Femtosecond Carrier dynamics in InGaN multiple-quantum-well laser diodes under high injection levels

Kian-Giap Gan and John E. Bowers
Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106
giap@ece.ucsb.edu

Chi-Kuang Sun
Department of Electrical Engineering and Graduate Institute of Electro-Optical Engineering, National Taiwan University, Taipei 10617, Taiwan, R.O.C.

1. Introduction

Recently, the group-III nitride semiconductor alloys AlN-GaN-InN has been recognized as an important material system for optoelectronic devices in the spectra range from infrared to ultraviolet. GaN-InN based III-V nitride semiconductors have many commercial applications, such as light emitting diodes [1] and laser diodes [2]. The carrier dynamics, important for high speed devices design, have recently been studied by femtosecond time-resolved pump-probe [3] or coherent spectroscopy [4] with above bandgap photons under low excitation level. In this paper, we report on the carrier dynamics of an InGaN multiple-quantum-well (MQW) laser diode under the high current injection level, for the first time, using time-resolved pump-probe measurements.

2. Experiment and sample

The schematic diagram of the pump-probe measurement is shown in Fig. 1. The pump and probe beam are derived from second harmonic generation (SHG) of a tunable 100-fs Ti:Sapphire modelocked laser. Pump and probe beam are combined collinearly with a 10 to 1 ratio and directed to the laser diode under investigation. A polarizer was used to block the reflected pump beam, and the power of the reflected probe beam was measured with a lock-in amplifier as a function of delay.

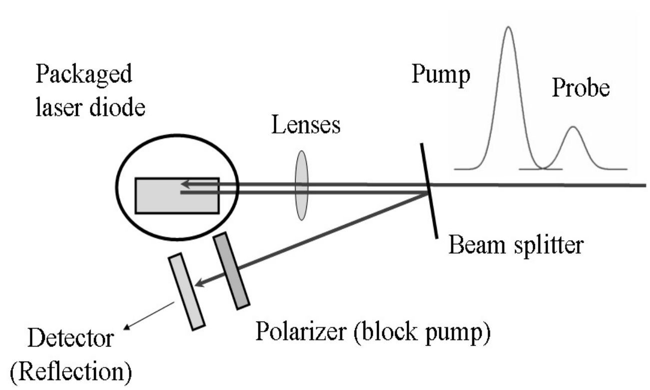

Fig. 1. Schematic diagram of the pump probe measurement

The sample studied in this work is a commercial blue laser diode with threshold current of 33 mA and lasing wavelength of 404 nm. The sample is packaged in a TO-can and the back facet of the laser diode is not accessible for transmission measurement. To overcome this limitation reflection measurement was employed to study the carrier dynamics of the InGaN MQW laser diode. The contributions to the measurement response from the waveguide region will dominate the contributions from the two facets because the waveguide region is long (670 µm).

3. Results and discussions

From the TE-pump TM-probe measurement at 402 nm excitation, the transparency injection current level can be determined to be 20 mA (~10^{19} cm^{-3}) by looking at the sign of the reflectivity change at long delay.

When the polarization of pump and probe are exchanged (TM pump and TE probe), different behavior is observed. As show in Fig. 2, the reflection change at long delay (4 ps) is always positive regardless of the injection current level. This means that TM pump light always increases the number of carrier in the subbands that are sensitive to the TE probe light, because the TM-generated hole in the HH2 and LH2 subband will transfer to the HH1 and LH1 subband that are sensitive only to the TE polarized light, as demonstrated previously [5]. A negative response near zero delay is attributed to two photon absorption. At low injection current level (5 mA and 10 mA), there is a transient increase in reflection (absorption bleaching). The magnitude of this absorption bleaching decreases as the injection current level was increased. We believe this phenomenon is due to the ultrafast transferring of the TM generated holes into the TE sensitive subbands and thus causing a transient increase in reflection (decrease in absorption) due to phase space filling effect. This phase space filling effect will decrease as the number of the carrier increase, so it also explains the observation that the magnitude of the transient increase in reflection diminish as the injection current level increase. Once the holes transfer to the TE sensitive subbands, they will then increase the hole temperature in the TE sensitive subbands through carrier-carrier scattering, the resulting hot hole distribution will cool down to the lattice temperature at time constant of 0.8 ps through carrier-phonon interaction. It is interesting to note that, the intersubband hole relaxation and hole heating processes are found to dominate carrier dynamic response in InGaN laser diodes and this is very different from previous GaAs [6] and InP [7] based devices. Previous studies on GaAs and InP based devices found that carrier dynamics are dominated by electron heating through free carrier absorption or interband transitions.

