Accurate Determination of Junction Temperature in a GaN-Based Blue Light-Emitting Diode using Nonlinear Voltage-Temperature Relation

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Research Article

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Accurate determination of junction temperature in a GaN-based blue light-emitting diode using nonlinear voltage-temperature relation

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Abstract

We investigate the junction temperature measurements for GaN-based blue light emitting diodes (LEDs) using nonlinear dependence of the forward voltage (V_f) on temperature. Unlike the conventional linear model of the dependence of V_f on temperature, the modeling of the temperature dependent V_f with a quadratic function showed good agreements with measured data in the temperature range between 20 and 100 ^{o}C. Using the proposed quadratic model, the junction temperature and thermal resistance of the measured LED could be accurately determined as the ambient temperature varied. It was observed that the junction temperature increment remained almost unchanged as the ambient temperature increased from 20 to 80 ^{o}C, which could be attributed to the interplay between the decrease in series resistance and the increase in non-radiative recombination with increasing temperature. The presented method for accurate determination of the junction temperature is expected to be advantageously employed for the thermal management of high-power LEDs.

Keywords: Light-emitting diode, Blue LED, GaN, Junction temperature

1. Introduction

The demand for light emitting diodes (LEDs) as applied to commercial and residential solid-state lighting, display backlighting, and automobile headlights continues to rise (Chang et al. 2012, Pust et al. 2015, Cho et al. 2017, Bhardwaj et al. 2017). The internal quantum efficiency (IQE) of state-of-the art blue LEDs can exceed 90% (Hurni et al. 2015, Kuritzky et al. 2018, David et al. 2020). However, the IQE of GaN-based blue LEDs may be reduced significantly at high current density and at high temperature, respectively referred to as current droop and thermal droop (David et al. 2019, Meneghini et al. 2020). Increasing the operation temperature of an LED decreases light output power (LOP) mainly because of the increase in non-radiative recombination with increasing temperature (Schubert 2016). Therefore, thermal management of LEDs has become increasingly important with the development of high power LEDs. Junction temperature (T_j) is an important parameter which could significantly influence IQE, device reliability, and color stability of LEDs. High electrical power consumption by commercial high-power LEDs results in device heating, making T_j an essential figure of merit that requires a reliable method of measurement. Because of the importance of thermal management in LEDs, T_j of GaN-based LEDs has been intensively studied.

In addition to LOP, the forward voltage (V_f) of GaN-based LEDs has been demonstrated to show strong dependence on temperature (Xi et al. 2004, Ryu et al. 2005). V_f decreases with increasing temperature mainly because of the reduction in the energy band gap and series resistance (Varshini 1967, Xi et al. 2005). The large variation of V_f with temperature can provide a convenient and reliable method to determine T_j (Xi et al. 2004, Ryu et al. 2005, Keppens et al. 2008, Feng et al. 2012). This forward voltage method has been known to be more accurate than the emission-peak-shift method (Xi et al. 2005). In the forward voltage method, the temperature coefficient of voltage (K), which is defined as the derivative of forward voltage with respect to temperature, is measured firstly. Then, T_j is determined by dividing the voltage difference between pulsed and continuous-wave (CW) operation by the measured K value. Up to now, K was mostly regarded to be constant independent of temperature in determining T_j of LEDs, assuming almost linear dependence of V_f on temperature. However, K can be a strong function of temperature because of nonlinear dependence of V_f on temperature, which should be considered in determining T_j.

In this paper, we report on the method for accurate determination of T_j of a GaN-based blue LED package in the temperature range between 20 to 100 ^{o}C using nonlinear temperature dependence of the forward voltage. It will be shown that V_f can be fit quite well with a quadratic function of the temperature, and hence the K value depends linearly on the temperature. Using the obtained K-factor, the junction temperature increment (ΔT_j) relative to the ambient temperature was determined. In addition, thermal resistance (R_{th}) of the measured LED package was determined using ΔT_j and dissipated electrical power. We compare the temperature dependence of T_j and R_{th} for the constant and variable K values, and show the importance of using nonlinear temperature dependence of V_f for the accurate characterization of thermal properties of LEDs.

2. Theory

The relation between V_f and injection current (I) at temperature T of a diode is given by the Shockley equation that includes a series resistance term (Xi et al. 2005):

$$I = I_s[\exp(\frac{eV_f - eIR_s}{nkT}) - 1], \quad (1)$$

where I_s is the saturation current, R_s is the series resistance, and n is the diode ideality factor.

Solving Eq. (1) for the case of $eV_f \gg kT$, V_f is expressed as

$$V_f = V_j + IR_s = \frac{nkT}{e} \ln(\frac{I}{I_s}) + IR_s \, , \tag{2}$$

where V_j is the junction voltage. By taking the derivative of V_f with respect to T in Eq. (2), the temperature coefficient of voltage, K is obtained:

$$K \equiv \frac{dV_f}{dT} = \frac{dV_j}{dT} + I\frac{dR_s}{dT} \, , \tag{3}$$

According to Refs. (Xi et al. 2005, Feng et al. 2012, Chen et al. 2017 el al.), Eq. (3) can be written as

$$K = \frac{dV_j}{dT} - \frac{1}{2}\frac{E_a + 2SkT}{kT^2} IR_s \, , \tag{4}$$

where E_a is the acceptor activation energy of p-GaN and S is the exponent of temperature dependence in the carrier mobility model.

In Eq. (4), dV_j/dT was found to be weakly dependent on the temperature, which showed an almost constant value around -1.5 mV/K for InGaN blue LEDs (Xi et al. 2005, Meyaard et al. 2013). The second summand of the right hand side of Eq. (4), which corresponds to the contribution of the series resistance, can be strongly dependent on the temperature and current. This term has complicated temperature dependence as R_s is also dependent on the temperature. Up to now, K of LEDs was mostly regarded to be constant independent of temperature and current (Xi et al. 2004, Keppens et al. 2008, Meyaard et al. 2013, Kim et al. 2016, Chen et al. 2017,). However, this assumption is valid only for the cases of low injection current and a limited temperature range, suggesting that the temperature dependence of K should be considered in determining T_j for LEDs operating at high current.

