Thermal characterization of GaN-based laser diodes by forward-voltage method

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An expression of the relation between junction temperature and forward voltage common for both GaN-based laser diodes (LDs) and light emitting diodes is derived. By the expression, the junction temperature of GaN-based LDs emitting at 405 nm was measured at different injection current and compared with the result of micro-Raman spectroscopy, showing that the expression is reasonable. In addition, the activation energy of Mg in AlGaN/GaN superlattice layers is obtained based on the temperature dependence of forward voltage. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4716003]

I. INTRODUCTION

GaN-based laser diodes (LDs) are of significance for the applications in such as optical data storage, communication systems, and micro projectors. For practical applications of LDs, the device reliability is indispensable. The junction temperature is a critical parameter and affects internal efficiency, maximum output power, and reliability.[1–3] Several groups have reported measurements of the junction temperature of LDs using such as forward-voltage method,[1] micro-Raman spectroscopy,[4,5] and thermal resistance.[6] The forward-voltage method is non-contacting and can be employed to fully packaged devices, which makes it commonly usable for measuring the junction temperature of semiconductor diode devices.

In this letter, a common expression of the relation between junction temperature and forward voltage for both GaN-based LDs and light emitting diodes (LEDs) is derived. The forward-voltage method is employed to measure the junction temperature of GaN-based LDs emitting at 405 nm and compared with the result obtained by micro-Raman spectroscopy.

II. PRINCIPLE

In order to derive the relation between the forward voltage and the junction temperature of both LD and LED devices which may have very different series resistance in the device structures, we will take the influence of series resistance on junction temperature into consideration.

The Shockley equation of a diode structure with series resistance R_s can be written as

$$I = I_s\left\{\exp\left[\frac{q(V-IR_s)}{nk_BT}\right]-1\right\}, \tag{1}$$

where I_s is the saturation current and n is the ideality factor, R_s is the series resistance. For GaN-based p-n junction devices, the ideality factor is taken to be 1. The saturation current I_s can be expressed as

$$I_s = Ae\left(\frac{D_n n_{p0}}{L_n}+\frac{D_p p_{n0}}{L_p}\right), \tag{2}$$

where D_n and D_p are diffusion constants of electrons and holes, respectively, and L_n and L_p are diffusion lengths of electrons and holes, respectively, A is the area of injection current. In the range of the real junction temperature, these parameters are assumed to have no temperature dependence.

The intrinsic carrier concentration, n_i, which is strongly temperature-dependent, is given by

$$n_i^2 = N_C N_v \exp\left(\frac{-E_g}{k_BT}\right), \tag{3}$$

where N_C and N_v are effective densities of states at the conduction-band and valence-band edges, respectively. The effective densities of states are given by

$$N_C = 2\left(\frac{2\pi m_{de}k_BT}{h^2}\right)^{3/2}M_c, \tag{4}$$

$$N_v = 2\left(\frac{2\pi m_{dh}k_BT}{h^2}\right)^{3/2}, \tag{5}$$

where m_{de} and m_{dh} are the density-of-state effective mass for electrons and holes, respectively. M_c is the number of equivalent minima in the conduction band.

By substituting Eqs. (2)–(5) into Eq. (1), the fundamental temperature dependence of the forward voltage can be given as

$$V = IR_s + \left\{\frac{k_BT}{q}[\ln(I)-\ln(B)-2.25\ln(T)]+\frac{2E_g-E_A}{2q}\right\}, \tag{6}$$

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where B is a constant. For GaN-based p-n junction devices, we assume

$$\frac{2E_g - E_A}{2q} \approx V_{bi} \approx V_0, \tag{7}$$

where V_{bi}, V_0 are the built-in voltage and the turn-on voltage, respectively. Substitute Eq. (7) into Eq. (6), and we can get

$$V = IR_s + \left\{ \frac{k_B T}{q}[\ln(I) - \ln(B) - 2.25\ln(T)] + \mathrm{V}_0 \right\}. \tag{8}$$

Equation (8) is a common expression for GaN-based p-n junction devices, the first term in right hand stands for the partial voltage on the series resistance and the second term stands for the junction voltage. It implies that the forward voltage is a function of junction current I and temperature T.

