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Stimulated emission in GaN-based laser diodes far below the threshold region

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Abstract: We identify that the stimulated emission of GaN laser diodes (LDs) emerges far below the traditionally recognized threshold from both optical and electrical experiments. Below the threshold, the linear-polarized stimulated emission has been the dominating part of overall emission and closely related to resonant cavity. Its intensity increases super linearly with current while that of spontaneous emission increases almost linearly. Moreover, the separation of quasi-Fermi levels of electrons and holes across the active region has already exceeded the photon emission energy, namely, realized the population-inversion.

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1. Introduction

GaN-based laser diodes (LDs) are one of the main applications in III-Nitrides materials. For decades, the researchers were striving their efforts on reducing the threshold current [1–5], improving the output power [6–9], and expanding the wavelength range [10–14] among other things. They focus their attentions mainly on the behavior of LDs above the threshold region. Nowadays, the life time of commercially available GaN LDs has extended over 10000 hours.

The researches on GaAs- and InP-based LDs manifest that the output light of a LD consists mainly of spontaneous emission below the threshold condition [15]. A further increase of injection current reaching threshold leads to the light emission of photons through the stimulated emission process. Above threshold region, the stimulated emission becomes dramatically significant and the light output power increases with current linearly. In 1976, Paoli and Barnes presented an electrical derivative technique to determine the threshold and

demonstrated the saturation of junction voltage at the onset of lasing in stripe-geometry (AlGa)As double-heterostructure junction lasers [16, 17]. Recently, Wang's group developed a method based on alternating current (ac) admittance measurement combined with direct current (dc) *I-V* plotting (ac *IV* method) to reveal the electrical behavior of a LD in greater detail. After systematically studied the GaAs- and InP-based LDs (typical lasing wavelengths at 650, 780, 870 and 1320 nm), they pointed out the synchronous step offsets of electrical parameters occurred at the onset of lasing. In particular, the separation of the quasi-Fermi levels of electron and holes across active region (V_j) suddenly jumps to a saturated value at the onset of lasing [18–20]. Lately, we reported the stimulated emission related anomalous behavior in GaN-based LD. Specifically, V_j showed a drop (or "pinning") in threshold region, followed by an increase with current. All the changes of electrical parameters in LDs always satisfies the need of sufficient carriers for stimulated emission in the process of transition to lasing as well as lasing enhancement [21].

However, it is also essential to investigate the behavior of GaN-based LD below the threshold region for understanding the physical mechanisms during the generation of lasing. Some of the fundamental physical problems in LDs still deserve close attentions. The emergence of stimulated emission and the amplification of stimulated emission into lasing are undoubtedly challenging topics among them. The information hidden in the compositions, polarizations, and intensities of spectra which varies with current could provide effective clues to these topics. Unfortunately, these are rarely reported in literatures perhaps due to the lack of precise measurements under low injection with extremely weak emissions.

In this letter, we present the optical spectra below threshold of a commercial GaN-LD under the different polarization angles. Then the spectra are compared with that from extremely low Q-factor resonant cavity to clarify the origins of emissions. V_j is also explored for electrical confirmation. We observe that the domination of the spectra below the threshold is linear-polarized and closely related to resonant cavity. Taking the essential evidences from electrical aspect, V_j had already realized the population-inversion at very low injection. Therefore, we conclude from experiments that stimulated emission can emerge even far below the traditional threshold in GaN-based LDs.

2. Experiments

The schematic of the optical measurement system was in Fig. 1. The LDs were driven under DC source Keithley 2601A. And the edge emission light along the cavity from LDs became parallel through quartz convex lens. Then the parallel light propagated through the Glan prism as a polarizer, and was finally collected by Thorlabs optical power meter PM100D with an S130C sensor head as the detector and Ocean Optics S2000 as the spectrometer at the end. As shown in the upper-left, the angle between the transverse electrical (TE) mode direction and the polarization direction of the Glan prism was denoted as θ. So that the TE mode direction was defined as $\theta = 0°$ with power maximum P_{max} while the output power in $\theta = 90°$ was denoted as P_{min}. Its ac admittance profile was measured by an Agilent 4294A precision impendence analyzer.
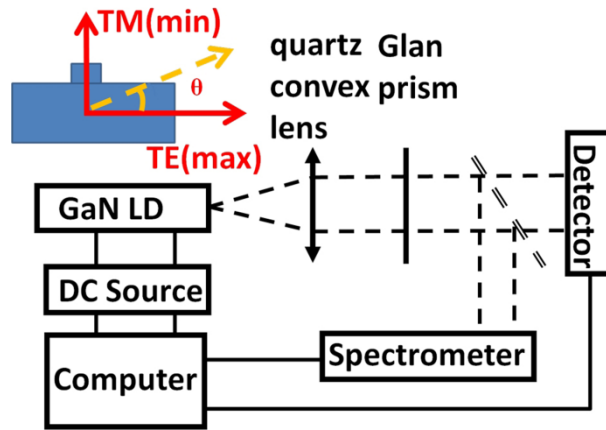
Fig. 1. The schematic of the optical measurement setup.

