Time delay in InGaN multiple quantum well laser diodes at room temperature*

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(Received 11 March 2010; revised manuscript received 26 April 2010)

This paper reports that a long delay between the beginning of pumping current pulse and the onset of optical pulse is observed in InGaN laser diodes. The delay time decreases as the pumping current increases, and the speed of the delay time reduction becomes slower as the current amplitude increases further. Such delay phenomena are remarkably less serious in laser diodes grown on GaN substrate than those on sapphire. It attributes the delay to the traps which cause a large optical loss by saturable absorption and retard the laser action. The traps can be bleached by capturing injected carriers. The effect of GaAs laser irradiation on InGaN laser action demonstrates that the traps responsible for the delay are deep centres which can be filled by the photo-assisted processes.

Keywords: InGaN, laser diode, delay effect, saturable absorber, traps

PACC: 4255P, 7280E, 7220J, 8240M

1. Introduction

Nitride semiconductors and devices have attracted wide attention since the first GaN-based laser diode (LD) was demonstrated by Nichia *et al.*[1] Violet LDs have been commercially used in highdensity optical data storage systems.[2−4] The blue and underdeveloped pure green LDs are promising light sources for RGB (red, green, blue) full colour laser projection displays.[5] However, there are still many fundamental properties which require further study and evaluation. There is always a relative long time delay between the beginning of pumping current pulse and the onset of optical pulse in our InGaN multiple quantum well (MQW) laser diodes at room temperature. Even though such delay phenomena have been reported and discussed a lot for some other kinds of semiconductor lasers,[6−9] they have not been reported in GaN-based lasers before. This delay is much longer than it takes to achieve the population inversion, which, in fact, controls the delay behaviour in most semiconductor lasers at low temperature. In this paper, firstly we present the experimental data of time delay in lasing InGaN lasers grown on either sapphire or GaN substrate. Next we discuss and explain the delay of laser diodes based on the theoretical model of saturable absorption due to a number of empty traps which cause optical loss and prevent lasing action. Finally, we prove the validity of our model by an optical biasing experiment.

2. Experimental details

The GaN-based laser diode structures were grown in a Thomas Swan $3 \times 2''$ close-coupled showerhead reactor of metal organic chemical vapour deposition (MOCVD) system on both sapphire and free-standing GaN substrates. The TMGa, TMAl, TMIn, CP_2Mg, SiH_4 and ammonia were used as precursors.[10] The GaN-based LD device structures consisted of an n-type GaN:Si contact layer, a 1-μm-thick $Al_{0.16}Ga_{0.84}N$/GaN:Si superlattice (SL) cladding layer, a 0.1-μm-thick n-type GaN:Si waveguiding layer, an $In_{0.15}Ga_{0.85}N/In_{0.02}Ga_{0.98}N$ MQW

*Project supported by the National Natural Science Foundation of China (Grant Nos. 60976045, 60506001, 60836003 and 60776047), the National Basic Research Program of China (Grant No. 2007CB936700), and the National Natural Science Foundation for Distinguished Young Scholars of China (Grant No. 60925017).

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structure composed of five 3-nm-thick undoped $In_{0.15}Ga_{0.85}N$ well layers separated by six 20-nm-thick Si-doped $In_{0.02}Ga_{0.98}N$ barrier layers, a 20-nm-thick p-type $Al_{0.2}Ga_{0.8}N$:Mg electron blocking layer, a 0.1-μm-thick p-type GaN:Mg wave-guiding layer, a 0.6 μm-thick $Al_{0.16}Ga_{0.84}N$/GaN:Mg SL cladding layer, a 0.2-μm-thick p-type GaN:Mg contact layer.