For GaN-based blue/violet LDs, it is reasonable to assume that the main source of series resistance comes from p-regions, mainly p-AlGaN/GaN superlattice cladding layers in the LD structure, due to low hole mobility and hole concentration.[1] The series resistance of p regions can be expressed as

$$R_s = \frac{C}{\sigma} = \frac{C}{e\mu p} = DT^{-3/4}\exp\left(\frac{E_A}{2k_B T}\right), \tag{9}$$

where σ, μ, p, E_A denote conductivity, hole mobility, hole concentration, and the activation energy of acceptors, respectively. C and D are the scale factors.

By substituting Eq. (9) into Eq. (8), the temperature dependence of the forward voltage for GaN-based blue/violet LDs can be expressed as

$$V = IDT^{-3/4}\exp\left(\frac{E_A}{2k_B T}\right) + \left\{ \frac{k_B T}{q}[\ln(I) - \ln(B) - 2.25\ln(T)] + \mathrm{V}_0 \right\}, \tag{10}$$

LDs usually operate under large current injection and the junction voltage changes little after reaching the turn-on voltage, but the series resistance of p-regions, especially p-AlGaN/GaN superlattice cladding layers, has large temperature dependence, therefore, the second term in right hand of Eq. (10) can be approximately taken as a constant, V_0. Then we can take an approximation and have the following temperature dependence:

$$V - V_0 \propto \exp\left(\frac{E_A}{2k_B T}\right), \tag{11}$$

which is similar to what Ryu *et al*. derived for LDs.[1] Using this method, we can also estimate the activation energy of the acceptor in AlGaN/GaN superlattice layers.

For GaN-based LEDs, they operate under small current injection. The junction voltage changes with current I and temperature T. However, the temperature dependence of series resistance is very small because no p-AlGaN/GaN superlattice cladding layers exist in the diode structure. In Eq. (8), the first term can be neglected in comparison with the second term. If we take $[\ln(I) - \ln(B) - 2.25\ln(T)]$ which is a slow-varying function of the temperature as a constant, we can approximately get a linear temperature dependence of $(V - V_0)$

$$V - V_0 \propto T. \tag{12}$$

It is noted that this approximation form of $(V - V_0)$ is similar to what was reported by Xi and Schubert.[7] In the above-mentioned formulae, the junction temperature of GaN-based LDs and LEDs can be measured based on the temperature dependence of the forward voltage at fixed junction current.

With micro-Raman spectroscopy, normally the E_2-high mode is recorded and used to study the thermal properties of GaN-based LDs. With increasing the injection current, a red shift of E_2-high peak would be observed, being caused by lattice thermal expansion. The junction temperature according to Raman shift of E_2-high mode can be calculated using the following equation as reported in Ref. 8:

$$\omega(T) = \omega_0 - \frac{A}{\exp(B\hbar\omega_0/k_B T) - 1}, \tag{13}$$

where ω_0 is the phonon frequency of E_2-high mode at 0 K, A and B are the fitting parameters. For GaN-based LDs grown on free-standing GaN substrate, $A = 19.9 \pm 1.1\ \mathrm{cm}^{-1}$, $B = 1.13 \pm 0.03$,[8] respectively. It is noted that ω_0 is sensitive to stress, then different samples may have different values. For our diode samples, the value of ω_0 is calculated by the measured value of $\omega(T = 300\mathrm{K})$ under no injection current.

III. RESULTS AND DISCUSSION

The measurements about the junction temperature of GaN-based LEDs by using forward-voltage method have been well reported, which demonstrate the validity of the Eq. (12).[7,9] In this paper, we mainly measure the junction temperature of GaN-based LDs.

The measured LD samples were grown by the metal organic chemical vapor deposition on free-standing GaN substrate as were described elsewhere.[10] The LD chips were contained in TO 56 package and placed on small Cu heat sink. Fig. 1 shows the light power-current-voltage (L-I-V) characteristics of a fabricated GaN-based LD under continuous-wave (CW) operation condition.