3. Results and discussions

The sample under discussions was a GaN-based LD Sony SLD3132VF diode lasing at 404 nm manufactured by Sony Corp. Its electrical characterizations are accomplished using ac *IV* method, which were described in detail elsewhere [18–20]. As shown in Fig. 2, V_j (solid line) of the sample temporarily dropped between 27.1 mA (the lower threshold I_{th}^l) and 29.8 mA (the upper threshold I_{th}^u). Then it kept increasing with current beyond. And series resistance r_s (dashed line) changes accordingly. Corresponding first (solid line) and second derivatives (dashed line) of the optical output power were also plotted. The two kink points of the first derivatives corresponded to the lower threshold I_{th}^l and the upper threshold I_{th}^u, respectively. Similar behavior was also found in a number of commercially-available LDs, including Nichia NDV4312 and Sanyo DL-4146-301S. Above results were similar to the ones reported in [21].
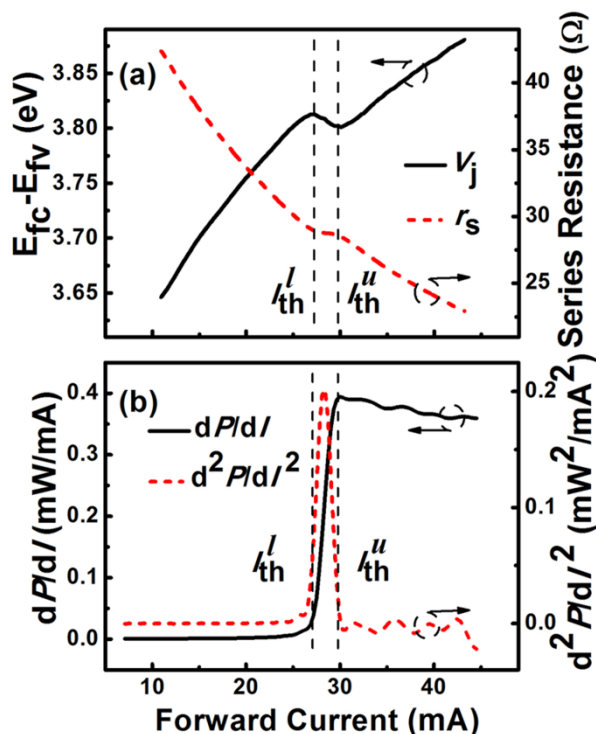
Fig. 2. (a) Dependence of the separation of the quasi-Fermi levels of electron and holes across active region V_j (solid line) and series resistance r_s (dashed line) of the sample on the injected current. (b) Corresponding first (solid line) and second derivative (dashed line) of the optical output power. The two kink points of the first derivatives correspond to I_{th}^l and I_{th}^u, respectively.

We record the spectra at different polarization angles under different injection levels to clarify their origins. From spectral analysis to these recorded results, we discover that below the threshold the spectra are comprised of two parts with different polarization properties. We denote the spectra recorded when the Glan prism was set θ at 0° and 90° as Peak A (PA) and Peak B (PB), respectively. As shown in Fig. 3, PA, around 404 nm, is the main part of the overall spectra even at the injection low to 3 mA. The intensity of PA could be attenuated by rotating the angle of the Glan prism until vanished at $\theta = 90°$. So PA exhibits highly polarized properties with polarization direction identical to the lasing TE mode. However, PB is considerable weak and only became visible when the Glan prism is far away from $\theta = 0°$. So it is hard to identify PB's polarization in this configuration.