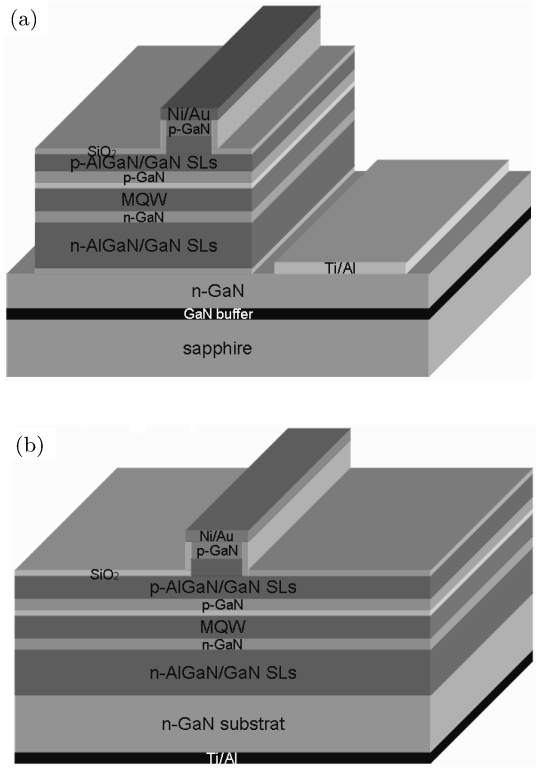


Fig. 1. The schematic diagrams of the GaN-based MQW ridge-waveguide structure LDs: (a) on sapphire substrate (b) on free-standing GaN substrate.

The schematic diagrams of the LD structures grown on sapphire substrate (device A) and on free-standing GaN substrate (device B) are shown in Figs. 1(a) and 1(b). For both LD devices, a 2.5-μm-wide ridge stripe along the $[1\bar{1}00]$ direction of GaN was formed by photolithographic etching until the p-type AlGaN/GaN SL cladding layer was exposed. The SiO_2 was deposited on the surface as insulator. The Ni/Au was used as p-electrode for both devices. In order to form a co-planar LD structure on insulating sapphire substrate as shown in Fig. 1(a), a part of top p-type GaN layer was etched away until the n-type GaN layer was exposed and Ti/Al contact was then evaporated as n-electrode. The fabrication process of LDs on free-standing GaN substrate is rather simple. After Ni/Au was evaporated onto p-type GaN contact layer, the substrate was thinned to be less than 100 μm and Ti/Al was evaporated onto the backside of the substrate as n-electrode. The cavity length of both LDs was 800 μm.

The optical characteristics of LDs were measured under pulsed current condition (pulse frequency was 10 Hz) at room temperature with an Agilent 8114A Pulse Generator. The output power from one facet was detected by a fast photomultiplier tube. In this way, the light intensity versus time for a particular current could be observed on a synchronously triggered oscilloscope connected to the photomultiplier tube. There is about a 30-ns delay between the optical signal and the electric signal attributed to the capacitance and inductance in the test system.

3. Results and discussion

Figure 2 shows the pumping current wave forms and the light output power (LOP) wave forms of the LD on sapphire substrate (device A) at different pumping currents. The current pulse width is a constant of 625 ns, and the current amplitude increases monotonously from I_1 to I_9 as shown in Fig. 2.

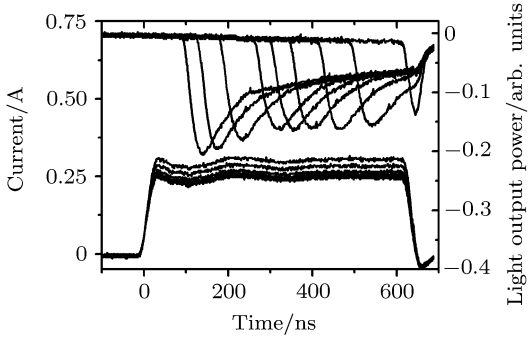


Fig. 2. Pumping current wave forms (lower part) and LOP wave forms (upper part) of the LD on sapphire substrate at different current amplitudes above threshold from I_1 to I_9.

At I_1 of 250 mA the stimulated emission occurs 29.2 ns later than the trailing edge of the current pulse, and the beginning of the optical pulse shifts forwards with increasing pumping current. After the correction of the measuring system the obtained delay time is determined to be almost the full length of the current pulse at the current of I_1 which is just above the threshold, and the delay time decreases as the pumping current increases. In addition, the LOP increases quite fast at the beginning of the optical pulse and then decreases gradually with the time when the injected current increases above 250 mA. We attribute such a decrease to the heating effect.

