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# Optical Gain in Er Doped GaN Multiple Quantum Wells

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## ABSTRACT

We report the realization of lasing in Er-doped GaN multiple quantum wells in the technologically crucial 1.54-μm wavelength at room temperature. We have obtained optical gain in the multiple quantum well structure by using a variable stripe technique. The stimulated emission from the material has been revealed from the characteristic threshold behavior of spectral linewidth narrowing, and the emission intensity as a function of pump fluence.

**Keywords:** Infrared laser, Silicon, GaN, Rare earth, Quantum wells, Lasing

## 1. INTRODUCTION

Semiconductor lasers in the near-infrared region are important for spectroscopy and imaging, optical telecommunication, medical applications, and military defense.[1-3] In this framework, erbium (Er) doping of semiconductors is a potential candidate for near-infrared applications.[1, 3] The emission of $Er^{3+}$ ions at the 1.54 μm coincides with the minimum absorption band of optical fibers.[3-7] With great effort, a number of 1.54 μm Er-doped semiconductor lasers has been obtained by using crystalline Si,[3, 8-12] $SiO_2$:Er sensitized with Si nanocrystals,[13-15] or AlGaAs and GaAs.[16] However, due to the strong thermal quenching effect of the emission taking place in the indirect and/or narrow band-gap materials, applications of these materials are limited at room temperature.[16]

GaN semiconductor with direct and wide bandgap (~3.3 eV) is a promising host material for Er doping. Er-doped GaN materials show a low thermal quenching and strong photoluminescence (PL) at room temperature.[2, 4] We have successfully grown Er-doped GaN epi-layers using the metal organic chemical vapor deposition (MOCVD) method, which provides strong PL at room temperature.[17-19] Near-infrared lasers at room temperature have been realized in Er-doped GaN (GaN:Er) epi-layers.[20] Recently, Er-doped GaN/AlN multiple quantum wells (MQWs:Er) have been fabricated.[19] The materials show a significant enhancement of PL intensity with an order of magnitude higher than that of the GaN:Er epi-layer due to the quantum confinement effect.[19, 21] Here, we report the room temperature lasing in MQWs of AlN/GaN:Er for the emission at 1.54 μm under the over bandgap excitation by using the variable stripe length technique.

## 2. EXPERIMENTAL RESULTS

### 2.1. Er-doped GaN/AlN multiple quantum wells fabrication

The aluminum, gallium and nitrogen sources from trimethylaluminum (TMA), trimethylgallium (TMGa) and ammonia ($NH_3$), respectively, were used to fabricate GaN/AlN multiple quantum wells. Tris (isopropylcyclopenta-

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dienyl) erbium (TRIPEr) was employed for the *in-situ* Er doping process. The precursors for Ga and Er were held at temperatures 3 ºC and 60 ºC, respectively, and were carried into the reactor by $H_2$ gas. Firstly, buffer layers were grown on a sapphire wafer. A 30-nm AlN layer was grown at 950 ºC and 30 mbar, then a 100-nm AlN layer at 1100 ºC grown at 30 mbar, followed by a 1.0-µm AlN layer grown at 1325 ºC and 30 mbar. Secondly, the MQWs:Er structure was grown at 1000 ºC and 30 mbar, in which the 2-nm Er-doped GaN quantum wells and 10-nm AlN barriers were grown alternatively. A detailed fabrication and characterization of MQWs:Er were presented in our previous report.[21]

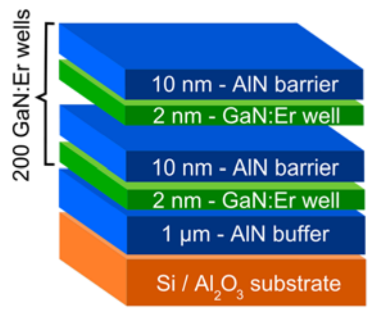


**Figure 1:** Schematic of 200 periods of GaN:Er/AlN structure. The width of the GaN:Er quantum well and AlN barrier are 2 nm and 10 nm, respectively.