For detailed quantitative analyses, we carefully record the spectra and the light output power under different injection with respect to θ. In most cases of our measurements, the intensity of PA is much stronger than that of PB, so we provide here only the spectra recorded at 78°, where the intensities of PA and PB are comparable at this polarization configuration. It is found that the spectrum recorded at 78° is remarkably identical to the combination of spectra of the one at 90° and the one at 0° attenuated by 4.3% ($\cos^2 78°$) ([Fig. 3(a)] at 3 mA). This spectra analyses further manifest that PA with highly polarization is the principle part in the emission from a GaN LD. Similar behavior is also found at other injection below the threshold region, for example, [Fig. 3(b)] at 10 mA. When current increases, the intensity of PA increases much faster than that of PB. PA's peak intensity is 7.4 times of PB at 3mA and climbs up to 11.4 times of PB at 10 mA.
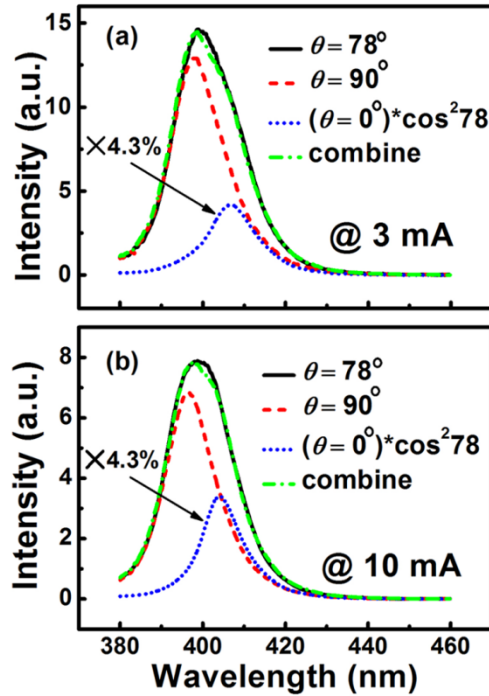
Fig. 3. The spectra collected along cavity exhibited two types of polarity. The combination (dot dash) of spectra at $\theta = 90°$ (dash) and at $\theta = 0°$ (with attenuation of $\cos^2 78°$ about 4.3%, dot) is identical to the one recorded at $\theta = 78°$ (solid). The one with lower energy is dominate emission when injection below the threshold. (a) at 3mA and (b) at 10 mA.

Since PA is the main part of the emission, the polarization of PA can be further revealed by the output power as a function of θ. The polarized output power P_θ are recorded and presented here five typical angles at $\theta = 0°$, 30°, 45°, 60°, and 90° [Fig. 4(a)]. The slope values of $P_\theta - I$ for $\theta = 0°$, 30°, 45°, and 60° in semilogarithmic coordinates are larger than the linear increase one for $\theta = 90°$. Hence the output powers increase super-linearly with current under all angles except the one at 90°, indicating the property of stimulated emission. From above spectra analysis, the output powers recorded at 90° are totally from PB with notation P_{min}. Assuming PB is isotropic (Though this assumption might be not that accurate, it does not hinder to reveal the polarization characteristics of PA considering the small fractions of PB in output.), the power ratio $R_{s\theta} = (P_\theta - P_{min})/(P_{max} - P_{min})$ are proposed to identify the polarization of PA. $R_{s\theta}$ follows with relation $R_{s\theta} = \cos^2 \theta$ when Glan prism set at the angle $\theta = 30°$, 45° and 60° [Fig. 4(b)]. It evidentially proves that the principle emission PA below the threshold is linear-polarized. This linear-polarized property of PA emerges far below the threshold region and maintains till the lasing with the same direction as that of lasing light.
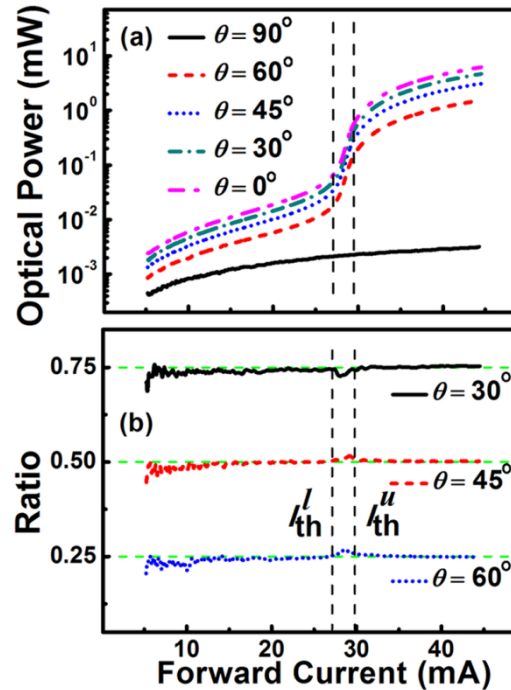
Fig. 4. (a) Dependance of the optical power as a function of the current. The slope values of for $\theta = 0°$, 30°, 45°, and 60° are larger than the linear increase one for $\theta = 90°$, exhibiting the property of super-linear increase. (b) The dominate emission is linear-polarized as the power ratios $R_{s\theta} = (P_\theta - P_{min})/(P_{max} - P_{min})$ are almost coincident with relation $R_{s\theta} = \cos^2 \theta$ when Glan lens set at the angle of $\theta = 30°$, 45° and 60° to transverse electrical mode.

