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Near infrared photonic devices based on Er-doped GaN and InGaN

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ABSTRACT

Er-doped III-nitride semiconductors have emerged as very attractive materials to achieve photonic devices with multiple functionalities for photonic integrated circuits (PICs). Optical sources and amplifiers based on these materials, particularly GaN and InGaN alloys, can operate at 1.54 μm and are expected to be temperature insensitive and have high signal gain with low noise. There is also the potential for these devices to be electrically pumped and to be integrated onto PICs, which is not possible with either Er-doped silica glasses or narrow bandgap semiconductors like InGaAsP. Here we present results on near infrared emitters and optical amplifiers based on Er-doped GaN/InGaN epilayers grown on different substrates by metal organic chemical vapor deposition (MOCVD). In particular, we report on chip-size current injected emitters and amplifiers fabricated by heterogeneously integrating Er-doped GaN/InGaN epilayers with UV nitride light-emitting diodes. The feasibility of developing electrically pumped optical amplifiers for PIC integration will also be discussed.

1. Introduction

Due to advances in semiconductor photonic device fabrication techniques and design, much research has been devoted to the incorporation of Erbium (Er) into semiconductors aimed at achieving photonic integrated circuits (PICs) with multiple functionalities [1,2]. It is not possible to attain such functionalities from either Er-doped silica glasses or narrow bandgap semiconductor materials such as InGaAsP. Optical sources and amplifiers based on Er-doped GaN and InGaN operating at 1.54 μm, have the potential to be electrically pumped, integratable, and cost effective with the performance benefits of linear gain, temperature insensitivity, and low noise. These characteristics are extremely attractive for local- and wide-area networks, cable TV distribution, and anticipated fiber-to-the-home applications where multiple amplification steps are required.

Although the wavelength of emission is not significantly affected by the solid host, the transition probability (i.e., emission intensity) is affected by the neighboring environment. It has been observed that the 1.54 μm emission from Er in small bandgap semiconductors has a low efficiency at room temperature (RT) due to a strong thermal quenching effect. In general, the thermal stability of the Er emission increases with an increase in energy bandgap or crystalline quality in the semiconductor host material [3]. Of the various wide bandgap semiconductor systems, GaN and InGaN alloys appear to be excellent hosts for Er ions due to their structural and thermal stability as well as their ability to create efficient light emitting devices.

Until recently, it has been a great challenge to incorporate Er ions into III-nitride materials to produce predominantly 1.54 μm emissions by any growth method. Previous work has been concentrated on the optical property studies of Er dopants with samples doped either by ion implantation or by *in situ* doping using the molecular beam epitaxy (MBE) growth technique [3–12]. GaN and AlGaN epilayers doped with Er ions have shown a highly reduced thermal quenching of the Er luminescence intensity from cryogenic to elevated temperatures when compared to other semiconductor host materials such as Si and GaAs [13]. There have also been reports of Er incorporation into GaN by MBE, leading to 1.54 μm electroluminescent devices [4]. However, all such devices require a high field injection of electrons under reverse bias (several hundred volts) to produce infrared (IR) emission at 1.54 μm (no 1.54 μm emission was observed under forward bias conditions). Under such reverse bias conditions, the excitation of Er ions was through an impact energy transfer mechanism. Furthermore, these devices suffer from strong emission lines in the visible region, severely limiting their prospects for practical devices in optical communication applications. Compared to ion implantation, *in situ* doping provides, in principle, precise control of Er dopants position in the device structure. In contrast to other epitaxial growth techniques, MOCVD is the established growth method in the III-nitride semiconductor industry [14].

