# Current-injected 1.54 $\mu$m light emitting diodes based on erbium-doped GaN

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Current-injected 1.54 $\mu$m emitters have been fabricated by heterogeneously integrating metal organic chemical vapor deposition grown Er-doped GaN epilayers and 365 nm nitride light emitting diodes. It was found that the 1.54 $\mu$m emission intensity increases almost linearly with input forward current. The results represent a step toward demonstrating the feasibility for achieving electrically pumped optical amplifiers for optical communication that possess advantages of both semiconductor optical amplifiers and Er-doped fiber amplifiers. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2955834]

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 with multiple functionalities,[1,2] which are not possible to attain from either Er-doped silica glasses or narrow gap semiconductor materials such as InGaAsP. The optical sources and amplifier operating at 1.54 $\mu$m based on Er-doped semiconductors, if obtained, will be electrically pumped, integratable, and low cost, with the performance 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 affected by the solid host, the transition probability (i.e., emission intensity) is affected by the neighboring environment. It has been universally observed that the 1.54 $\mu$m emission from Er in semiconductors of smaller bandgaps has a low efficiency at room temperature (RT) due to a strong thermal quenching effect. In general, the thermal stability of Er emission increases with an increase in the energy gap and the crystalline quality of the semiconductor host material.[3] Of the various wide bandgap semiconductor systems, III-nitrides appear to be an excellent host system for Er ions due to their structural and thermal stability as well 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 $\mu$m 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 molecular beam epitaxy (MBE) growth technique.[3–12] 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.[13] There also have been reports of Er incorporation by MBE, leading to 1.54 $\mu$m electroluminescent devices.[4] However, all such devices require high field injection of electrons under reverse bias (several hundred volts) to produce infrared (IR) emission at 1.54 $\mu$m (no 1.54 $\mu$m 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 for optical communication applications. Compared to ion implantation, *in situ* doping in principle provides precise control of Er dopants position in the device structure. In contrast to other epitaxial growth techniques, metal organic chemical vapor deposition (MOCVD) is the established growth method in III-nitride semiconductor industry, and almost all the commercial III-nitride photonic devices including light emitting diodes (LEDs) and laser diodes (LDs) are grown by MOCVD technique.[14]

Recently, we have synthesized by MOCVD GaN:Er epilayers that exhibit predominantly the desired optical emission for optical communication at 1.5 $\mu$m.[15] However, true current-injected 1.5 $\mu$m LEDs operating under low forward bias voltages have not been realized. We report here on MOCVD growth of GaN:Er and InGaN:Er epilayers which exhibit predominantly the desired 1.5 $\mu$m emission and fabrication of current-injected 1.54 $\mu$m LEDs by heterogeneous integration of GaN:Er (or InGaN:Er) epilayers with III-nitride LEDs. These 1.54 $\mu$m LEDs 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.

GaN:Er and $In_{0.06}Ga_{0.94}N$:Er epilayers of about 0.5 $\mu$m in thickness were grown by MOCVD on 1.2 $\mu$m GaN templates on (0001) sapphire substrates. A more detailed description about MOCVD growth of Er-doped III-nitride epilayers can be found in our previous publication.[15] In order to design efficient photonic devices, we have measured the photoluminescence excitation (PLE) spectra probed at 1.54 $\mu$m and optical absorption spectra of these epilayers to gain understanding of the mechanisms for obtaining efficient 1.54 $\mu$m 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) ranged from below to above the bandgap of the GaN and InGaN host

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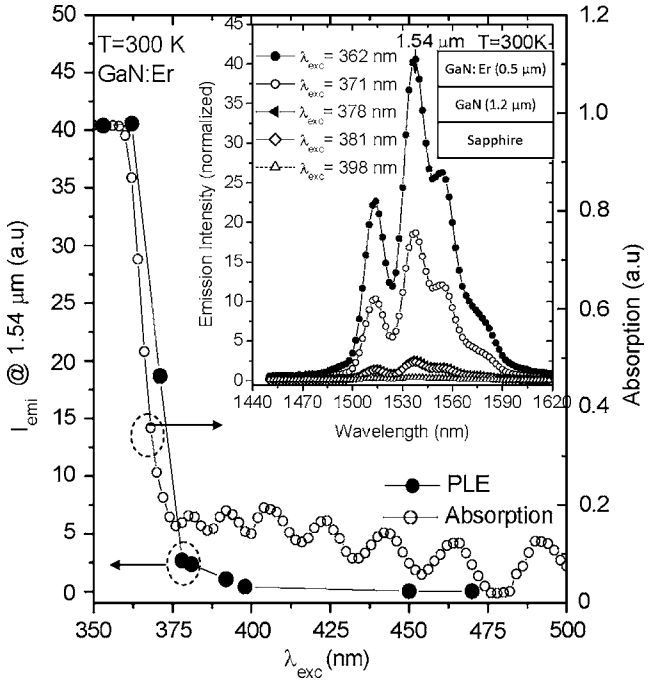