Figure 3 shows the current wave forms and LOP wave forms of the LD on GaN substrate (device B) at different current amplitudes. The current pulse width is a constant of 600 ns and the current amplitude increases monotonously from I_1 to I_9, where I_1 is a little below the threshold current, and I_2–I_9 are all above threshold. The LOP wave forms of device B are quite different from those of device A. We did not observe the delay in lasing which coincided with the duration of pumping current pulse if the current pulse width was larger than 500 ns. In Fig. 3 the longest delay in lasing is 300 ns at I_2 of 95.3 mA and the delay decreases as the current increases. At lower current amplitudes, the light power changes little during the optical pulse because the heating effect is not important. Only at higher current amplitudes, the light power increases quite fast at the beginning of the optical pulse and then decreases gradually with the time, like that in the case of device A. It is understood that the higher thermal resistance due to the low thermal conductivity of sapphire and the higher operation current make the LDs on sapphire (device A) suffer more from the heating effect.

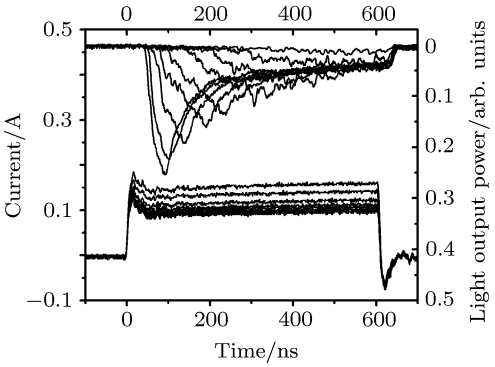


Fig. 3. Pumping current wave forms (lower part) and LOP wave forms (upper part) of the LD on GaN substrate at different current from I_1 to I_9.

Figure 4 shows a plot of the delay time $t_{\rm d}$ versus the ratio $I/I_{\rm th}$ of both devices A and B. The delay time decreases as the pumping current I increases, and the speed of the delay time reduction becomes slower as the current amplitude increases further. We will discuss it in more details in the next text.

There may be more than one physical mechanism responsible for the delay behaviour of the LDs. If the delay between the beginning of the current pulse and the onset of the optical pulse is mainly attributed to the time necessary to inject sufficient carriers to reach the threshold population, the delay $t_{\rm d}$ is given by:[11,12]

$$t_{\rm d} = \tau_{\rm s} \ln \frac{I}{I - I_{\rm th}}, \qquad (1)$$

where I is the pumping current for laser diodes, $I_{\rm th}$ is the minimum value of I for which lasing can be achieved, and $\tau_{\rm s}$ is the spontaneous lifetime. The inset of Fig. 4 shows a plot of the delay time $t_{\rm d}$ versus $\ln[I/(I-I_{\rm th})]$ of device A. The delay time $t_{\rm d}$ decreases monotonously with increasing pumping current, but the proportionality between $t_{\rm d}$ and $\ln[I/(I-I_{\rm th})]$ is not linear. The delay cannot be mainly attributed to the time necessary to inject sufficient carriers to reach the threshold population. Besides, although equation (1) predicts a very long delay for $I \to I_{\rm th}$, in practice the heating and irregularities of the injection pulse will limit $t_{\rm d}$ to less than 10 $\tau_{\rm s}$ even at the threshold.[13] Considering the strong polarization fields in the InGaN MQW the value of $\tau_{\rm s}$ is determined to be less than 20 ns.[14] The delay time observed in this article is actually substantially longer than that it takes to achieve the population inversion.

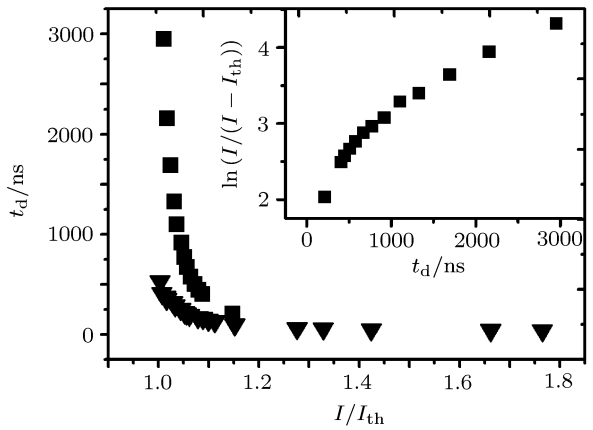


Fig. 4. The delay time of lasing $t_{\rm d}$ vs. $I/I_{\rm th}$ of both devices A (solid squares) and B (solid triangles). The inset shows the delay time $t_{\rm d}$ vs. $\ln[I/(I-I_{\rm th})]$ of device A.