Our group has synthesized GaN:Er and InGaN:Er epilayers that predominantly exhibit the desired optical emission for optical communication at 1.5 μm [15,16]. We discuss here the MOCVD

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growth of GaN:Er and InGaN:Er epilayers on sapphire and Si substrates, with the desired 1.5 μm emission, and also the fabrication of current-injected 1.54 μm LEDs and optical waveguide amplifier by heterogeneous integration of GaN:Er (or AlGaN/GaN:Er/AlGaN) epilayers and waveguide structures with III-nitride LEDs. These 1.54 μm LEDs and waveguide amplifier require only a few volts of bias (determined by the nitride LEDs) for operation and are fully compatible with existing optoelectronic devices for scalable integration. These results indicate the feasibility of Er-doped III-nitride materials and photonics structures, which could lead to novel current injected emitters and optical amplifiers for Si photonics. Integration of optical amplifiers based on Er-doped III-nitrides with other functional optical devices, such as wavelength routers, optical switches, light sources, and detectors, would not only enhance the functionality but also improve the performance and the reliability of future communication networks.

2. MOCVD growth of GaN:Er and InGaN:Er on different substrates

GaN:Er epilayers of about 0.5 μm in thickness were grown by MOCVD on (0 0 0 1) GaN/sapphire and AlN/Si templates. Growth of GaN:Er epilayer on sapphire substrate began with a thin GaN buffer layer, followed by a GaN epilayer template with a thickness of about 1.2 μm and an Er-doped GaN layer. The growth temperature of the GaN template and Er-doped GaN layer was 1040 °C. GaN: Er epilayer grown on Si substrate began with a thin AlN buffer layer and a 0.5 μm AlN epi-template followed by an Er-doped GaN:Er layer grown at 760 °C. The details of Er-doped GaN and InGaN can be found in our publications [15,16,19]. The layer structures of GaN:Er grown on sapphire and Si substrates employed in this study are shown in Fig. 1(a) and (b), respectively.

3. Results

3.1. Photoluminescence excitation (PLE) spectroscopy of GaN/InGaN:Er epilayers grown on different substrates

In order to design efficient optical source and amplifier, we have measured the photoluminescence excitation (PLE) spectra probed at 1.54 μm and optical absorption spectra of these epilayers to gain further understanding of the mechanisms for obtaining efficient 1.54 μm emission. For PLE spectra measurements, a set of commercially available nitride LEDs was used as the optical pumping sources with the emission wavelengths (352, 362, 371, 378, 381, 398, 411, 450, 470, and 520 nm), ranging from below to above the bandgap of the GaN host epilayer. We have also included the emission intensity probed at 1.54 μm under 980 nm laser as a excitation source. The typical full width at half maximum (FWHM) of each LED was 15–20 nm. For PLE measurements, Er-doped epilayers were mounted on top of nitride LEDs with a distance of about 2 mm from LED's top surface. The IR emission was detected by an InGaAs detector in conjunction with a monochromator, while visible emission was detected by a multichannel plate photomultiplier tube (PMT) in conjunction with another monochromator. The absorption spectra were measured using a deuterium light source in conjunction with a monochromator and PMT.

Fig. 2 shows the RT emission intensity probed at 1.54 μm of a GaN:Er epilayer under excitation with nitride LEDs of different wavelengths and 980 nm laser. The emission intensities at 1.54 μm were taken at a constant current of 20 mA and were normalized to the optical power output of each LED. The emission intensity clearly demonstrates that the emission intensity increases sharply as the excitation energy (E_{exc}) approaches the bandgap of GaN (~3.35 eV or ~370 nm at RT) from below. The PLE and optical absorption spectra shown in Fig. 2 follow exactly the same trend near the energy bandgap of GaN and a strong correlation between the two is evident. The PLE spectrum probed at 1.54 μm shows that the onset excitation wavelength for obtaining efficient 1.54 μm emission is $\lambda_{exc} < 370$ nm and the emission intensity at 1.54 μm saturates for $\lambda_{exc} < 362$ nm. Moreover, there is a little or no emission from excitation for $\lambda_{exc} > 400$ nm. These results clearly demonstrate that, in GaN:Er epilayers, excitation of free electrons and holes with above bandgap excitation and the subsequent energy transfer to Er^{3+} ion from electrons and holes is much more efficient compared to below bandgap excitation as well as resonance excitation by 980 nm laser. These excited Er^{3+} ions emit photons at 1.54 μm due to intra-4*f*-transition of $^4I_{13/2}$ level to the ground state ($^4I_{15/2}$).

