# Junction–temperature measurement in GaN ultraviolet light-emitting diodes using diode forward voltage method

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A theoretical model for the dependence of the diode forward voltage ($V_f$) on junction temperature ($T_j$) is developed. An expression for $dV_f/dT$ is derived that takes into account all relevant contributions to the temperature dependence of the forward voltage including the intrinsic carrier concentration, the band-gap energy, and the effective density of states. Experimental results on the junction temperature of GaN ultraviolet light-emitting diodes are presented. Excellent agreement between the theoretical and experimental temperature coefficient of the forward voltage ($dV_f/dT$) is found. A linear relation between the junction temperature and the forward voltage is found. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1795351]

III–V nitride semiconductors have a direct band gap and thus are very suitable for solid-state ultraviolet (UV) light sources. Such UV sources have a wide variety of applications, including UV-induced fluorescence, lighting, displays, spectrofluometry, photocatalytic processes, and high-resolution optics. Double-heterostructure GaInN/AlGaN UV light-emitting diodes (LEDs) emitting at 371 nm with an external quantum efficiency of 7.5% and output powers of 5 mW have been demonstrated.[1] The junction temperature is a critical parameter and affects internal efficiency, maximum output power, reliability, and other parameters. Several groups have reported measurements of the junction temperature of laser diodes (LDs) using micro-Raman spectroscopy,[2] threshold voltage,[3] thermal resistance,[4] photothermal reflectance microscopy,[5] electroluminescence,[6] photoluminescence,[7] and a noncontact method.[8]

In this letter, the diode forward voltage is employed to measure the junction temperature of GaN UV LEDs emitting at 375 nm. The theoretical foundation of the temperature dependence of the forward voltage is analyzed in detail. The experimental and theoretical results are compared and discussed.

In order to derive the relation between the forward voltage ($V_f$) and the junction temperature, we start with the Shockley equation:

$$J_f = J_s\left[\exp\left(\frac{eV_f}{n_{\text{ideal}}kT}\right) - 1\right], \tag{1}$$

where $J_s$ is the saturation current density and $n_{\text{ideal}}$ is the ideality factor. The saturation current density, $J_s$, can be expressed as

$$J_s = e\left[\sqrt{\frac{D_n}{\tau_n}}\frac{n_i^2}{N_D} + \sqrt{\frac{D_p}{\tau_p}}\frac{n_i^2}{N_A}\right], \tag{2}$$

where $D_n$ and $D_p$ are diffusion constants of electrons and holes, respectively, and $\tau_n$ and $\tau_p$ are the minority carrier lifetimes of electrons and holes, respectively. Both, the diffusion constants and the lifetimes are temperature dependent. For phonon scattering, the diffusion constants decrease with temperature according to a $T^{-1/2}$ dependence. The carrier lifetimes can decrease (nonradiative recombination) or increase (radiative recombination) with temperature. In the following theoretical derivation, dopants with concentration $N_D$ and $N_A$ are assumed to be fully ionized so that the free carrier concentration has no temperature dependence.

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

$$n_i = \sqrt{N_C N_V}\exp\left(\frac{-E_g}{2kT}\right), \tag{3}$$

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

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

$$N_V = 2\left(\frac{2\pi m_{dh}kT}{h^2}\right)^{3/2} \propto T^{3/2}, \tag{5}$$

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.

Figure 1 shows the schematic dependence of $\ln|J|$ on the voltage $V$ for different junction temperatures, as inferred from the Shockley equation. Inspection of Fig. 1 shows that, for a constant current density, the junction voltage decreases with increasing temperature.

For $V_f \gg kT/e$, Eq. (1) can be rewritten as

$$J_f = J_s \exp\left(\frac{eV_f}{n_{\text{ideal}}kT}\right). \tag{6}$$

Solving Eq. (6) for the junction voltage yields

$$V_f = \frac{n_{\text{ideal}}kT}{e}\ln\left(\frac{J_f}{J_s}\right). \tag{7}$$

The derivative of the junction voltage with respect to the junction temperature can be written as

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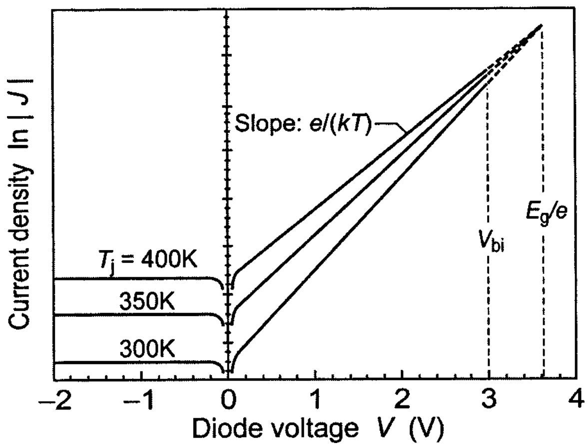


FIG. 1. Schematic dependence of $\ln|J|$ on the voltage $V$ of a GaN $p$-$n$ junction for junction temperatures $T_j$=300 K (low), 350 K (middle), and 400 K (high).