Similar delay effect between the application of an excitation pulse and the onset of stimulated emission has been reported for many semiconductor lasers.[6–9] This effect was first observed in homostructure GaAs junction lasers by Crowe and Niebuhr.[6] It was established that for homostructure lasers the delays appeared only above a transition temperature $T_{\rm t}$, which was characteristic of the way of fabricating a particular laser. Closely related to this is another effect, termed as internal Q-switching. Under certain conditions the delay is actually the full length of the pulse and stimulated emission only occurs after the end of the pulse. We did not observe such a phenomenon probably because of the limited response speed of our test system. Pankove studied homostructure LDs made from $GaAs_{1-x}P_x$ and reported long delays at the temperature as low as 2 K, implying the possible absence of any transition temperature in these

diodes.[7] The long delay effect and the transition temperature were also observed in single-heterostructure lasers of $Ga_{1-x}Al_xAs$[8] and $GaAs_{1-x}P_x$.[9] The transition temperature was found to be dependent on the width of the active region and fabrication procedures.

Several theories have been presented in an attempt to explain the long delay phenomena which involve the massive trapping model[15] or the saturable absorber trap model.[16] Konnerth assumed that a large number of traps captured most of the injected electrons. Only after these traps were filled would it then be possible for electrons to fill states in the conduction band, leading to the optical gain. This model is unreasonable because the number of trapping centres required in this model is tremendous (10^{19} traps/cm^3). Besides, in our experiment the pumping current of device A at which the delay is 2 μs is 272 mA while the pumping current at which the delay is only 0.5 μs is 269 mA. The number of traps responsible for the long delay of the same sample is estimated quite different by this model in the two cases and it cannot be well explained.

Fenner proposed a saturable absorber model that optical absorption due to a number of traps prevents the build-up of the stimulated emission.[16] These traps which are located in the vicinity of the active region, are rendered transparent by capturing electrons from the injection current rather than by the absorption of photons. After a sufficient number of traps are bleached, the absorption loss is reduced and lasing action can start. Experimental evidences absorbing traps could be bleached either optically or electrically which were later observed in $GaAs_{1-x}P_x$ homostructure laser diodes.[17]

Figure 5 shows the calculated result of normalized absorption coefficient due to the traps α/α_0 versus injection current pulse length t in units of the trap emptying time τ_e for several values of $A \times J$ according to Eq. (8) in Ref. [16], where α and α_0 are the absorption coefficients at time t and time 0 respectively, J is the injection current density, A is a parameter related to the capture of carriers by traps. The $A = B\tau_e(D\tau)^{1/2}/\mu kT$, where B is the capture possibility, D is the diffusion constant, and τ is the minority carrier lifetime. For $t/\tau_e \to \infty$, $\alpha(\infty) = \alpha_0/(AJ+1)$. For pulse lengths being an appreciable fraction of τ_e, the relative reduction of the optical absorption becomes noticeably less as $A \times J$ increases.

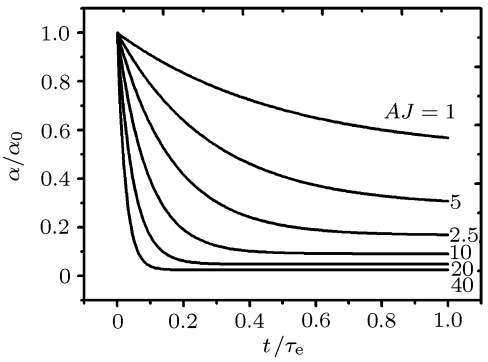


Fig. 5. Relative optical absorption coefficient vs. current pulse length in units of trap emptying time τ_e.