We have also grown and carried out similar measurements for $In_{0.06}Ga_{0.94}N$:Er epilayers. The PLE and optical absorption spectra of Er-doped $In_{0.06}Ga_{0.94}N$ epilayers showed similar features as those of Er-doped GaN epilayers [17]. The room temperature PL spectra of an $In_{0.06}Ga_{0.94}N$:Er epilayer under the excitation of 411 (below bandgap) and 378 nm (near bandgap) InGaN LEDs are plotted in Fig. 3. It is evident that PL intensities at 1 μm (intra-4*f*-transition of $^4I_{11/2}$ level to the ground state $^4I_{15/2}$) and 1.54 μm (intra-4*f*-transition of $^4I_{13/2}$ level to the ground state $^4I_{15/2}$) under

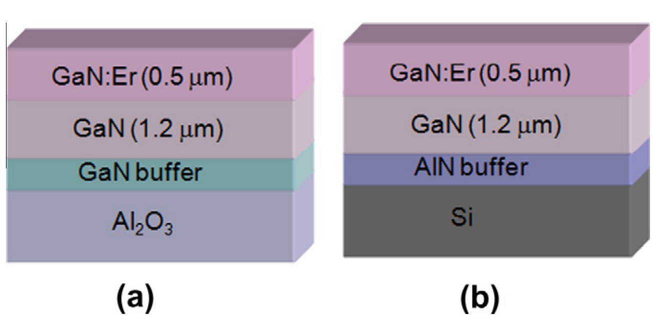

Fig. 1. Schematic layer structure of GaN:Er grown on (a) sapphire and (b) Si substrates.

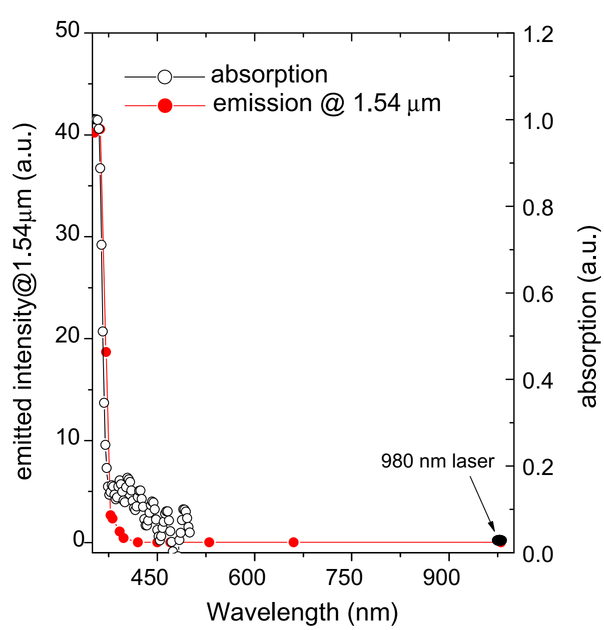

Fig. 2. PLE spectrum probed at 1.54 μm (left axis) and optical absorption spectrum (right axis) of GaN:Er grown on sapphire substrates. Fringes in the absorption spectrum are due to thin film (GaN:Er) interference effects. The excitation wavelength (λ_{exc}) was varied from 362 to 470 nm, and also includes 980 nm laser.

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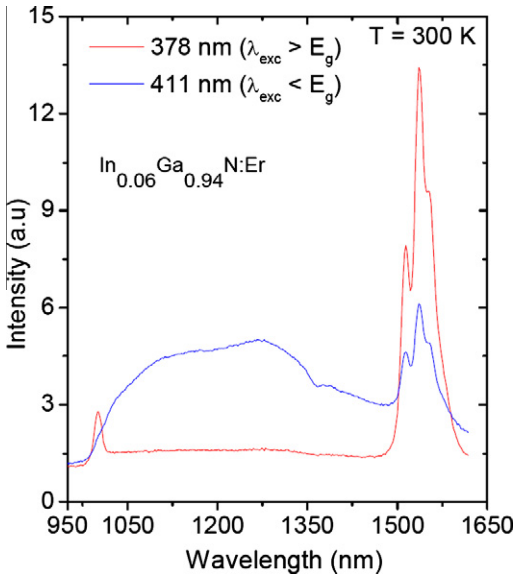

