge of the measured spontaneous emission at 1537 nm wavelength after the pump laser at 1480 nm was switched off at $t=0$.

level. The measured falling edge of the spontaneous emission after switching off the pump shown in Fig. 5 exhibits a fast time constant of 1.5 ms and a slower time constant of 2.8 ms. The nonexponential decay indicated the existence of Auger recombination and cooperative upconversion[14] which is responsible for exciting carriers to higher energy levels.

Figure 6 shows the measured emission spectrum in the $400-1100$ nm wavelength window using a charge coupled device-based optical spectrometer which is OSA2 in Fig. 2. Although the waveguide was excited by a 1480 nm pump, spectral components shown in Fig. 6 include the recombination from all the higher energy levels of Er-ion up to the $^2H_{11/2}$. This energy upconversion is attributed to the interaction between the doped Er-ions and the semiconductor lattice structure.
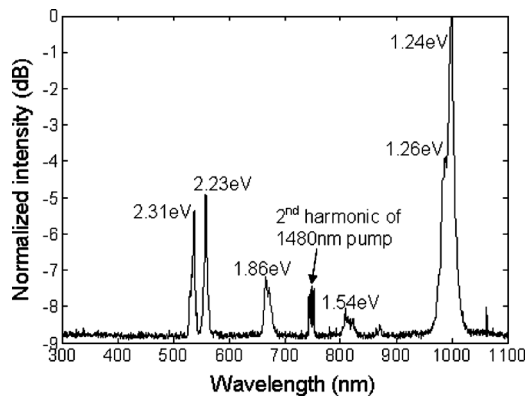

FIG. 6. Room temperature emission spectrum of Er-doped GaN waveguide in the short wavelength region with 1480 nm pumping.

In conclusion, we have measured the performance of an erbium-doped GaN waveguide for the potential application as an optical amplifier in 1540 nm wavelength window. By using 1480 and 980 nm pumping, which excited the carriers into the $^4I_{13/2}$ energy band, the uncertainty of energy loss due to intraband transition was minimized in comparison with the short wavelength pumping in UV and green wavelength regions. A shorter carrier lifetime of 1.5 ms and a longer one of 2.8 ms were determined through the transient measurement of 1537 nm emission. The nonexponential decay indicated a cooperative upconversion at high pump power. This carrier lifetime is slightly shorter than that in EDFA due to the interaction between the erbium ions and the semiconductor lattice structure. But it is significantly longer than the carrier lifetime in a typical semiconductor optical amplifier which is in the nanosecond regime. The loss of 1540 nm emission efficiency of approximately 1 dB was determined primarily due to Auger recombination and cooperative upconversion.

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