Erbium-doped GaN optical amplifiers operating at 1.54 μm

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Strip optical waveguides based on erbium (Er)-doped AlGaN/GaN:Er/AlGaN heterostructures have been fabricated and characterized in the optical communication wavelength window near 1.54 μm. The propagation loss of these waveguide amplifiers have been measured at 1.54 μm and found to be 3.5 cm^{-1}. Moreover, the optical amplification properties of the waveguides were measured using a signal input at 1.54 μm and a broadband GaN light-emitting diode at 365 nm as pump source. A relative signal enhancement of ~8 cm^{-1} was observed. The implications of such devices in photonic integrated circuits for optical communications are discussed. *© 2009 American Institute of Physics*. [doi:10.1063/1.3224203]

Erbium (Er)-doped fiber amplifiers are part of a well established technology for long distance optical communications near 1.54 μm. They offer stable and low-noise amplification properties due to the atomic intra-4f transition of Er^{3+}. However, the narrow band and extremely small absorption cross section (~10^{-21} cm^{-3}) require not only long interaction distance but also a precisely tuned, powerful external laser excitation source. Such requirements hinder the realization of compact and inexpensive Er-doped waveguide amplifiers (EDWAs), which are key component for local and wide area networks, cable television distribution, and anticipated fiber-to-the-home applications where multiple amplification steps are required. Optical waveguide amplifiers based on rare-earth-doped silica glasses, ceramics, and polymers have been demonstrated and widely studied.[1–5] However these waveguide amplifiers need high power laser excitation and relatively long cavities to achieve net optical gain. Earlier reports addressed increasing the absorption cross section by introducing Yb^{3+} as a sensitizer in Er-doped host medium (silica glasses) and demonstrated optical gain with 477 nm broadband light-emitting diode (LED) excitation.[6] While prior EDWA research has focused on Er-doped silica glasses, silicon, or polymers,[7,8] here we report on EDWAs operating near 1.54 μm based on the III-N material system.

Rare-earth-doped III-N wide band-gap semiconductors have potential applications in areas ranging from highly densed photonic integrated circuits (PICs) with multiple functionalities to full color display system, which are not possible to attain either with Er-doped silica glasses or narrow gap semiconductor materials such InGaAsP. Planar waveguide amplifiers based on Er doped III-N materials, are expected to show better performance in terms of linear gain response, temperature insensitivity, and low noise. These are fundamental characteristics of waveguide amplifiers, a key component of chip size PICs, operating in the c-band communication wavelength region (1530–1550 nm). The III-N material system is essentially transparent in this wavelength range and optical signal absorption is expected to be negligible since the material band gap is far from the signal wavelength.

Recently we have synthesized, by metal organic chemical vapor deposition (MOCVD), GaN:Er and InGaN:Er epilayers with excellent optical qualities and demonstrated a host band gap-mediated excitation of Er^{3+} in these epilayers with a predominate optical emission at 1.54 μm.[9–11] Much research on Er-doped GaN/AlGaN has concentrated on the growth and optical properties for application in full color display system.[12,13] There appears to be no report of EDWAs based on Er-doped GaN. We report here on the MOCVD growth of AlGaN/Er:GaN/AlGaN heterostructures and the processing into strip waveguides. We have measured their low optical loss properties and demonstrated optical signal enhancement at 1.54 μm under broadband LED excitation.

The multilayer structure of optical waveguide devices consists of 0.5 μm $Al_{0.03}Ga_{0.97}N$ top cladding, 0.5 μm GaN:Er optically active core medium, and 1.5 μm $Al_{0.03}Ga_{0.97}N$ bottom cladding grown on c-plane sapphire substrate by MOCVD. The Er concentration in the active waveguide core medium was ~10^{21} cm^{-3}. The details of MOCVD growth of GaN:Er epilayers can be found in our earlier publications.[9,10] The strip waveguides were fabricated using standard optical lithography and inductively coupled plasma dry etching techniques, followed by the deposition of a 250 nm SiO_2 passivation layer by plasma enhanced CVD.

Figure 1(a) shows a schematic of the multilayer structure of the fabricated strip waveguide. The waveguide width is about 5 μm and the etch depth is ~2 μm. Waveguide facets were prepared by polishing vertically mounted waveguides using diamond paste and finally lapping on a cotton pad with silica solution. The length of the prepared waveguides was ~3 mm. Figure 1(b) contains an atomic force microscopy image of an array of fabricated waveguides. The optical microscopy image of polished facets is shown in the inset of Fig. 1(b).