Fig. 3. RT PL spectrum of a $In_{0.06}Ga_{0.94}N$:Er epilayer under excitation of 378 nm (above bandgap) and 411 nm (below bandgap) InGaN LEDs.

near bandedge excitation (378 nm) are distinct and stronger compared to PL intensities under excitation of 411 nm (below bandgap) LED. Under below bandgap excitation of 411 nm LED, the PL intensity at 1.54 μm is weaker and there is a broad band emission starting from 0.95 μm to near 1.50 μm. The results obtained for $In_{0.06}Ga_{0.94}N$:Er show the similar behavior as those of GaN:Er epilayer and further support the conclusion that the electron and hole mediated energy transfer to Er^{3+} ions with above bandgap excitation is much more effective than below bandgap excitation [17].

We have also measured PL spectra of GaN:Er epilayer grown on Si substrate under excitation of a 365 nm nitride LED. Fig. 4 shows the room temperature PL spectrum with predominant peak at 1.54 μm due to the intra-4*f*-transition of $^4I_{13/2}$ level to the ground state ($^4I_{15/2}$). The peak intensity probed at 1.54 μm of GaN:Er grown on Si substrate is about half compared to peak intensity probed at 1.54 μm of GaN:Er grown on sapphire substrate. The lower intensity at 1.54 μm from GaN:Er grown on Si substrate is due to the lower crystalline quality of GaN grown on Si substrate. However, these results indicate the feasibility of Er-doped III-nitride materials and photonics structures, which could lead to novel current injected emitters and optical amplifiers for Si photonics.

3.2. Current injected 1.54 μm emitter and optical amplifier based on Er-doped GaN

Current injected 1.54 μm emitter and optical amplifier based on Er-doped GaN possess the advantages of linear gain, temperature stability and low crosstalk, which are extremely attractive features for PICs applications where multiple amplification steps are required. The optical results shown in Figs. 2 and 3 indicate that efficient current-injected 1.54 μm emitters and optical amplifiers could be obtained by monolithically or heterogeneously integrating highly efficient UV/blue/green nitride LEDs or LDs with InGaN:Er or GaN:Er epilayers. Based on the PLE results for obtaining the most efficient 1.54 μm emission, current-injected 1.54 μm emitters were fabricated by heterogeneously integrating GaN:Er epilayer with 365 nm nitride LEDs. The integration process started with the back polishing of GaN:Er grown on sapphire wafer down to ~100 μm and then dicing into 500 × 500 μm^2 chips. The diced chip was then bonded onto a 365 nm nitride LED chip using UV transparent epoxy with GaN:Er surface facing the LED. There was a distance of about 0.5 mm between the GaN:Er epilayer and top surface of the LED chip due to the presence of epoxy. A schematic of the heterogeneously integrated device is illustrated in the inset of Fig. 5. Near IR emission spectrum of a heterogeneously integrated device under 20 mA injection current at forward bias of 3.5 V is shown in Fig. 5.

The attainment of current-injected 1.54 μm emitters by heterogeneous integration suggests that it is highly feasible to directly grow Er-doped nitride layers either on the top or on the back side of the polished sapphire substrate of the UV/blue/green nitride LED structure to achieve monolithic current-injected 1.54 μm optical emitters. It also appears feasible to obtain current-injected optical amplifiers based on a GaN:Er (or InGaN:Er) waveguide layer deposited on top of a completed III-nitride UV (blue) emitter structure or