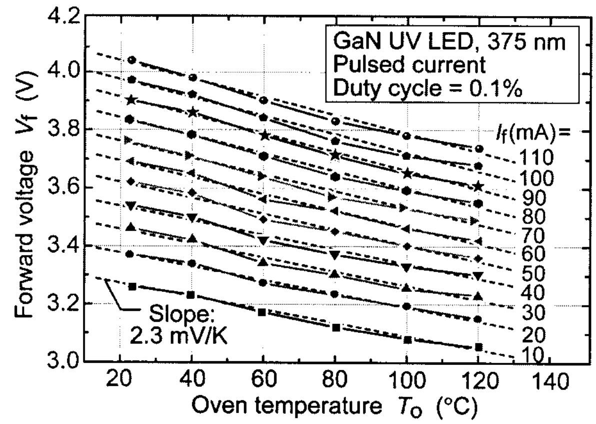


FIG. 2. Experimental forward voltage vs oven temperature for different pulsed injection currents. Also shown is a linear fit for the experimental data (dashed line).

$$\frac{dV_f}{dT} = \frac{d}{dT}\left[\frac{n_{\text{ideal}}kT}{e}\ln\left(\frac{J_f}{J_s}\right)\right]. \tag{8}$$

By substituting Eqs. (3)–(5) into Eq. (8), the temperature dependence of $n_i$, $E_g$, $N_C$, and $N_V$ are taken into account. Executing the derivative yields

$$\frac{dV_f}{dT} = \frac{eV_f - E_g}{eT} + \frac{1}{e}\frac{dE_g}{dT} - \frac{3k}{e}. \tag{9}$$

This equation gives the fundamental temperature dependence of the forward voltage. The first summand on the right-hand side of the equation is due to the intrinsic carrier concentration. The second summand is due to the temperature dependence of the band-gap energy. Note that the second summand was not included in earlier derivations.[9] The contribution of this new term is about 24% for GaN, 29% for GaAs, and 15% for Si. The third summand, $3k/e$, is due to the temperature dependence of $N_C$ and $N_V$. Inclusion of the temperature dependences of diffusion constants and lifetimes would only yield a minor contribution to the temperature coefficient ( $\leqslant$5% by calculation) and we, therefore, neglect these contributions. LEDs are typically operated with their forward voltage close to the built-in voltage, i.e., $V_f \approx V_{\text{bi}}$. For nondegenerate doping concentrations, we can write

$$eV_f - E_g \approx kT\ln\left(\frac{N_D N_A}{n_i^2}\right) - kT\ln\left(\frac{N_C N_V}{n_i^2}\right)$$
$$= kT\ln\left(\frac{N_D N_A}{N_C N_V}\right). \tag{10}$$

Furthermore, the band-gap energy can be expressed as

$$E_g = E_0 - \frac{\alpha T^2}{\beta + T}, \tag{11}$$

where $\alpha$ and $\beta$ are the Varshni parameters. For GaN,[10] $\alpha$ =0.77 meV/K$^2$, $\beta$=600 K. Substituting Eqs. (10) and (11) into Eq. (9) yields

$$\frac{dV_f}{dT} \approx \frac{k}{e}\ln\left(\frac{N_D N_A}{N_C N_V}\right) - \frac{\alpha T(T+2\beta)}{e(T+\beta)^2} - \frac{3k}{e}. \tag{12}$$

This equation is a very useful expression for the temperature coefficient of the forward voltage. Note that this expression is a *lower limit* for the magnitude of $dV_f/dT$, because the *junction voltage* is *less* than the *built-in voltage* in all practical cases. For GaN with $N_D = N_A = 2\times10^{16}$ cm$^{-3}$, one obtains $dV_f/dT = -1.76$ mV/K. For a Si $p$-$n$ junction with the same doping concentration, one obtains $dV_f/dT = -1.74$ mV/K, in good agreement with Millman and Halkias.[9] For GaAs with $N_A = N_D = 10^{17}$ cm$^{-3}$, one obtains $dV_f/dT = -1.2$ mV/K from Eq. (12). We have measured the temperature coefficient of the forward voltage of a GaAs diode and obtained $dV_f/dT = -1.17$ mV/K.

The diode forward voltage can be used to assess the junction temperature of $p$-$n$ junction diodes. The forward voltage method consists of two series of measurements, a calibration measurement and the actual junction–temperature measurement. In the calibration measurement, a pulsed forward current (with duty cycle 0.1%) drives the LED sample located in a temperature-controlled oven. The small duty cycle ensures that the junction temperature is equal to the ambient temperature. An oscilloscope is used to measure the forward voltage $V_f$ of the LED sample at different oven temperatures. The calibration measurement establishes the relation between the forward voltage and the junction temperature.