FIG. 1. PLE spectrum probed at 1.54 $\mu$m (left axis) and optical absorption spectrum (right axis) of a MOCVD grown GaN:Er epilayer. Emission intensity at 1.54 $\mu$m, $I_{emi}$, increases sharply at excitation energies greater than 3.35 eV ($\lambda_{exc} < 370$ nm), which coincides with the RT bandgap of GaN. Fringes in the absorption spectrum are due to thin film (GaN:Er) interference effects. The inset shows the RT emission spectra near 1.54 $\mu$m of the same sample, from which the PLE spectrum was constructed. The excitation sources for PLE measurements were III-nitride LEDs with wavelengths ($\lambda_{exc}$) varying from 362 to 470 nm, corresponding to energies from below to above bandgap of the host GaN and the emission intensities were normalized to the LED optical power outputs.

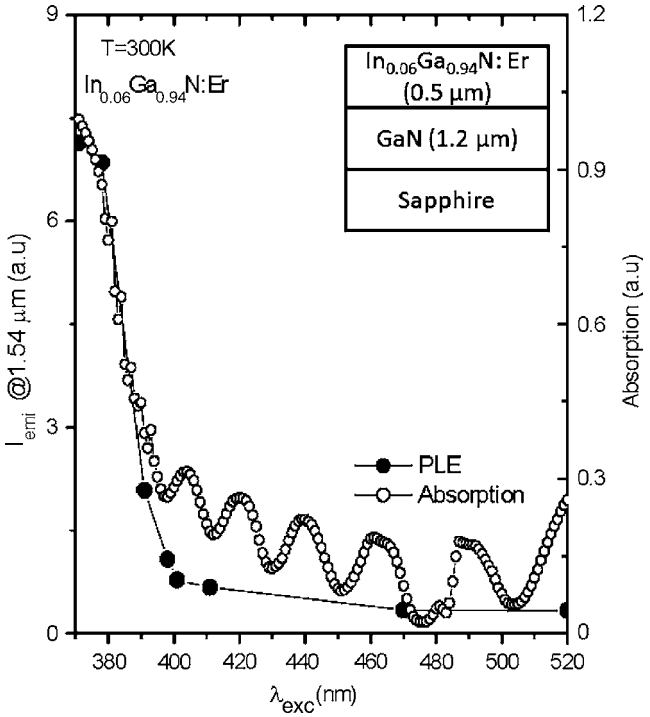


FIG. 2. PLE spectrum probed at 1.54 $\mu$m (left axis) and absorption spectrum (right axis) of a MOVCD grown $In_{0.06}Ga_{0.94}N$:Er epilayer. Emission intensity at 1.54 $\mu$m, $I_{emi}$, increases sharply for excitation energy greater than 3.18 eV ($\lambda_{exc} < 390$ nm) corresponding to the RT bandgap of $In_{0.06}Ga_{0.94}N$.

epilayers. The typical full width at half maximum 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 deuterium light source in conjunction with a monochromator and PMT.

The inset of Fig. 1 shows the RT emission spectra of a GaN:Er epilayer under excitation with different excitation wavelengths using nitride LEDs. The emission spectra were taken with the LEDs under constant current of 20 mA and were normalized to the optical power output of each LED. The emission spectra clearly demonstrate 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. This point is further supported by the PLE and optical absorption spectra shown in Fig. 1. The PLE spectrum probed at 1.54 $\mu$m shows that the onset excitation wavelength for obtaining efficient 1.54 $\mu$m emission is for $\lambda_{exc} < 370$ nm and the emission intensity at 1.54 $\mu$m saturates for $\lambda_{exc} < 362$ nm. Moreover, there is little or no emission from excitation for $\lambda_{exc} > 400$ nm. Compare the PLE spectrum measured at 1.54 $\mu$m and absorption spectrum of GaN:Er, a strong correlation between the two is evident. The two spectra follow exactly the same trend near the energy bandgap of GaN. 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 absorption. These excited $Er^{3+}$ ions emit photons at 1.54 $\mu$m due to intra-4*f*-transition of $^4I_{13/2}$ level to the ground state ($^4I_{15/2}$).

To further confirm these results, we have also grown and carried out similar measurements for $In_{0.06}Ga_{0.94}N$:Er epilayers. Due to the lower growth temperatures of InGaN epilayers, the incorporation of Er into InGaN is much more difficult and hence the relative emission intensity at 1.54 $\mu$m in $In_{0.06}Ga_{0.94}N$:Er epilayers is about three times weaker than in GaN:Er epilayers. Nevertheless, the PLE and optical absorption spectra of Er-doped $In_{0.06}Ga_{0.94}N$ epilayers show similar features as those of Er-doped GaN epilayers. The PLE spectrum probed at 1.54 $\mu$m and optical absorption spectrum of an $In_{0.06}Ga_{0.94}N$:Er epilayer are plotted in Fig. 2. It is evident that PLE and absorption spectra are again strongly correlated, especially near the energy bandgap of $In_{0.06}Ga_{0.94}N$, which is about 3.18 eV (~390 nm) at RT. In general, $In_{0.06}Ga_{0.94}N$:Er exhibits a similar trend as that seen in GaN:Er shown in Fig. 1, except that the onset excitation energy for obtaining an efficient 1.54 $\mu$m emission is reduced because of the smaller bandgap of $In_{0.06}Ga_{0.94}N$ than GaN (~3.18 eV for $In_{0.06}Ga_{0.94}N$ versus ~3.35 eV for GaN). The results obtained for $In_{0.06}Ga_{0.94}N$:Er further support the conclusion that the electron and hole energy transfer to $Er^{3+}$ ions is much more effective than below bandgap excitation.