To measure the optical loss in a fabricated waveguide, one end of the waveguide was illuminated from the top side by a 371 nm nitride laser beam to excite Er^{3+} ions and to generate 1.54 μm light within the waveguide. The beam diameter spot size was ~10 μm. The 1.54 μm light emission propagated through the waveguide and was collected from

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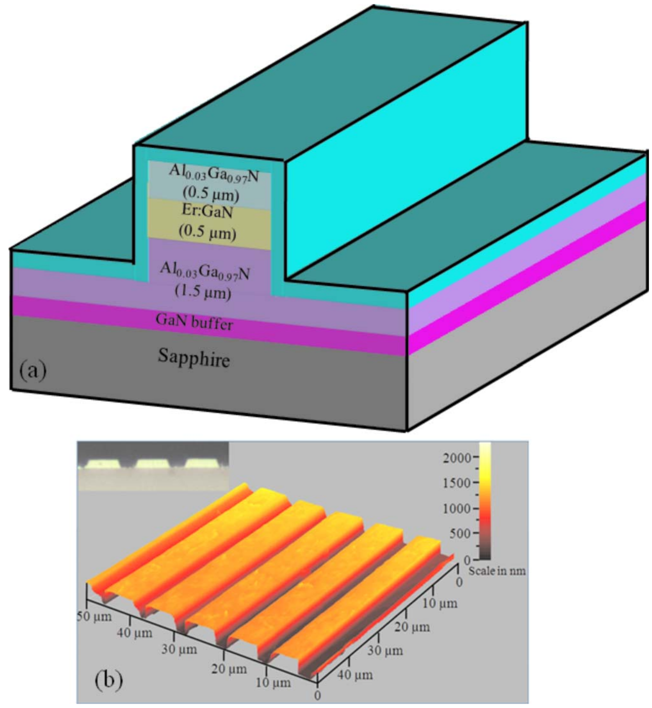


FIG. 1. (Color online) (a) Schematic layer structure of fabricated strip Er-doped GaN waveguide amplifier, which utilizes GaN: Er as optical gain medium with $Al_{0.03}Ga_{0.97}N$ as top and bottom cladding layers, (b) atomic force microscopy image of fabricated devices. The inset shows the optical microscopy image of waveguide facets prepared by mechanical polishing.

the far end using tapered fiber coupled with a monochromator and an InGaAs detector. Figure 2 shows the 1.54 μm photoluminescence (PL) spectra measured at room temperature from far end of waveguide after excitation by the 371 nm laser beam. The inset in Fig. 2 shows an illustration of the measurement setup for the optical loss measurement. PL spectra peaks at 1.54 μm corresponding to the intra-4f Er^{3+} transitions from the $^4I_{13/2}$ level to the ground state ($^4I_{15/2}$). The integrated PL emission intensity collected at the exit facet of the waveguide is plotted in Fig. 3 as a function of laser excitation spot distance, d.

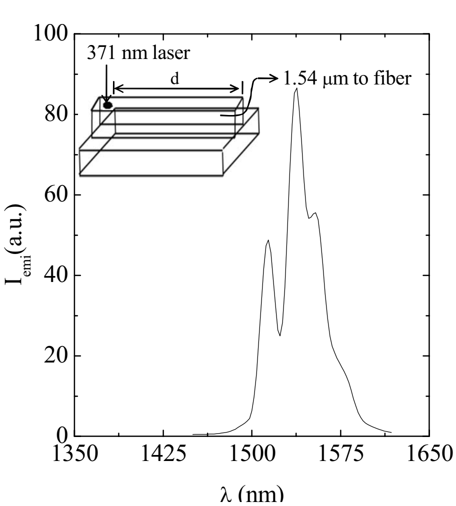


FIG. 2. PL spectra of Er-doped GaN waveguide amplifier taken from the end facet of the waveguide when the other end is illuminated by a 371 nm nitride laser. 1.54 μm emission was generated at the laser excitation spot within the core of the waveguide and guided to the end facet of the waveguide. The inset shows the optical loss measurement setup.

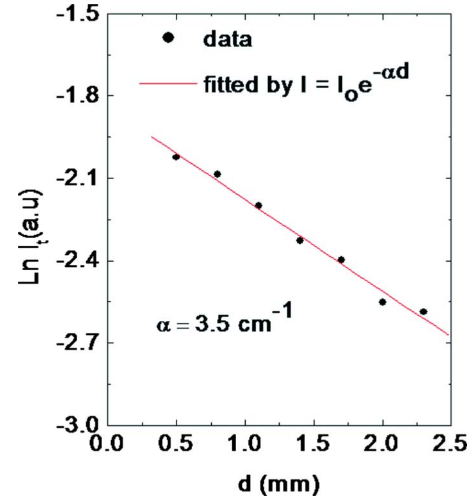


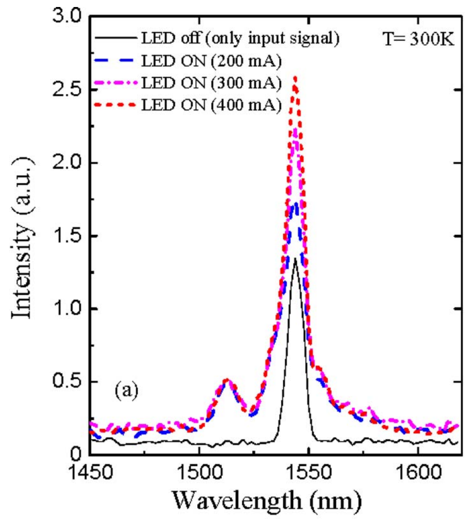
FIG. 3. (Color online) Plot of 1.54 μm peak intensity as a function of laser excitation spot distance, d. The slope of the plot gives the optical loss, which is about 3.5 cm^{-1}.