Experimental results reveal that the experimental $V_f$ versus $T$ relation is very close to linear and can be fitted by the equation

$$V_f = A + BT_o, \tag{13}$$

where $T_o$ is the oven temperature, $A$ and $B$ are fitting parameters. Since the duty circle of the pulsed current is 0.1%, the heat generated by the pulsed current can be neglected and the junction temperature can, with very good accuracy, be assumed to be equal to the oven temperature. The same process is repeated for different (pulsed) current levels.

After the calibration measurement, a dc forward current is applied to the sample and the dc forward voltage values are measured. Using the calibration measurement, the junction temperatures for different dc currents are given by

$$T_j = \frac{(V_f - A)}{B}. \tag{14}$$

To demonstrate the viability of the method, the junction temperature of GaN UV LEDs (Nichia Corp. with a peak wavelength of 375 nm) was determined. Equipment for the experiments included a HP 214B pulse generator, a Wiscon-

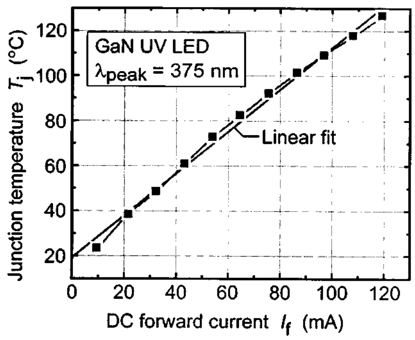


FIG. 3. Junction temperature as a function of dc forward current for a GaN UV LED.

sin oven with thermal sensor, a Tektronix TDS 3054B four channel color digital oscilloscope, an Ando AQ-6315A optical spectrum analyzer, an Agilent E3649A dual output dc power, and HP 34401A multimeter to measure the dc forward voltage.

During the calibration measurement, the pulsed current increased from 10 mA to 110 mA in 10 mA increments. The measured forward voltage versus junction–temperature relation is shown in Fig. 2. The dashed lines are linear fits to the experimental data. From Fig. 2, the temperature coefficient of the forward voltage at low currents is −2.3 mV/K, slightly larger in magnitude than the theoretical result. The small difference between the experimental temperature coefficient and the theoretical result of Eq. (12) is fully consistent with Eq. (12) giving the lower limit of the magnitude of $dV_f/dT$. The difference could also be due to a decrease in *p*-type GaN layer resistivity, caused by more complete acceptor activation at elevated temperature.

Figure 3 shows the junction temperature versus the dc forward current. The $T_j$ versus $I_f$ curve is approximately linear. As the dc forward current increases from 10 mA to 110 mA, the junction temperature increases from 23 to 126 °C. A linear fit is shown in the same diagram. Such a type of linear relation between the junction temperature and the forward current has also been found in LDs.[11]

In conclusion, a theoretical expression of the temperature coefficient of the diode forward voltage is developed. The three main contributions to the temperature coefficient are: (i) the intrinsic carrier concentration, (ii) the bandgap energy, and (iii) the effective density of states. Experimental results are presented for GaN UV LEDs. For $I_f = 10$ mA, the experimental temperature coefficient is $dV_f/dT = -2.3$ mV/K. The theoretical temperature coefficient, which is shown to be a lower limit in magnitude, is −1.7 mV/K, close to the experimental coefficient. A similar linear relation between the junction temperature and the forward current is found.

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[1] T. Mukai, D. Morita, and S. Nakamura, J. Cryst. Growth **778**, 189 (1998).
[2] S. Todoroki, M. Sawai, and K. Aiki, J. Appl. Phys. **58**, 1124 (1985).
[3] H. I. Abdelkader, H. H. Hausien, and J. D. Martin, Rev. Sci. Instrum. **63**, 2004 (1992).
[4] S. Murata and H. Nakada, J. Appl. Phys. **72**, 2514 (1992).
[5] P. W. Epperlein, *Proceedings of 17th International Symposium of Gallium Arsenide and Related Compounds*, IOP Conference Series (IOP, London, 1990), Vol. 112, p. 633.
[6] P. W. Epperlein and G. L. Bona, Appl. Phys. Lett. **62**, 3074 (1993).
[7] D. C. Hall, L. Goldberg, and D. Mehuys, Appl. Phys. Lett. **61**, 384 (1992).
[8] Y. Gu and N. Narendran, Proc. SPIE **5187**, 107 (2004).
[9] J. Millman and C. Halkias, *Integrated Electronics* (McGraw–Hill, New York, 1972).
[10] http://www.ioffe.rssi.ru/SVA/NSM/Semicond/.
[11] J. M. Rommel, P. Gavrilovic, and F. P. Dabkowski, J. Appl. Phys. **80**, 6547 (1996).