### 2.2. Edge-emission measurements

To demonstrate the lasing action from the MQWs:Er sample, we performed edge-emission measurements by using the variable stripe length technique. The laser beam was expanded by a beam expander, and selected by a $5 \times 5$- mm$^2$ slit to obtain a homogeneous excitation beam. The beam was focused by a cylindrical lens of 75 mm to achieve a stripe-shaped excitation beam with 6-µm width. The homogeneous stripe of the pump beam was confirmed by a beam profile setup including an UV photodetector mounted on a two-dimensional linear stage. The MQWs:Er sample was mounted at the focal plane of the cylindrical lens. An adjustable shied on the sample can vary the length of the excitation stripe. The total length of the excitation area on the sample was 1000 µm. The edges of the MQWs:Er sample were polished to create a cavity. Two lenses with $f = 10$ cm and $f = 24$ cm have been used to collect the edge-emission from the sample. Then, the emission was focused onto the entrance slit of the Horiba *i*HR550 spectrometer with a 900 grooves/mm grating blazed at 1500 nm and detected by the InGaAs *DSS-IGA* detector. The edge-emission measurements of the MQWs:Er sample were excited by a 351-nm cw Argon laser at room temperature.

## 3. DISCUSSION

The percentage of optically active Er centers is an important parameter to realize the optical gain in the MQWs:Er sample. We compared the PL intensity at room temperature between a $SiO_2$:Er reference sample and the MQWs:Er sample using a tunable Ti:sapphire laser operating at 809 nm for the resonant excitation of the $^4I_{15/2} \rightarrow {}^4I_{9/2}$ transition. The percentage of the optically active $Er^{3+}$ centers emitting 1.54 µm is estimated about 65% of the total $Er^{3+}$ ions.[18] A large number of the optically active $Er^{3+}$ center indicates a high possibility of obtaining amplified spontaneous emission in the MQWs:Er materials.

To realize the room temperature lasing from $Er^{3+}$ optical centers in the MQWs:Er structure, we performed the edge-emission experiments under the over bandgap excitation using a 351-nm cw Argon laser. A strip area with 6.0-µm width and 200-µm length on the sample has been excited. The pump fluence was changed from 0.04 to 120 mJ cm$^{-2}$. The edge-emission spectra from the MQWs:Er sample were collected under different pump fluences in



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Figure 2. The $Er^{3+}$ emission at 1.54 µm shows the spontaneous emission under pump fluence below 15 mJ $cm^{-2}$. The spectrum of emission has broad characteristics, in which its full width at half maximum (FWHM) is 30 meV (~60 nm).[19, 21] However, the intensity of the 1.54-µm emission increases exponentially under a high pump fluence, higher than 15 mJ $cm^{-2}$. Under this condition, the spontaneous emission is exponentially amplified by the stimulated emission when emission photons travel through the active medium, which leads to a superlinear increase of emission. The PL spectra present a number of narrow and strong PL lines that appear on the broad spontaneous emission spectrum. This is an evidence of lasing from $Er^{3+}$ optical centers at 1.54 µm. We deconvoluted the emission spectra at high excitation pump fluence and obtained three strongest emission lines at 797.3, 805.3 and 807.5 meV.