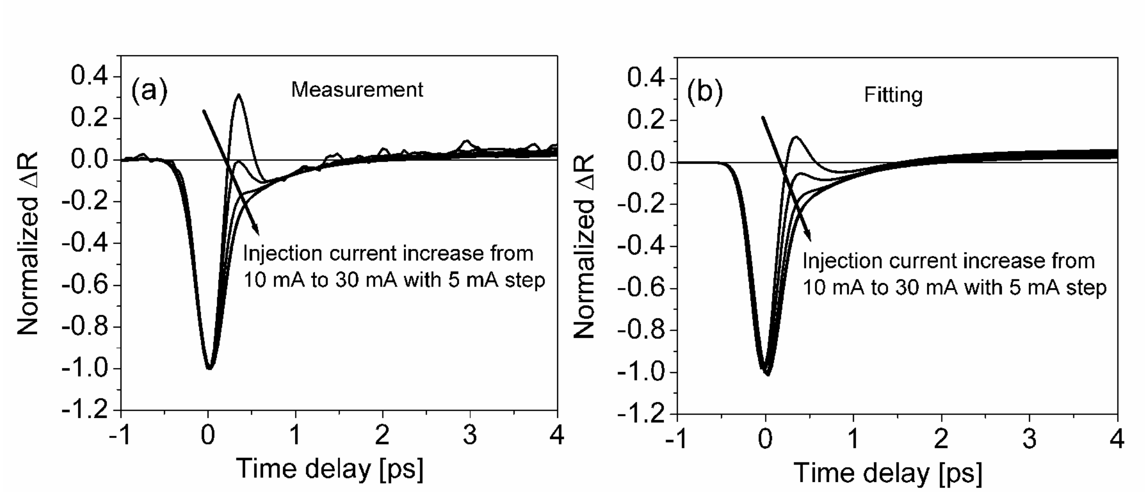

Fig. 2. (a) Time resolved reflectivity change measurements with TM polarized pump and TE polarized probe at a wavelength of 402 nm. The injection current was increased from 10 mA to 30 mA with a step of 5 mA. The trace with 25 mA and 30 mA are almost overlapping with each other. (b) Convolution fitting using four components (delta function, step function, 0.2 ps time constant, and 0.8 ps time constant) convolute with a Gaussian pulse of 0.35 ps pulse width.

4. Summary

In summary, we use time resolved reflection pump-probe measurements to study the carrier dynamics in an InGaN MQW laser diode under high injection level (~10^{19} cm^{-3}). Subpicosecond intersubband hole relaxation and hole heating processes are found to dominate carrier dynamics responses, different from GaAs and InP based laser diodes.

5. Reference

[1] S. Nakamura et al., Appl. Phys. Lett. **62**, 2390-2392 (1993).
[2] S. Nakamura et al., Appl. Phys. Lett. **72**, 211-213 (1998).
[3] C.-K. Sun et al., Appl. Phys. Lett. **70**, 2004-2006 (1997).
[4] S. Pau et al., Phys. Rev. B **56**, R12718–R12721 (1997).
[5] K.-G. Gan et al., Appl. Phys. Lett. **84**, 4675-4677 (2004).
[6] C. T. Hultgren et al., Appl. Phys. Lett., **61**, 2767-2769 (1992).
[7] K. L. Hall et al., Appl, Phys. Lett. **61**, 2512-2514 (1992).