Using the definition of K in Eq. (3), the difference in V_f between CW and pulsed operation is expressed as

$$\Delta V_f = \int_{T_a}^{T_j} K dT \, , \tag{5}$$

where T_a is the ambient temperature. Eq. (5) is based on the assumption that the temperature of LEDs corresponds to T_j and T_a for the CW and pulsed operation, respectively. It should be noted that both ΔV_f and K are negative quantities. If the voltage-temperature (V-T) relation was assumed to be linear, K would be constant. In that case, ΔT_j is simply given by

$$\Delta T_j \equiv T_j - T_a = \frac{\Delta V_f}{K} \tag{6}$$

If V_f is quadratically proportional to the temperature as will be shown experimentally, K can be written as

$$K = aT + b \, , \tag{7}$$

where a and b are fitting parameters that can be obtained by the fit of measured V-T relation. Using Eqs. (5) and (7), the following quadratic equation for T_j is obtained:

$$aT_j^2 + 2bT_j - (aT_a^2 + 2bT_a + 2\Delta V_f) = 0 \tag{8}$$

Solving Eq. (8) yields T_j for given T_a and ΔV. In addition, thermal resistance of the LED package can be calculated using the measured T_j and light output power, P:

$$R_{th} = \frac{\Delta T_j}{IV_f - P} \tag{9}$$

3. Experiments

The epitaxial layers of an LED used for this study were grown on a c-plane sapphire substrate by metal-organic chemical vapor deposition. The layer structure consisted of a Si-doped n-GaN layer, InGaN/GaN multiple-quantum-well active region, a Mg-doped p-AlGaN electron-blocking layer, and a Mg-doped p-GaN contact layer. The peak emission wavelength was ~450 nm at 20 °C. The LED chip was fabricated as a lateral-injection structure with the chip dimension of 650 μm × 650 μm. The fabricated LED chip was encapsulated with epoxy resin and mounted in a ceramic package as a type of surface-mount device. Then, the LED package was soldered on a metal PCB and the temperature was controlled by a thermo-electric cooler.

The optical and electrical characteristics of an LED sample were measured as the injection current increased up to 150 mA for a fixed ambient temperature (T_a) from 20 to 100 °C, and the LOP versus current (*L-I*) and V_f versus current (*V-I*) relations were obtained for each temperature. The LED sample was operated under CW and pulsed current injection for a given T_a. For the pulsed operation, the pulse width and the duty cycle were 0.1 ms and the duty cycle of 1%, respectively, which is expected to have negligible effect on temperature rise of the LED junction.

Figure 1 shows *L-I* curves of the measured LED sample under CW operation for T_a of 20, 40, 60, 80, and 100 °C. The LOP increased sublinearly with injection current, and it decreased slowly with increasing temperature. Figure 2 shows *V-I* curves of the measured LED sample. In Fig. 2(a), *V-I* curves under pulsed operation are shown for various T_a between 20 and 100 °C. It is observed that V_f decreased with increasing temperatures. In Fig. 2(b), *V-I* curves under pulsed and CW operation are compared when the ambient temperature is 20 °C. V_f under pulsed operation was higher than that under CW operation as a result of the difference in the LED temperature between pulsed and CW operation. The voltage difference, ΔV_f between pulsed and CW operation is used to determine T_j using Eq. (6) or (8).

4. Results and Discussion

An accurate thermal measurement evaluation requires an ideal fit to the forward voltage versus temperature (*V-T*) relation. Figure 3(a) shows V_f under pulsed operation as a function of T_a when the injection current was 100 mA. Because of the pulsed operation, it can be regarded that T_a is the same as T_j in Fig. 3(a). The linear fit (red line) and a quadratic fit (blue line) to the measured data are also shown in Fig. 3(a). As mentioned before, the dependence of V_f on temperature has often been modelled with a linear function (Xi et al. 2004). However, inspection of Fig. 3(a) shows that the linear fit did not agree well with the measured data. In fact, a linear fit implies a constant slope and consequently a single value of the series resistance in the entire temperature, which in reality is not the case. Increasing the temperature activates the acceptor atoms in the *p* doped region resulting in a changing series resistance. For this reason, one would expect a varying slope. By modelling the temperature dependent forward voltage with a quadratic function, $V_f = \alpha T^2 + \beta T + \gamma$, a nearly ideal fit which agreed well with the experimental data was demonstrated. The R^2 value for the linear and quadratic fit was 0.9936 and 0.9998, respectively.

The temperature coefficient of voltage, K is the slope of the *V*-*T* relation, which is obtained by the derivative of the fit function. For the linear fitting, K was constant value of -3.91 mV/K at 100 mA. For the quadratic fitting, K is given by a temperature dependent function, $K = 2\alpha T_a + \beta$. Figure 3(b) shows the variation of K with T_a for the quadratic fit. In this case of 100-mA injection current, α and β were obtained to be -8.74×10^{-6} V/K^2 and 4.96×10^{-3} V/K, respectively. It has been shown that the slope of the *V*-*T* curve decreases as the series resistance is reduced (Meyaard et al. 2013). Therefore, the negative value of the slope α with increasing temperature implies a decreasing value of the series resistance with temperature.

The junction temperature increment, ΔT_j can be determined using Eq. (6) and Eq. (8) for the linear and quadratic *V*-*T* fit, respectively. Figure 4(a) shows the variation of ΔT_j as a function of T_a for 100-mA injection current. The result reveals slowly varying ΔT_j for the quadratic V-T fitting and rapidly decreasing ΔT_j for the linear fitting. The conventional linear V-T fit could lead to large errors in determining ΔT_j of LEDs at low and high T_a. ΔT_j for the quadratic V-T fitting varied between 19 to 23 K as T_a increased from 20 to 100 ^oC. Increase in temperature will increase the activation of acceptor atoms in the p-region thereby reducing the series resistance contribution to the junction heating. On the contrary, nonradiative recombination via SRH recombination and Auger recombination increases at elevated temperatures, resulting in the increase of heat generation at the junction. The slowly varying ΔT_j observed in Fig. 4(a) can be attributed to the interplay between the contributions of the series resistance of the p-region and the nonradiative recombination to the junction heating.