To clarify the origin of PA and PB, one facet mirror of resonant cavity is deliberately damaged by Focused Ion Beam so the reflectivity of the mirror is largely reduced. In practice, the reflectivity is hard to realize a complete zero value, leading to the residue of PA. Under this situation, PA is significantly weakened in spectra shown as Fig. 5 inset. And its peak intensity ratio to PB enormously dropped from 11.4 to 0.6 before and after damage at 10 mA, which is comparable to that of PB. As a result, the light output no longer increases super-linearly with current (Fig. 5). This comparison proves that PA is resonant cavity related while PB is the spontaneous part in GaN-based LD, which does not change much in both situations. PA experiences positive oscillating feedback in resonant cavity, which makes it distinct from superluminescence [22, 23], namely, amplified spontaneous emission. More detailed analyses indicate that PB should be partially polarized due to the anisotropy of GaN material structure, which would be described elsewhere.
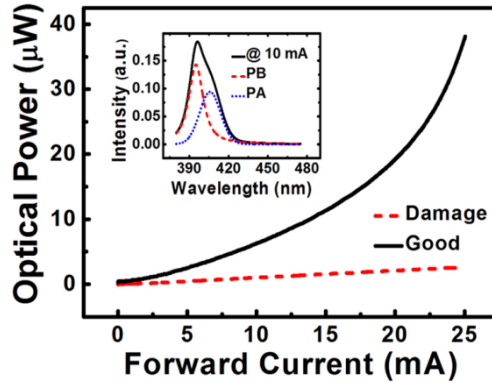
Fig. 5. The linear-polarized stimulated emission is strongly weakened after cavity damage and comparable to spontaneous emission (inset), causing the output power no longer super-linearly increased with current.

Combining the polarization property and the strong dependency of resonant cavity of PA from above discussions, we could conclude that the PA has been linear-polarized and dominant in GaN LD emission below the threshold. Coincidently, it is pointed out that the spontaneous emission from m-plane light emitting diodes (LEDs) could also present high polarization ratio. However, the behavior of PA is different from that of the m-plane spontaneous emission as the followings. First, the output power vs current relations (*L-I*) are different. The intensity of PA increases super-linearly with current while the spontaneous emission in m-plane increases linearly with current [24–26]. Second, the origins were different. The existent of PA is resonant cavity related while that of m-plane spontaneous emission originates from the valence band level splitting due to unbalanced biaxial stress during epitaxy [27–29], which is independent of cavity. Third, the dependences of polarization ratio on current are different. The polarization ratio of PA is almost unity with current while that of m-plane spontaneous emission slight decreases as reported by Krame [30] and DenBaars [31]. Therefore, the PA is distinct from the spontaneous emission observed in m-plane in phenomenology. Moreover, our experiments manifest that when the current injection is beyond 0.3 mA, V_j has been larger than the emission energy (Fig. 6). It is verified from experiment that the population-inversion $E_{fc} - E_{fv} > h\nu$ is realized far below the threshold, where E_{fc}, E_{fv} stands for the quasi-Fermi level for electrons and holes respectively, h denotes the Plank's constant, and ν is the photon frequency. Hence, the occurrence of stimulated emission below the threshold is reasonable and understandable. From all above evidences, it is more convincing to point out that the principle part of emission in GaN LD below the threshold region, PA, is stimulated emission.
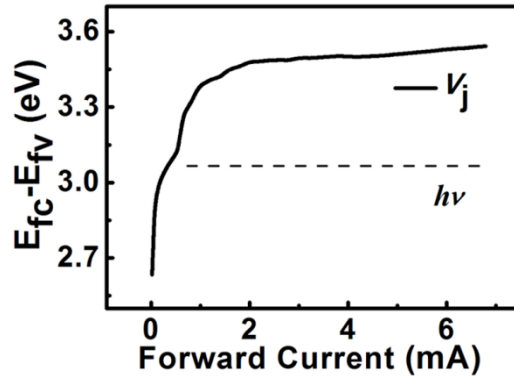
Fig. 6. The separation of quasi-Fermi levels of electrons and holes across the active region has already realized the population-inversion, namely, $E_{fc} - E_{fv} > hv$. Stimulated emissions may occur far below the threshold in GaN-based LDs.

4. Conclusion

In conclusion, we reveal that stimulated emission emerges and has been the dominating part in GaN LDs emission far below the traditionally recognized threshold. The existence of stimulated emission is proved from both optical and electrical properties. According to the optical analyses, the stimulated emissions are linear-polarized, which are identified from the spectra analyses and the *L-I* relations under different polarized angles. Furthermore, the stimulated emission is closely related to resonant cavity and increases super-linearly with current. From electrical aspect, V_j has already reached the population-inversion, namely, $E_{fc} - E_{fv} > hv$. This behavior might pave way for the understanding of the transition to lasing in GaN-based LD as well as provide essential evidences for advancing the theory of semiconductor lasers.

Acknowledgments