First, the LD sample was put into an oven. When the LD sample was operated under a junction current of pulsed mode, with 1 μs pulse width and 0.1% duty cycle, it could be assumed that the increase of junction temperature due to heating effect by the pulsed current was very small and could be neglected. The junction temperature of the LD sample was the same as heat-sink temperature. In Fig. 2, the change of forward voltage with heat-sink temperature and injection current is plotted. From the curves shown in Fig. 2, it can be derived that the forward voltage decreases considerably as junction temperature of the LD sample increases at a constant injection current; however, the relation between forward voltage and injection current is not linear as reported in GaAs-based laser diodes.[11]

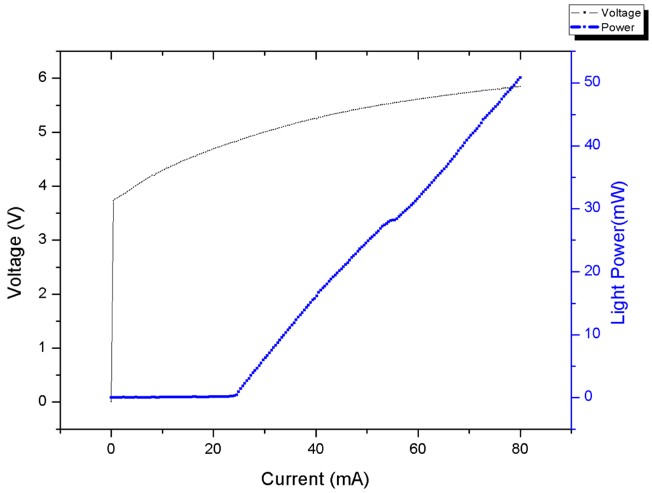

FIG. 1. L-I-V curve of a GaN-based LD in TO 56 package measured at 25 °C.

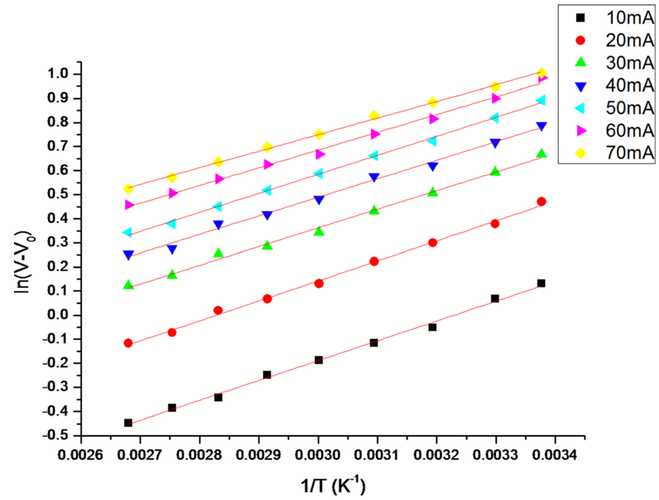

FIG. 3. Plot of $\ln(V - V_0)$ as a function of inverse absolute temperature. Solid dots and lines represent experimental data and linear fitting of the experimental data, respectively.

Then, the same GaN-based LD sample is operated under different CW injection current at an ambient temperature (T = 22 °C) and taken Raman measurement. The Raman spectra of GaN E_2-high phonon mode from the GaN-based LD were measured using Raman spectrometer (JY Horiba 800) in a backscattering geometry by using excitation laser line of 633 nm. And the forward operating voltage of the sample was also recorded simultaneously.

The result of Fig. 2 qualitatively shows that when the pulsed injection current keeps constant, the obtained forward voltage decreases with increasing oven temperature, i.e., junction temperature. It is found that the curves in Fig. 2 are not very well linear. However, if we assume that the turn-on voltage is 3 V,[1] and fit the curves using Eq. (11), then the linear dependence of $\ln(V - V_0)$ on 1/T becomes a good fit for the data points as shown in Fig. 3. These calibration curves clearly show the dependences of forward voltage on both current I and temperature T. When the heat sink is kept at ambient temperature (T = 22 °C), the junction temperature at different CW injection current can be calculated according to the recorded forward voltage based on the calibration curves.

The result is shown in Fig. 4 where the result of Raman spectroscopy is also plotted (solid circles) as a comparison.