With the obtained results of ΔT_j, LOP, and V_f under CW operation, R_{th} was calculated using Eq. (9). Figure 4(b) shows the variation of R_{th} with T_a for the linear and quadratic V-T fitting at 100-mA injection current. The dependence of R_{th} on T_a is similar to that of ΔT_j on T_a in Fig. 4(a) for both the linear and quadratic fitting. As the temperature increased from 20 to 100 ^oC, R_{th} decreased from 159 to 98 K/W for the linear fitting whereas it slowly varied from 126 to 147 K/W for the quadratic fitting. As in the case of ΔT_j, the linear fitting of V-T relation could lead to incorrect information on R_{th}. Since R_{th} is strongly influenced by thermal conductivity of thermal interface materials (TIMs), the slowly varying behavior of R_{th} with temperature can be attributed to the temperature dependence of TIMs in the LED package.

In addition, we evaluated ΔT_j for other injection currents using the quadratic fitting of V-T relations and Eq. (8). Figure 5 shows ΔT_j as a function injection current for T_a of 20, 40, 60, and 80 ^oC. ΔT_j increased nearly linearly with increasing current for all temperatures. This linear relationship has also been reported in previous works on the junction temperature of LEDs (Xi et al. 2005, Feng et al. 2012, Kim et al. 2020). The slope of ΔT_j versus current was calculated to be ~0.24 K/A. In addition, only slight difference in ΔT_j was observed at a given injection current for all temperatures from 20 to 80 ^{o}C. As the temperature increases, the series resistance decreases whereas nonradiative recombination increases. These counteractive effects are believed to result in the insensitivity of ΔT_j to ambient temperatures.

5. Conclusion

We have reported on the determination of the junction temperature of GaN blue LED using a non-linear modelling of the forward voltage dependence on temperature. It was found that the temperature dependence of V_f was fitted ideally with a quadratic function in contrast to the linear dependence in previous studies. This resulted in decreasing values of the temperature coefficient of voltage, which is an implication of the variation of the series resistance with temperature. Using the quadratic model, ΔT_j of the LED could be accurately determined as the ambient temperature increased from 20 to 100 ^{o}C. On the contrary, when the conventional linear fit of the voltage-temperature relation was employed, large errors could occur in determining ΔT_j. As the temperature varied between 20 to 80 ^{o}C, ΔT_j was found to change only slightly with the ambient temperature, which could be explained by the opposite temperature-dependent contribution of series resistance and nonradiative recombination to heat generation. The presented analysis model on the voltage-temperature relation is expected to provide the method to accurately determine the junction temperature of LEDs, and thereby contribute to the thermal management of high-power LEDs.

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Declarations

Funding

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Conflicts of interest/Competing interests

Not applicable

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Figures

Fig. 1. Light output power (LOP) as a function of injection current under CW operation for the ambient temperature (T_a) of 20, 40, 60, 80, and 100 ^{o}C.

Fig. 2. (a) Forward voltage (V_f) as a function of injection current (I) under pulsed operation for T_a of 20, 40, 60, 80, and 100 ^{o}C. (b) The V_f versus I relations under pulsed and CW operation are compared when T_a is 20 ^{o}C.

Fig. 3. (a) V_f under pulsed operation as a function of T_a for the injection current of 100 mA. The red and blue lines respectively correspond to the linear and quadratic fit to the measured data. (b) Temperature coefficient of voltage (K) as a function of T_a for the quadratic fit at 100 mA.

Fig. 4. (a) Junction temperature increment (ΔT_j) and (b) thermal resistance (R_{th}) as a function of T_a at 100-mA injection current for the linear and quadratic fit of the voltage-temperature relation.

Fig. 5. ΔT_j as a function injection current for T_a of 20, 40, 60, and 80 ^{o}C.