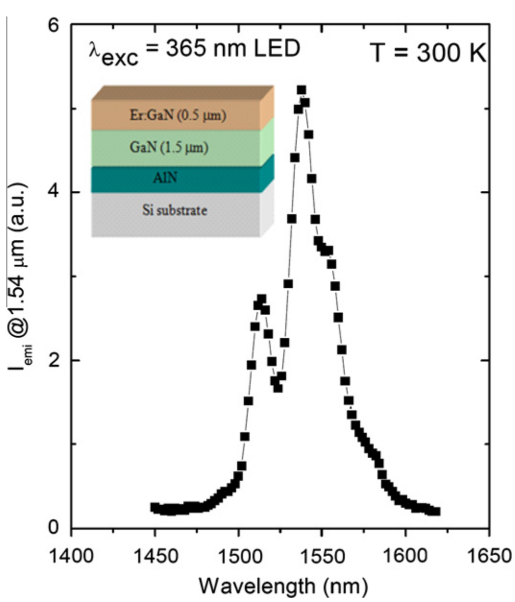

Fig. 4. PL spectrum (room temperature) of a GaN:Er epilayer grown on Si substrate under excitation of 365 nm (above bandgap) LEDs.

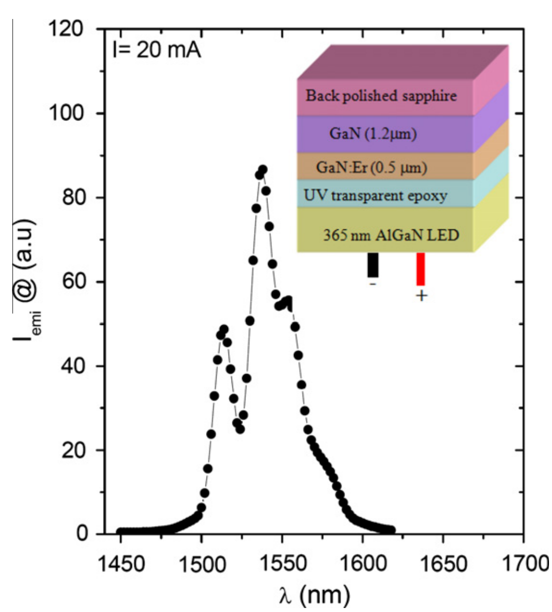

Fig. 5. IR emission spectra (room temperature) of a current-injected 1.54m μm LED under 20 mA injection current at forward voltage of 3.5 V. The inset is the schematic layer structure of fabricated LED.

AlGaN/(In)GaN:Er/AlGaN p–*i*–*n* quantum well (QW) structure [18]. Such a development would require further improvements in material quality and device architectures. However, our group has recently demonstrated the effective way to enhance the emission efficiency at 1.54 μm of Er-doped III-nitride through strain engineering [19]. However, it will be a challenging task to obtain highly conductive p-type AlGaN (GaN) cladding layers above GaN:Er (InGaN:Er) QW active region to achieve a current injected device.

We have also fabricated and studied the amplification characteristics near 1.54 μm region of AlGaN/Er:GaN/AlGaN waveguide heterostructures grown by MOCVD on sapphire substrates. The layer of waveguide amplifier consists of 0.5 μm thick $Al_{0.03}Ga_{0.97}N$ upper cladding layer, 0.5 μm Er-doped GaN as an active as well as guiding medium and 1.5 μm thick $Al_{0.03}Ga_{0.97}N$ lower cladding layer. The devices were processed into strip waveguides using standard optical lithography and dry etching techniques. 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 1.54 μm light emission propagated through the waveguide and was collected from the far end using tapered fiber coupled with a monochromator and an InGaAs detector. Fig. 6(a) shows the 1.54 μm PL spectra measured at room temperature from the far end of waveguide after excitation by the 371 nm laser beam. PL spectra peak at 1.54 μm corresponding to the intra-4*f* Er^{3+} transitions from the $^4I_{13/2}$ level to the ground state ($^4I_{15/2}$). The integrated PL emission intensity, I_t, collected at the exit facet of the waveguide is plotted as a function of laser excitation spot distance, *d*. 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} (1.5 dB/mm) [18]. 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 and gentle wet etching following plasma etching. The small value of optical loss in GaN:Er waveguide is what we expected because 1.54 μm wavelength is far from the bandgap 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 PICs.