For micro-Raman spectroscopy measurement, we have evaluated each peak frequency by fitting with a Lorentzian curve. According to the measurement value of ω(300K) under 0 mA, ω_0 of our sample is obtained to be 569.02 cm^{-1}. Based on Eq. (13), the junction temperature at different injection currents is calculated. As shown in the inset of Fig. 4, the junction temperature rises with increasing injection current. Actually, in the junction temperature range, the E_2-high mode shows almost a linearly frequency shift with temperature as shown in the inset of Fig. 4. The slope is about -0.0115 cm^{-1} K^{-1}, which is almost equal to -0.012 cm^{-1} K^{-1} as reported by Takahashi *et al.*[4]

As shown in Fig. 4, the junction temperature calculated by two methods, i.e., Raman spectroscopy method and forward-voltage method, are in good agreement considering the error bars of the forward-voltage measurement (±3 °C)[9]

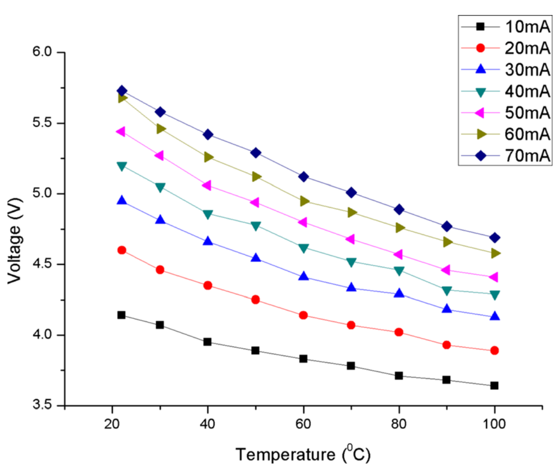

FIG. 2. The forward voltage vs oven temperature for different pulsed injection current (solid dots). Measurement is performed under pulsed operation condition with 1μs pulse width and 0.1% duty cycle.

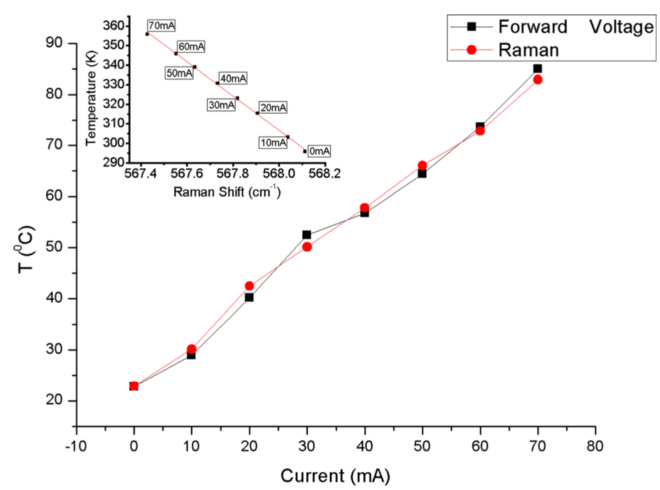

FIG. 4. The junction temperature vs CW injection current measured by the forward-voltage method (solid squares) and by micro-Raman spectroscopy (solid circles). The inset image shows the junction temperature vs Raman shift for various CW injection current (solid dots) and a linear fit of the data (solid lines).

and Raman spectroscopy (± 5 °C),[12] which implies a good validity and accuracy of the model employed in the derivation of the temperature dependence of the forward voltage.

It is noted that from Eq. (11) and the fitting to the experimental data, the activation energy E_A of the acceptor Mg used as the doping impurity in the *p*-AlGaN/GaN superlattice cladding layers can be calculated. It is obtained to be 132.6 meV. The activation energy of Mg in GaN is reported as 170 meV. The obtained E_A value of Mg in AlGaN/GaN superlattice is even smaller than in bulk GaN. However, the polarization field in the AlGaN/GaN superlattice layers could effectively change the energy band condition, which helps to lower the effective activation energy of Mg.[13–15] Therefore, a reduced value of E_A obtained by the measurements is reasonable.

IV. CONCLUSIONS

In conclusion, we have derived an expression of the relation between temperature and forward voltage for GaN-based *p-n* junction devices which is suitable to both LDs and LEDs. The junction temperature for GaN-based LDs emitting at 405 nm is measured using both forward-voltage method and micro-Raman spectroscopy. The results are in a good agreement. In addition, the activation energy of Mg in AlGaN/GaN superlattice layers is derived to be 132.6 meV based on the forward-voltage method.