Fig. 1

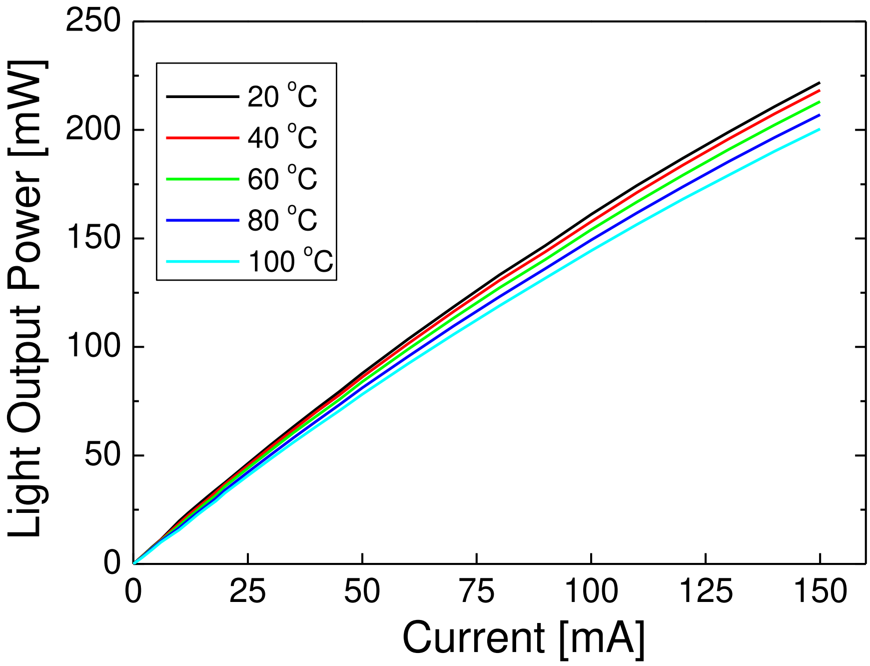
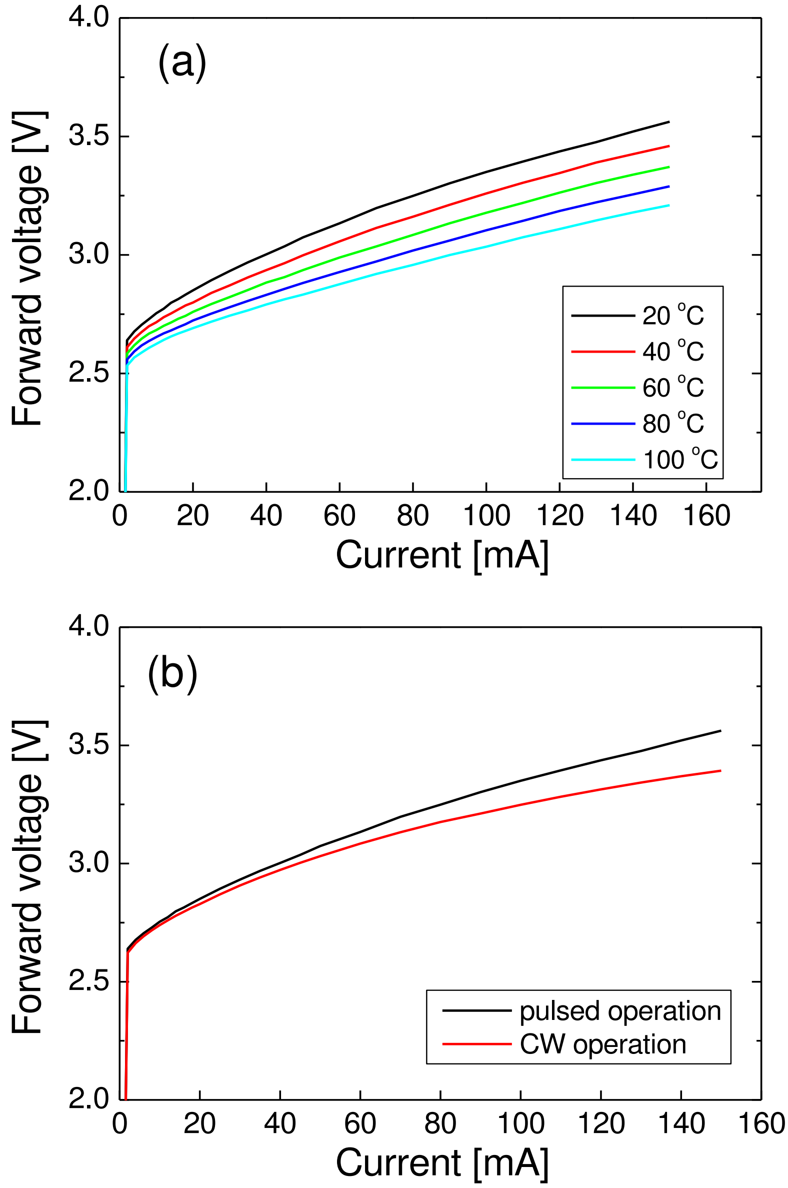
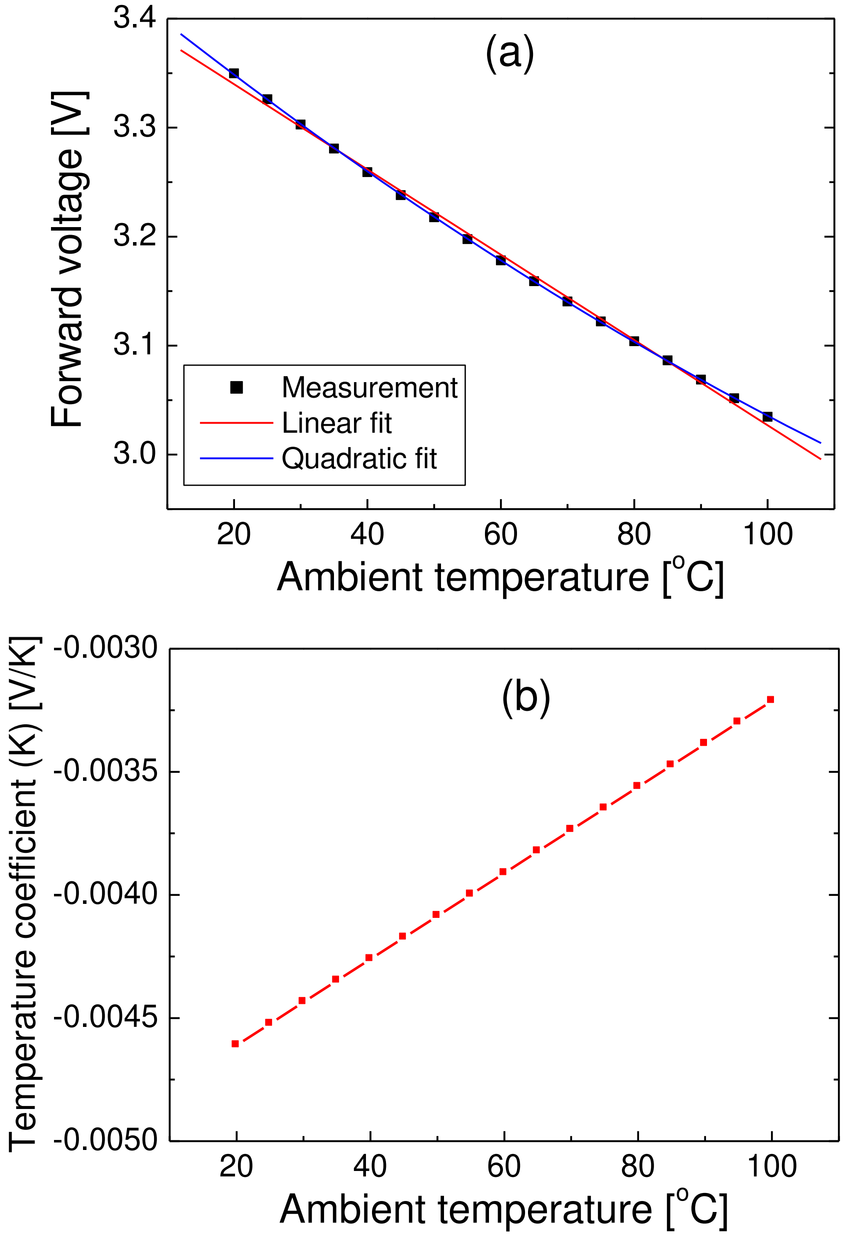