We can explain the time delay effect in our InGaN MQW laser diodes very well, based on the saturable absorber trap model. There are a number of traps which act as saturable absorbers and prevent lasing action in the InGaN MQW laser diodes. For device A operating at 250.7 mA, it needs 5028 ns to bleach a sufficient number of traps so that the absorption coefficient of traps is reduced to a certain level at which the gain can overcome the total loss (including the absorption coefficient due to the traps) and then lasing action can start. The gain increases and the absorption coefficient due to the traps decreases as the pumping current increases. So the gain can surpass the total loss and make the lasing action start earlier at a higher pumping current. That is why the delay time decreases with increasing the pumping current as shown in Fig. 4. On the other hand, the relative reduction of the optical absorption becomes noticeably less as the pumping current increases. So the speed of the delay time reduction becomes slower as the current amplitude increases further, as shown in Fig. 4.

In addition, the reduction of the delay time of device B in the current range just slightly above the threshold is much faster than that of device A. In fact, in Fig. 4 the current resolution of the pulse generator is high enough for displaying the delay of device A which is longer than 5 μs, but not high enough for displaying the delay of around 600 ns of device B. The possible reason is that the trap density is higher for the LDs grown on sapphire substrate in comparison with that grown on GaN substrate. In other words, the absorption coefficient of the LDs grown on sapphire is higher than that on GaN substrate. As we know, a very high density of dislocations (typically 10^8–10^{10}/cm^2) is presented in GaN-based laser structures grown on sapphire substrate due to the large lattice mismatch and thermal mismatch between

GaN and sapphire substrate. The dislocation density can be greatly reduced, for example, to the order of $10^6/cm^2$ by using homoepitaxial GaN substrate. It is therefore supposed that the trap density is higher for LDs grown on sapphire substrate (device A) than that on GaN substrate (device B), and the traps responsible for the delay are related to the dislocations. Then it can explain well why the reduction of the delay time of device B is much faster than that of device A. This result also corresponds to the fact that the other laser properties like threshold value and working lifetime measured from device B are much better in comparison with those from device A.

In order to check whether the delay in lasing can be reduced by filling the traps optically, we irradiated device A with the light beam from a GaAs laser at a wavelength of 810 nm, which is much longer than the emitting wavelength of device A. The GaAs laser is placed 15 cm away from the device A and the light is focused on its side. A fast photomultiplier tube insensitive to long wavelength red light is used to detect the output light from device A. The results are shown in Fig. 6. The dashed and solid lines indicate the wave forms with and without the irradiation, respectively. A delay of 265 ns is obtained in the InGaN LD without the irradiation of the GaAs laser. When a pumping current of 0.75 A is employed for the GaAs laser, the delay time is reduced to 245 ns. A similar experiment was done with the radiation of AlInGaP laser at a wavelength of 670 nm on InGaN LD. The lasing delay time reduces from 280 ns to 244 ns as the effect of optical irradiation. The photon energies used to bleach the traps are 1.53 eV and 1.85 eV in both cases, which are much smaller than the band gap of $In_{0.15}Ga_{0.85}N$. It demonstrates that the traps responsible for the delay are deep centres and can be filled by photo-assisted capture of carriers. Unfortunately these traps are difficult to identify and investigate in details at moment because the trap-produced absorption of the device is small and much less than the normal band-to-band absorption.

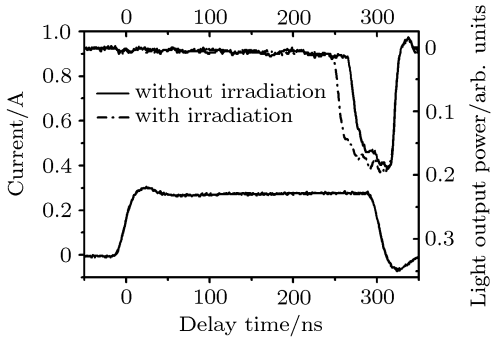


Fig. 6. Pumping current wave forms and LOP wave forms of device A with (dashed line) and without (solid line) the optical irradiation of GaAs laser, respectively.

4. Conclusion

Investigations on the effect of long lasing delay in InGaN MQW lasers have shown that the delay time decreases as the pumping current increases. In addition, the speed of the delay time reduction becomes slower as the current amplitude increases further. The saturable absorber trap model can account for the experimental features and the optical biasing experiment proves that the lasing delay can be reduced by filling the traps optically, showing that the delay-inducing traps are deep centres. The relationship between the delay and pumping current shows that the trap density of the LDs grown on sapphire substrate is remarkably different from that grown on GaN substrate.

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