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[1]H.-Y. Ryu, K.-H. Ha, J.-H. Chae, O.-H. Nam, and Y.-J. Park, "Measurement of junction temperature in GaN-based laser diodes using voltage-temperature characteristics," Appl. Phys. Lett. **87**, 093506 (2005).

[2]W. J. Hwang, T. H. Lee, O. H. Nam, H. K. Kim, J. S. Kwak, Y. J. Park, and M. W. Shin, "Thermal analysis of GaN-based laser diode package," Phys. Status Solidi C **3**(6), 2174–2177 (2006).

[3]P. Perlin, T. Swietlik, L. Marona, R. Czernecki, T. Suski, M. Leszczynski, I. Grzegory, S. Krukowski, G. Nowak, G. Kamler, A. Czerwinski, M. Plusa, M. Bednarek, J. Rybinski, and S. Porowski, "Fabrication and properties of GaN-based lasers," J. Cryst. Growth **310**, 3979–3982 (2008).

[4]K. Takahashi, D. Matsuoka, H. Harima, K. Kisoda, Y. Tsuda, T. Yuasa, and M. Taneya, "Temperature measurement of GaN-based blue-violet laser diodes in operation by Raman microprobe," Phys. Status Solidi C **4**(7), 2802–2805 (2007).

[5]S. Todoroki, M. Sawai, and K. Aiki, "Temperature distribution along the striped active region in high-power GaAlAs visible lasers," J. Appl. Phys. **58**, 1124 (1985).

[6]S. Murata and H. Nakada, "Adding a heat bypass improves the thermal characteristics of a 50 μm spaced 8-beam laser diode array," J. Appl. Phys. **72**, 2514 (1992).

[7]Y. Xi and E. F. Schubert, "Junction-temperature measurement in GaN ultraviolet light-emitting diodes using diode forward voltage method," Appl. Phys. Lett. **85**, 2163 (2004).

[8]M. S. Liu, L. A. Bursill, S. Prawer, K. W. Nugent, Y. Z. Tong, and G. Y. Zhang, "Temperature dependence of Raman scattering in single crystal GaN films," Appl. Phys. Lett. **74**, 3125 (1999).

[9]Y. Xi, J.-Q. Xi, Th. Gessmann, J. M. Shah, J. K. Kim, E. F. Schubert, A. J. Fischer, M. H. Crawford, K. H. A. Bogart, and A. A. Allerman, "Junction and carrier temperature measurements in deep-ultraviolet light-emitting diodes using three different methods," Appl. Phys. Lett. **86**, 031907 (2005).

[10]S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, H. Kiyoku, Y. Sugimoto, T. Kozaki, H. Umemoto, M. Sano, and K. Chocho, Appl. Phys. Lett. **73**, 832 (1998).

[11]D. L. Blackburn, in *Proceedings 20th Annu. Semicond. Therm. Meas. Manage. Symp.*, March 11–24 (San Jose, CA, 2004), pp. 70–80.

[12]R. J. T. Simms, J. W. Pomeroy, M. J. Uren, T. Martin, and M. Kuball, "Channel temperature determination in high-power AlGaN/GaN HFETs using electrical methods and Raman spectroscopy," IEEE Trans. Electron Devices **55**, 478–482 (2008).

[13]M. Z. Kauser, A. Osinsky, A. M. Dabiran, and P. P. Chow, "Enhanced vertical transport in p-type AlGaN/GaN superlattices," Appl. Phys. Lett. **85**, 5275 (2004).

[14]P. Kozodoy, Y. P. Smorchkova, M. Hansen, H. Xing, S. P. Denbaars, U. K. Michra, A. W. Saxler, R. Perrin, and W. C. Mitchel, "Polarization-enhanced Mg doping of AlGaN/GaN superlattices," Appl. Phys. Lett. **75**, 2444 (1999).

[15]P. Kozodoy, M. Hansen, S. P. Den Baars, and U. K. Mishra, "Enhanced Mg doping efficiency in $Al_{0.2}Ga_{0.8}N$/GaN superlattices," Appl. Phys. Lett. **74**, 3681 (1999).