Light Output Power [mW]
Current [mA]
20 °C
40 °C
60 °C
80 °C
100 °C
0
50
100
150
200
250
0
25
50
75
100
125
150

FIG. 2



(a)
Forward voltage [V]
4.0
3.5
3.0
2.5
2.0
0
20
40
60
80
100
120
140
160
Current [mA]
20 °C
40 °C
60 °C
80 °C
100 °C
(b)
Forward voltage [V]
4.0
3.5
3.0
2.5
2.0
0
20
40
60
80
100
120
140
160
Current [mA]
pulsed operation
CW operation

FIG. 3



(a)
Forward voltage [V]
3.4
3.3
3.2
3.1
3.0
Measurement
Linear fit
Quadratic fit
20
40
60
80
100
Ambient temperature [°C]
(b)
Temperature coefficient (K) [V/K]
-0.0030
-0.0035
-0.0040
-0.0045
-0.0050
20
40
60
80
100
Ambient temperature [°C]

FIG. 4

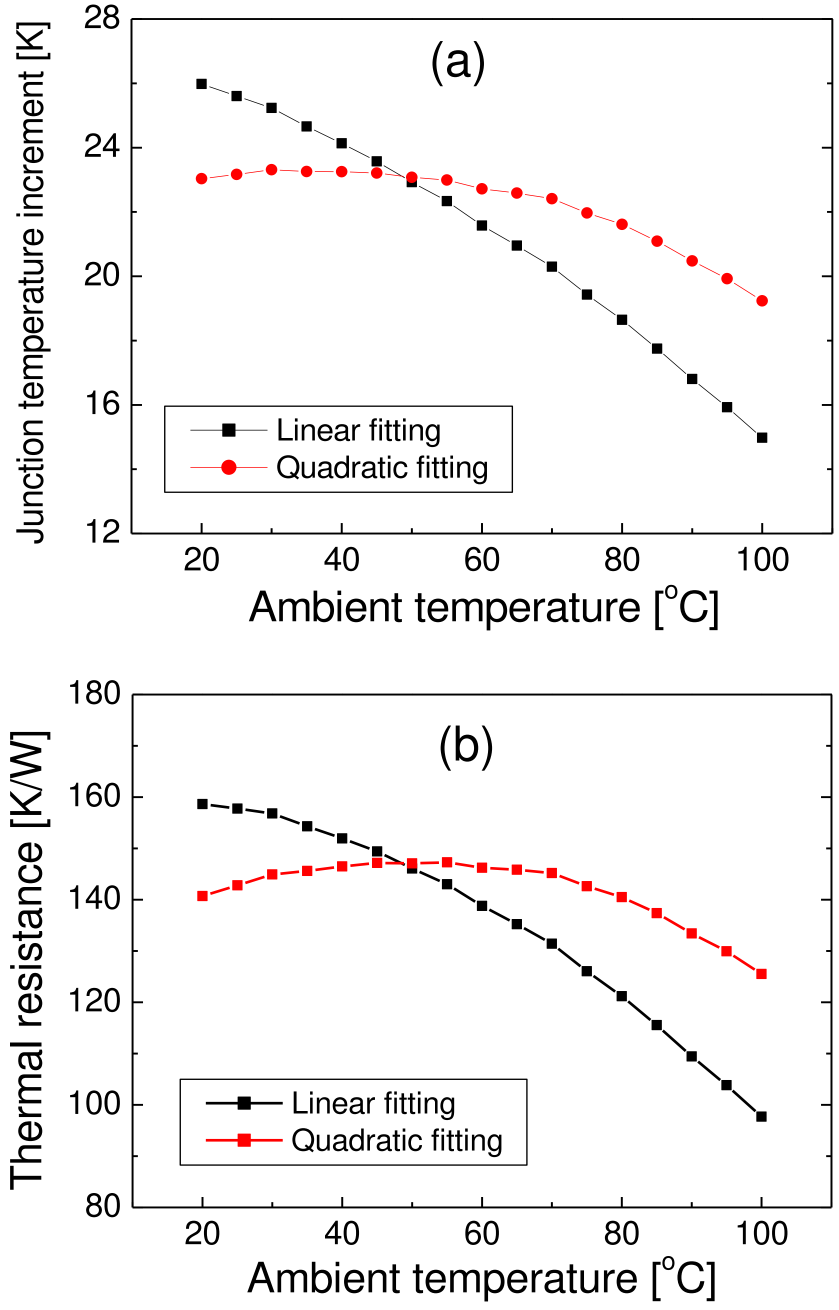
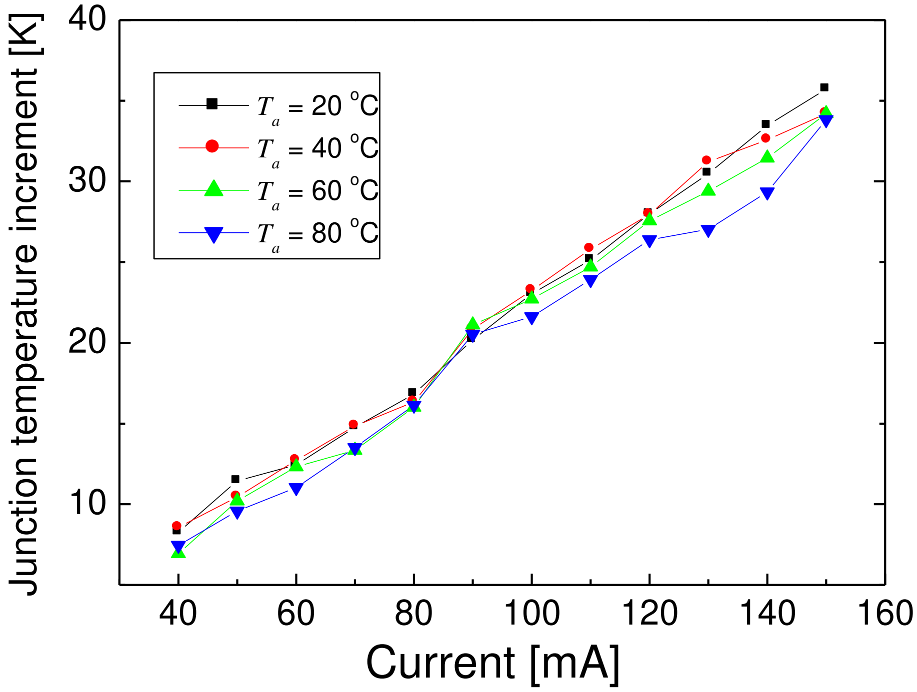