The optical results shown in Figs. 1 and 2 indicate that efficient current-injected 1.54 $\mu$m 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 $\mu$m

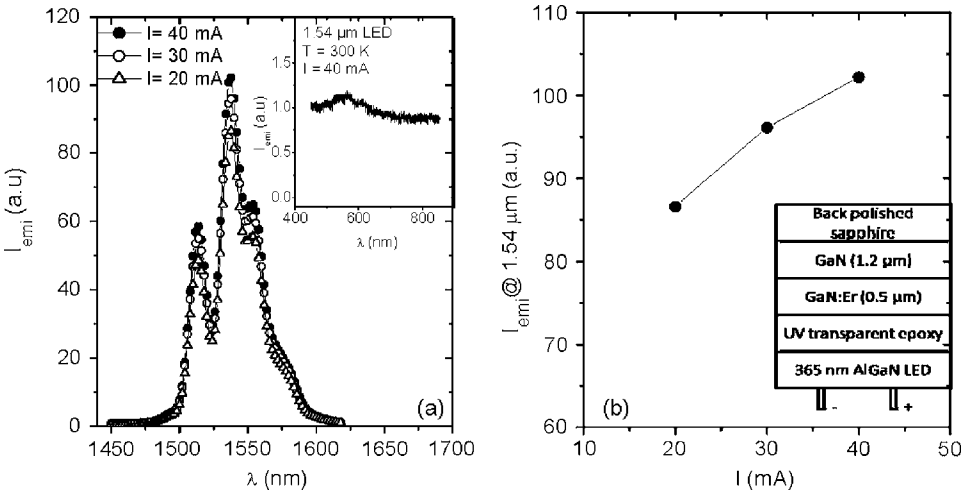


FIG. 3. (a) IR emission spectra of a current-injected 1.54 $\mu$m LED under different injection current levels. The inset is the visible emission spectrum of the same device, showing virtually no Er-related emission in the spectral range of 430–850 nm. (b) Emission intensity ($I_{emi}$) of the same 1.54 $\mu$m LED as a function of the forward injection current. The inset schematically illustrates that the 1.54 $\mu$m LED is fabricated by heterogeneous integration of a GaN:Er epilayer with a 365 nm III-nitride LED.

emission, current-injected 1.54 $\mu$m emitters were fabricated by heterogeneously integrating GaN:Er (or InGaN:Er) epilayers with 365 nm nitride LEDs. The integration process started with the back polishing of GaN:Er grown on sapphire wafer down to $\sim$100 $\mu$m and then dicing into 500 $\times$500 $\mu$m$^2$ 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 in Fig. 3(a). These 1.54 $\mu$m emitters were characterized in terms of spectral and power emission under different current levels at forward bias.

Figure 3(a) shows the IR emission spectra of a heterogeneously integrated device under different injection current levels at forward bias. The inset in Fig. 3(a) shows that no Er-related emission in the visible spectral range (between 420 and 850 nm) was observed. The emission intensity at 1.54 $\mu$m increases almost linearly with the input current, as shown in Fig. 3(b). The attainment of current-injected 1.54 $\mu$m emitters by heterogeneous integration here suggests that it is highly feasible to directly grow Er-doped nitride layers either on the top or back side of the polished sapphire substrate of UV/blue/green nitride LED structure to achieve monolithic current-injected 1.54 $\mu$m optical emitters. It also appears feasible to obtain current-injected optical amplifiers based on GaN:Er (or InGaN:Er) waveguide layer deposited on top of a completed III-nitride UV (blue) emitter structure or AlGaN/(In)GaN:Er/AlGaN *p-i-n* quantum well (QW) structure. Such a development would require further improvements in GaN:Er and InGaN:Er epilayer material quality and device architectures. In particular, it will be a challenging task to obtain highly conductive *p*-type AlGaN (GaN) cladding layers above GaN:Er (InGaN:Er) QW active region.

In summary, we have fabricated current-injected 1.54 $\mu$m 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 $\mu$m 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 $\mu$m emission compared to below bandgap excitation. It was shown that the 1.54 $\mu$m emission intensity increases almost linearly with the input forward current. These results open up possibilities for developing next generation IR photonic devices based on Er-doped III-nitride materials such as 1.54 $\mu$m emitters and optical amplifiers for optical communications that possess 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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