The emission intensity coming out of the waveguide facet I_t is described by the following relation:

$$I_t = I_0 e^{-\alpha d}, \tag{1}$$

where I_0 is the PL emission intensity measured at the laser excitation spot, d is the optical path length, and α is the optical loss of the waveguide. From the slope of the plot of ln I_t versus d, the measured optical loss at 1.54 μm of the Er-doped GaN waveguide is about 3.5 cm^{-1}. This is about a factor of 3 larger than the values reported for the state of art Er-doped oxide waveguide amplifiers.[14] The optical loss is mainly due to light scattering by etched sidewalls of the waveguide and can be minimized through techniques such as wavelength selective coating, gentle wet etching following plasma etching, etc. This measured value of optical loss in Er-doped GaN devices is smaller than an earlier reported value of 4.45 cm^{-1} for undoped GaN ridge waveguide devices measured at visible (488 nm) wavelength.[15] The small value of optical loss in GaN:Er waveguide is what we expected because 1.54 μm wavelength is far from the band gap of the guiding medium, GaN (362 nm). This low optical loss at 1.54 μm demonstrates the great promise of GaN:Er waveguides for optical amplification in optical communication networks.

To study the amplification properties, waveguides were analyzed by studying the relative change in transmitted signal intensity at 1.54 μm. For the optical excitation, a 365 nm GaN LED was used from the top side, which is intended to substitute the finely tuned high power laser required for Er-doped silica or ceramic based waveguide amplifier. The signal at 1.54 μm from a laser diode was coupled into one end (entrance end) of the waveguide through tapered fiber with focusing lens at the tip using microscope, x-micromanipulator, y-micromanipulator, and z-micromanipulator. Similarly the transmitted beam was collected at the other end (exit end) of the waveguide by tapered fiber with collecting lens at the tip using another x-micromanipulator, y-micromanipulator, and z-micromanipulator. The exit end of the fiber was coupled to a monochromator and InGaAs detector. Figure 4 shows the transmitted 1.54 μm signal spectra through the waveguide at different level of 365 nm LED excitation. It is clearly seen



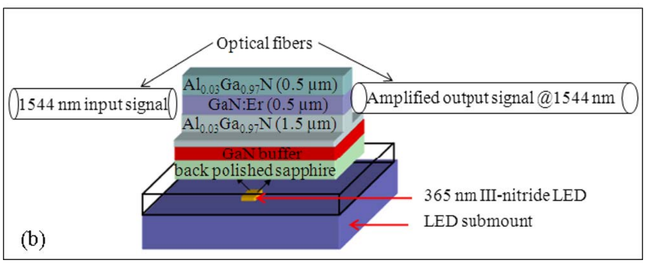


FIG. 4. (Color online) (a) Spectra of the transmitted 1.54 μm signal emerged from the exit end of the Er-doped GaN waveguide measured under the excitation by a 365 nm high power nitride LED operating at different forward currents. The intensity of the 1.54 signal guided through the waveguide increases with an increase of the forward current applied to the 365 nm LED, demonstrating a relative signal gain at 1.54 μm. (b) Schematic of the optical amplification property measurement setup.

that the relative signal intensity at peak signal wavelength (1.54 μm) increases with increasing the excitation intensity of the 365 nm LED. The measured relative signal enhancement is about 8 dB/cm for a 3-mm-long waveguide optically pumped by a 365 nm LED operating at 400 mA.

In summary, we have fabricated optical waveguide amplifiers based on MOCVD-grown Er-doped GaN. The measured optical loss of the fabricated devices was $\sim$3.5 cm^{-1} at 1.54 μm. The optical amplification characteristics of the devices were analyzed by studying the relative change in a 1.54 μm input signal intensity transmitted through the waveguide. It was observed that the transmitted 1.54 μm signal intensity through the waveguide was amplified under the excitation of a broadband 365 nm nitride LED and a relative signal enhancement of about 8 dB/cm was observed. The demonstrated 1.54 μm signal enhancement with a broadband LED excitation eliminates the finely tuned high power laser which is required for Er-doped silica glass waveguide amplifier. The results further exhibited the feasibility of achieving compact and cost effective current injected optical waveguide amplifiers based on Er-doped III nitride semiconductors for future optical communication applications.

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