(a)
Junction temperature increment [K]
Ambient temperature [°C]
Linear fitting
Quadratic fitting
(b)
Thermal resistance [K/W]
Ambient temperature [°C]
Linear fitting
Quadratic fitting

FIG. 5



Junction temperature increment [K]
Current [mA]
T_a = 20 °C
T_a = 40 °C
T_a = 60 °C
T_a = 80 °C
10
20
30
40
40
60
80
100
120
140
160

Figures

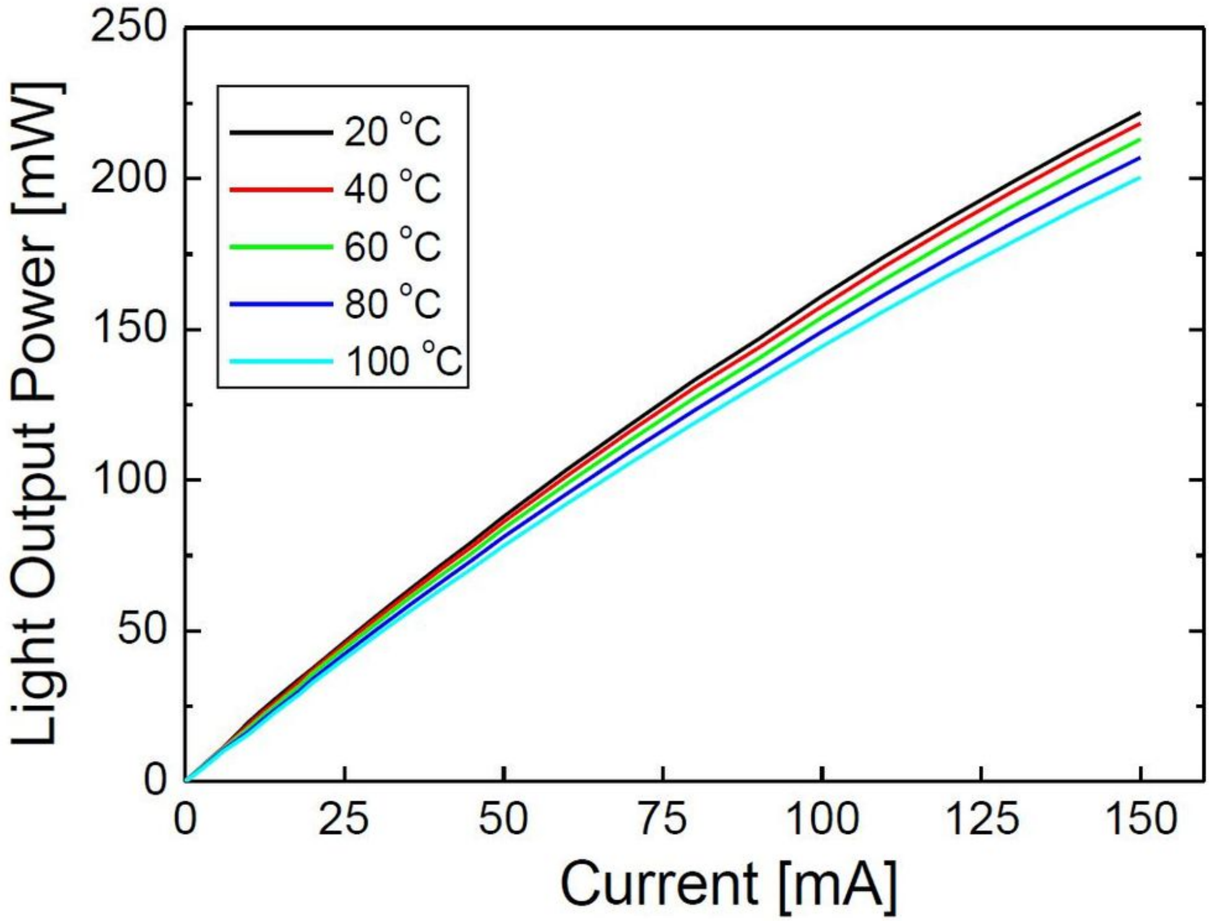


Figure 1

Light output power (LOP) as a function of injection current under CW operation for the ambient temperature (Ta) of 20, 40, 60, 80, and 100 oC.