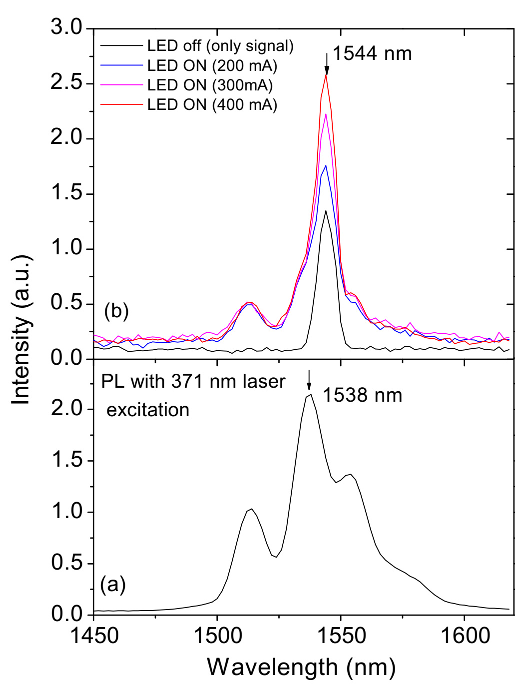

Fig. 6. (a) PL spectra of Er-doped GaN waveguide amplifier taken from the end facet of the waveguide when the other end is illuminated by a 371 nm nitride laser, and (b) Spectra of the transmitted 1.544 μm signal emerged from the exit end of waveguide measured under the excitation by a 365 nm high power nitride LED operating at different forward currents. The intensity of the 1.544 μm 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 1.544 μm.

The amplification characteristics of these waveguides were analyzed by studying the relative change in transmitted signal intensity at 1.544 μm. For the optical excitation, a 365 nm GaN LED was used from the bottom side, which is intended to substitute the finely tuned high power laser required for Er-doped silica or ceramic based waveguide amplifier. Fig. 6(b) shows the transmitted 1.544 μm signal spectra through the waveguide at different levels of 365 nm LED excitation. It is clearly seen that the relative signal intensity at peak signal wavelength (1.544 μm) increases with increasing the excitation intensity of the 365 nm LED. The optical excitation at 365 nm creates population inversion between the first excited state ($^4I_{13/2}$) and the ground state ($^4I_{15/2}$) of Er ion. The transition from the first excited state to the ground state due to input signal increases the intensity of the input signal when passing through the active medium of the waveguide. 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 optical gain measurement, we have not separated the contribution due to stimulated and spontaneous emission of Er ion. In order to determine the net optical gain, the contribution due to spontaneous emission should be eliminated which requires further measurements. The additional peaks besides 1.544 μm observed in Fig. 6(b) are from the spontaneous PL emission of Er ion. However, 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.

In summary, we have fabricated current-injected 1.54 μm LEDs based on heterogeneous integration of MOCVD grown Er-doped III-nitride epilayers with III-nitride UV LEDs. The Er emission intensity at 1.54 μm increases significantly as the excitation energy is tuned from below to above the energy bandgap of these epilayers, indicating that the band-to-band excitation of the host material and subsequent electron and hole mediated energy transfer to Er^{3+} ions is a much more effective excitation mechanism for 1.54 μm emission than below bandgap excitation as well as resonance excitation by 980 nm laser. It was shown that the 1.54 μm emission intensity increases almost linearly with the input forward current. These results open up possibilities for developing the next generation IR photonic devices based on Er-doped III-nitride materials such as 1.54 μm emitters and optical amplifiers for optical communications. Such devices possess the advantages of both semiconductor optical amplifiers (small size, electrical pumping, ability for photonic integration, etc.) and Er-doped fiber amplifiers (minimal cross-talk between different wavelength channels in wavelength-division multiplexing optical networks).

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