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III-Nitride Wide Bandgap Semiconductors for Optical Communications

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This paper provides a brief overview on recent advances in the exploitation of III-nitride semiconductors for optical communications, such as epitaxial growth of Er-doped III-nitride materials by MOCVD and optical waveguide fabrication Advantages and challenges of this emerging technology will be discussed.

The main applications of III-nitride wide bandgap semiconductors so far are light emitting diodes (LEDs) with emission wavelengths from UV to amber, and blue laser diodes (LDs) [1]. The III-nitride system has a tunable energy band gap ranging from 0.7 eV (InN) to 3.4 eV (GaN) to about 6.1 eV (AlN). These materials are excellent for photonic devices due to their large energy bandgaps, highly efficient light emission, and the ability of bandgap engineering through the use of alloying and heterojunctions. Recent advances have shown that nitrides are also promising materials for optical communications at 1.55 μm. The continuous variation of the refractive index of $Al_xGa_{1-x}N$ with x, from 2.34 (x=0) to 2.03 (x=1) at 1.55 μm makes III-nitrides ideal candidates for optical waveguide devices [2]. III-nitrides could be an alternative to InP-based alloys due to the better index match with silica optical fibers. Also it may be feasible to fabricate Er-doped III-nitride waveguide optical amplifiers. If successful, the optical amplifier based on Er-doped semiconductors will be electrically pumped, low cost, with the performance of linear gain and low noise. More importantly, they would lead to the integration with other functional optical devices, such as wavelength routers, light sources, and detectors. A superior thermal stability of Er emission is expected because of the wide energy gap of III-nitrides. These characteristics are extremely attractive for many applications, where multiple amplification steps are required. The large conduction band offset in AlN/GaN heterostructure (~1.9 eV) may allow the realization of intersubband emitters and detectors operating at 1.55 μm.

Intersubband transitions

The intersubband transitions in AlGaN/GaN quantum well (QWs) can be tailored to the optical communication wavelength at 1.55 μm. Such QW devices have distinct advantages compared to those based on other materials, including large electron effective mass and longitudinal optical phonon energy. These properties are crucial for the ultrafast intersubband relaxation of electrons. Optical absorption lines between n=1 and n=2 subbands in AlGaN/GaN QWs have been observed by several groups in structures grown by MBE and MOCVD [3-5]. For illustration, we plot in Fig. 1 the calculated emission wavelength (λ) vs. L_w of intersubband transition in AlN/GaN QWs. The whole optical communication band from 1.2 to 1.7 μm can be achieved.

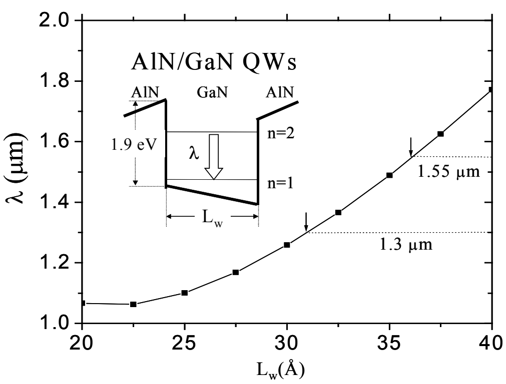

Fig. 1 Emission wavelength of the intersubband transition in the AlN/GaN quantum well system as a function of the well width, L_w.

Growth and optical studies of Er doped III-nitride materials

Recent studies have shown that III-nitrides are excellent host materials for erbium ions [6-9]. Several techniques, including *in situ* doping during eptaxial growth and ion-implantation of grown epilayers, have been employed to obtain Er doped GaN. In particular, nitride epilayers doped with Er ions have shown a highly reduced thermal quenching of the 1.55 μm emission intensity from cryogenic to elevated temperatures, as compared to other host materials such as Si and GaAs. The high thermal stability of the Er emission in nitrides may allow fabrication of novel electrically pumped optical amplifiers that possess advantages of both semiconductor optical amplifers (small size, electrical pumping, ability for optical integration) and Er-doped fiber amplifers (minimal cross-talk between different wavelength channels).

Recently, in collaboration with SVTA Inc. [10], we have successfully synthesized and characterized AlGaN/GaN:Er/AlGaN double heterostructures (DH). This effort involved a multistage growth process by taking the advantages of ease of Er incorporation by molecular beam epitaxy (MBE) and the ability of metal organic

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chemical vapor deposition (MOCVD) for growing high quality n- and p-type AlGaN epilayers. We have fabricated and demonstrated the operation of the first 1.55 μm current injection LED based on p-AlGaN/GaN-Er/n-AlGaN DH.

In recent years, Er incorporation into III-Nitride materials has also been obtained by ion implantation, hydride vapor phase epitaxy (HVPE), metal organic molecular beam epitaxy (MOMBE), or MBE. Er doped nitride materials grown by all of these methods suffer from two major problems – weak emission at 1.5 μm region and strong visible emission at 537 nm [11]. In-situ Er doping of III-Nitride materials by MOCVD has not been previously achieved, partly due to the low vapor pressure and lack of suitable, metal organic Er sources. Since n- and p- type III-nitride epilayers with excellent electrical properties and high crystalline quality are easily achieved by the MOCVD growth method, in-situ incorporation of Er into III-nitrides by MOCVD is a very attractive method for creating highly efficient optoelectronic devices operating at 1.54 μm. We have recently achieved for the first time synthesis of Er doped GaN by MOCVD. As shown in Fig. 2, photoluminescence (PL) spectra of these Er doped layers exhibit a strong 1.54 μm emission, corresponding to the intra-4f transition of the $^4I_{13/2}$ (first excited state) to the $^4I_{15.2}$ (ground state) of Er^{3+}. Most importantly, no emission lines in the visible region were observable. Optical and electrical properties for epilayers of different Er concentrations have been studied and will be reported.

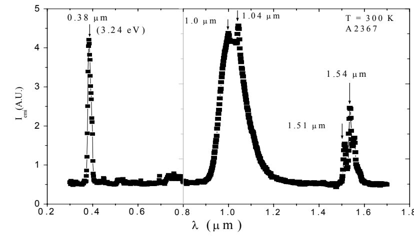

Fig.2 Room temperature photoluminescence spectrum of Er doped GaN grown by MOCVD under an excitation wavelength of 266 nm measured at room temperature. The green emission lines which are dominant in MBE grown GaN materials [11] are absent in MOCVD grown materials here.

Summary

The III-nitride materials have been at the central stage in the semiconductor R&D effort for the last decade with the main focus on photonic devices operating in the visible and UV regions. We believe that III-nitride photonics hold great promise for applications in optical communications at 1.55 μm. However, many fundamental issues must be addressed in order to realize this goal. For example, the optical propagation loss, temperature sensitivity, polarization effects in InGaN/AlGaN heterostructures, carrier-induced change of the index of refraction, modulation efficiency, and modulation induced polarization effects require further studies. Mechanisms that would enhance the Er emission at 1.55 μm in Er-doped nitrides must be further explored. Novel designs for device integration have to be developed. As further improvements in material quality as well as fundamental understandings are achieved, it is conceivable that the future of III-nitrides for optical communication applications will be as bright as for blue/green and UV applications.

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