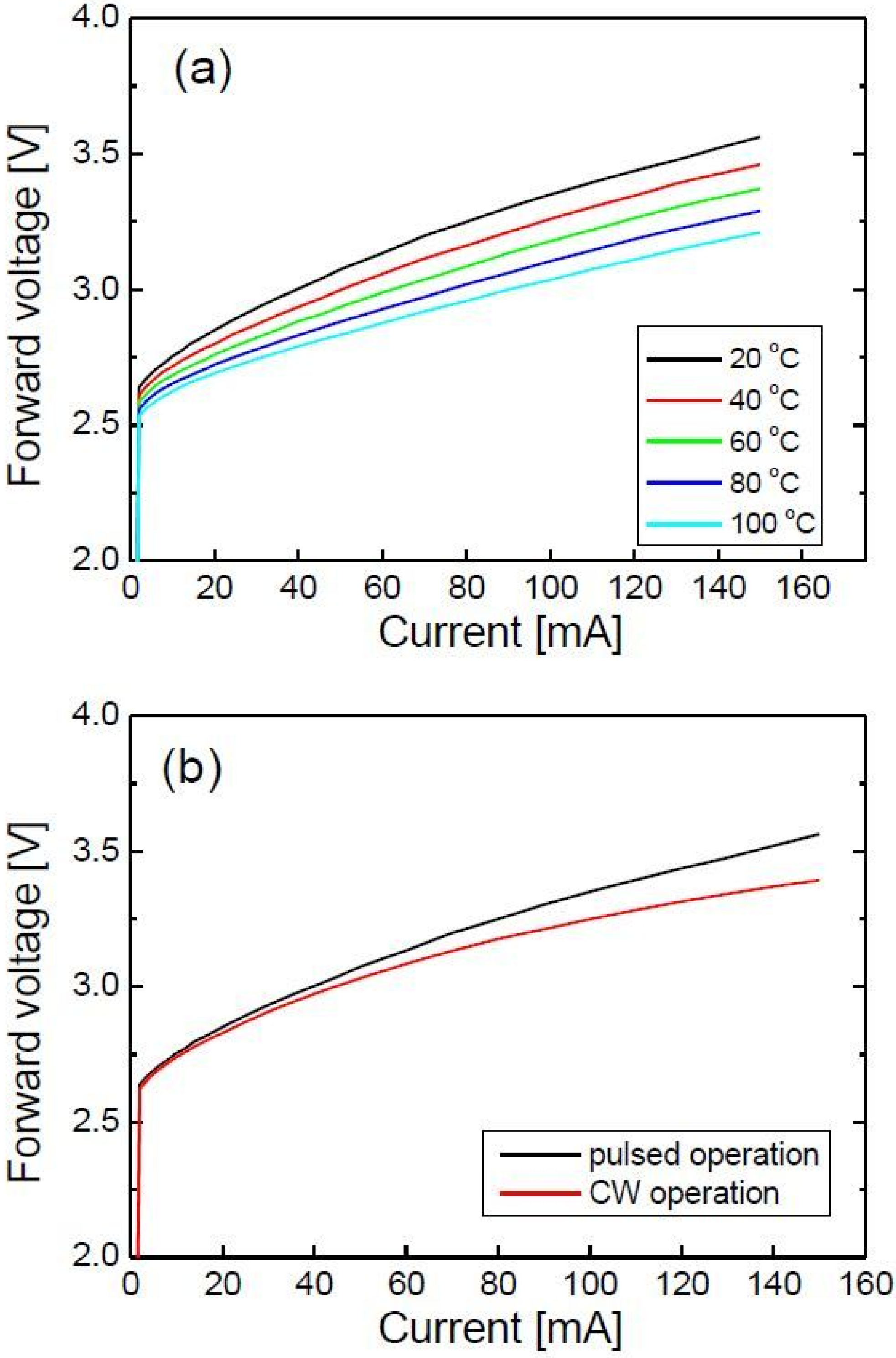


Figure 2

(a) Forward voltage (Vf) as a function of injection current (I) under pulsed operation for Taof 20, 40, 60, 80, and 100oC. (b) The Vfversus I relations under pulsed and CW operation are compared when Tais 20oC.