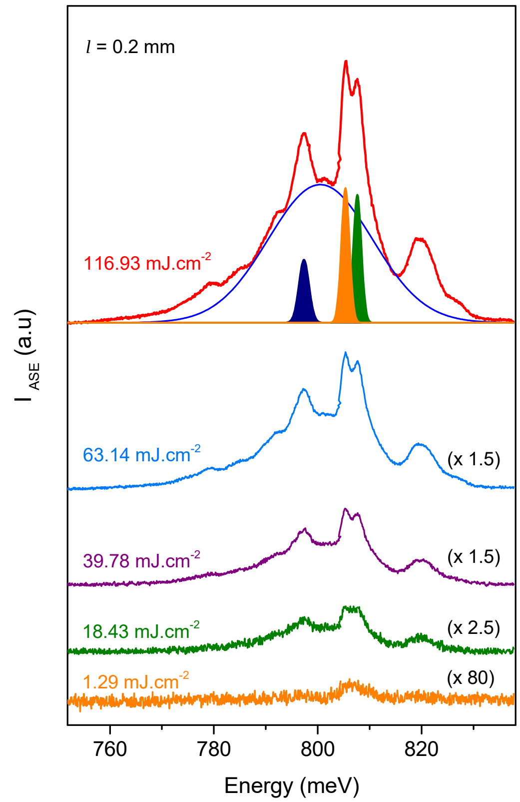


**Figure 2:** Emission spectra of the MQWs:Er using an Ar laser, $\lambda_{exc} = 351$ nm, under different pump fluences at room temperature.

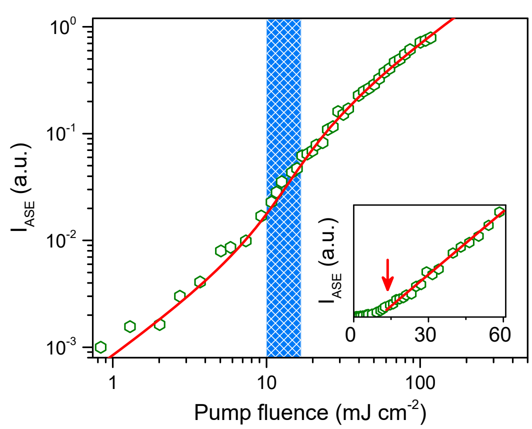


**Figure 3:** The edge-emission intensity at 805.3 meV under different pump fluence values on a log-log scale, and in the inset on a linear scale.



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The threshold behavior of the three PL lines shows a transition from spontaneous to stimulated emission. Figure 3 presents the strongest PL peak at 805.3 meV (1539.6 nm) as a function of pump fluence on the log-log scale. The PL intensity increases linearly with the pump fluence below the threshold (Figure 3, inset). It increases exponentially with the pump fluence above the threshold. A lasing threshold, $P_{th}$, is ~ 15 mJ cm$^{-2}$. Furthermore, when the pump fluencies were above the threshold value of 15 mJ cm$^{-2}$, the FWHM of the spectra reduces rapidly from 20 meV to 1.6 meV (Figure 4).

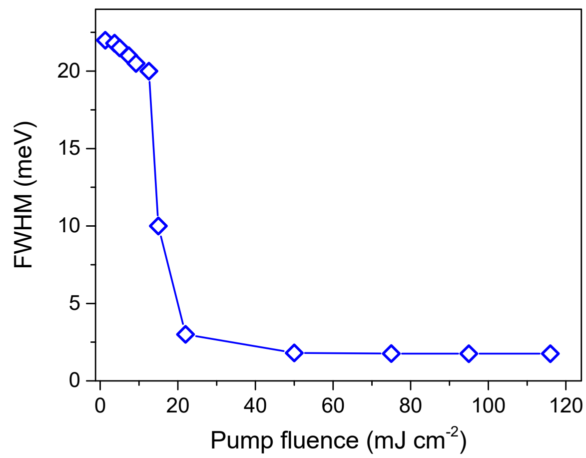


**Figure 4:** The FWHM of the Gaussian peak at 805.3 meV reduces rapidly at a high pump fluence.

## 4. CONCLUSION

In summary, we have investigated the lasing of MQWs:Er sample grown by MOCVD technique under the over bandgap excitation. The lasing action is confirmed by the spectral linewidth narrowing and the stimulated threshold in this material. Lasers operating at the near-infrared region based on MQWs:Er could provide opportunities in optoelectronic integration between high power electronics and photonics.

## ACKNOWLEDGMENTS

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