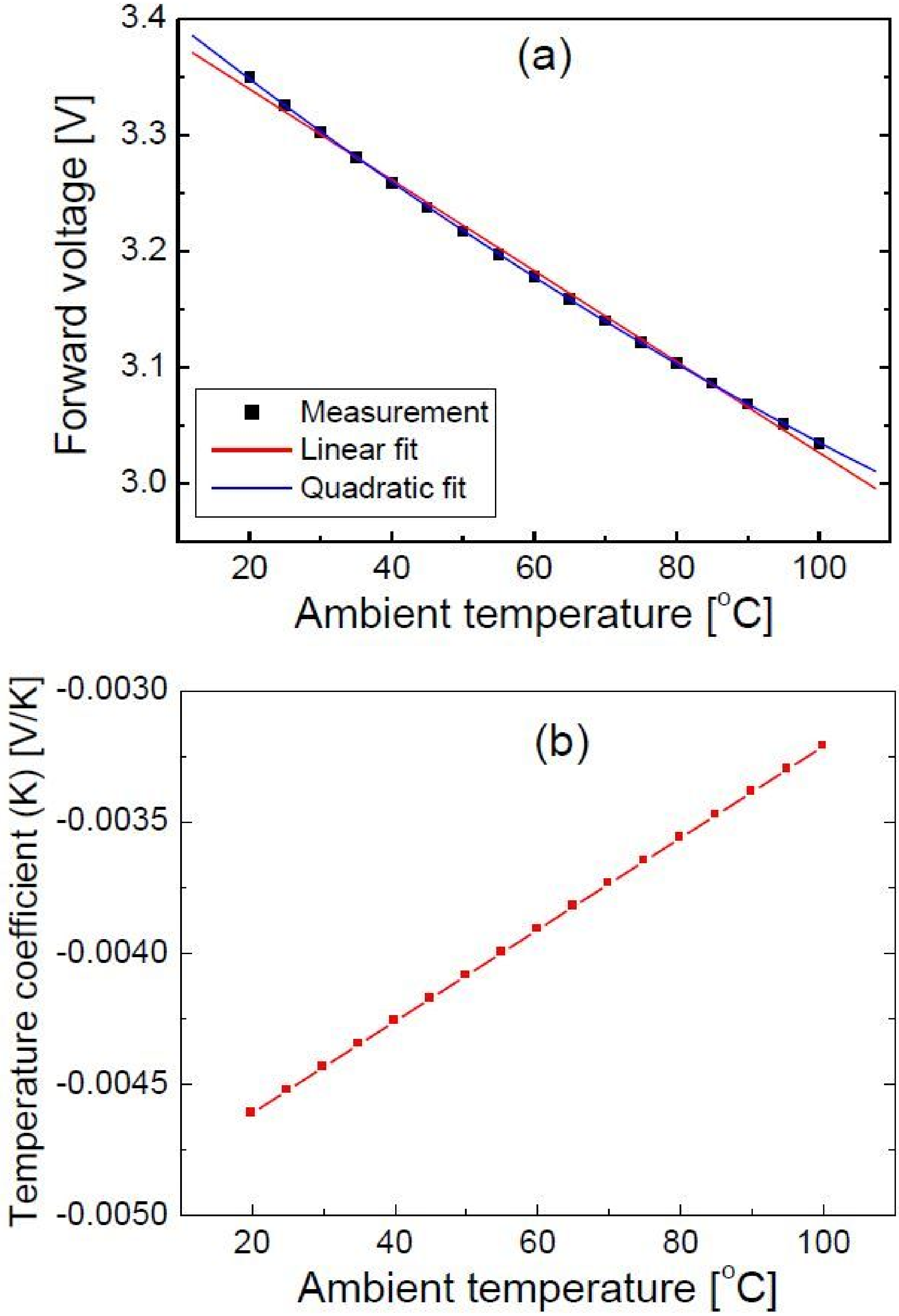


Figure 3

(a) Vf under pulsed operation as a function of Ta for the injection current of 100 mA. The red and blue lines respectively correspond to the linear and quadratic fit to the measured data. (b) Temperature coefficient of voltage (K) as a function of Ta for the quadratic fit at 100 mA.

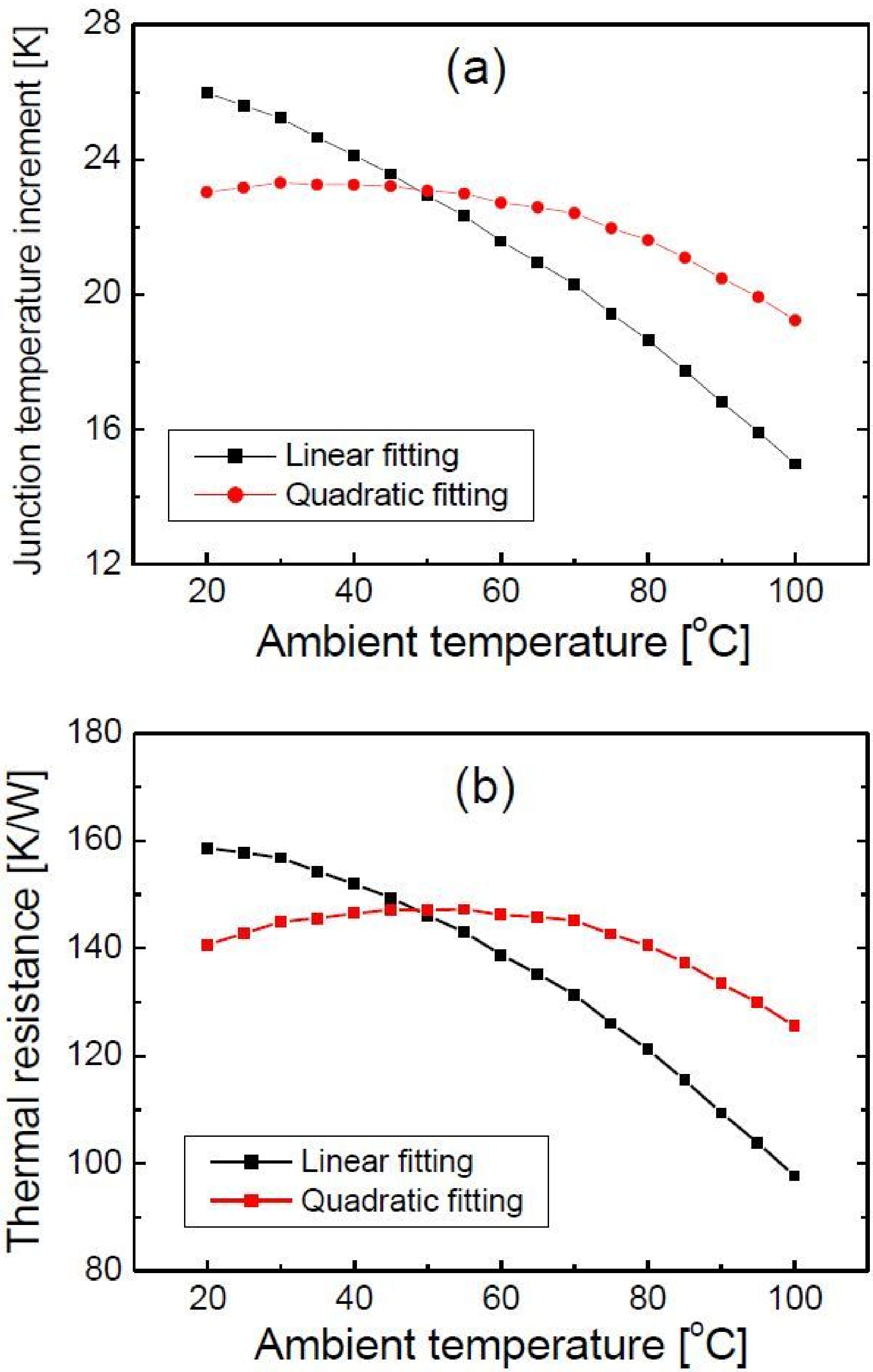


Figure 4

(a) Junction temperature increment (ΔTj) and (b) thermal resistance (Rth) as a function of Ta at 100-mA injection current for the linear and quadratic fit of the voltage- temperature relation.

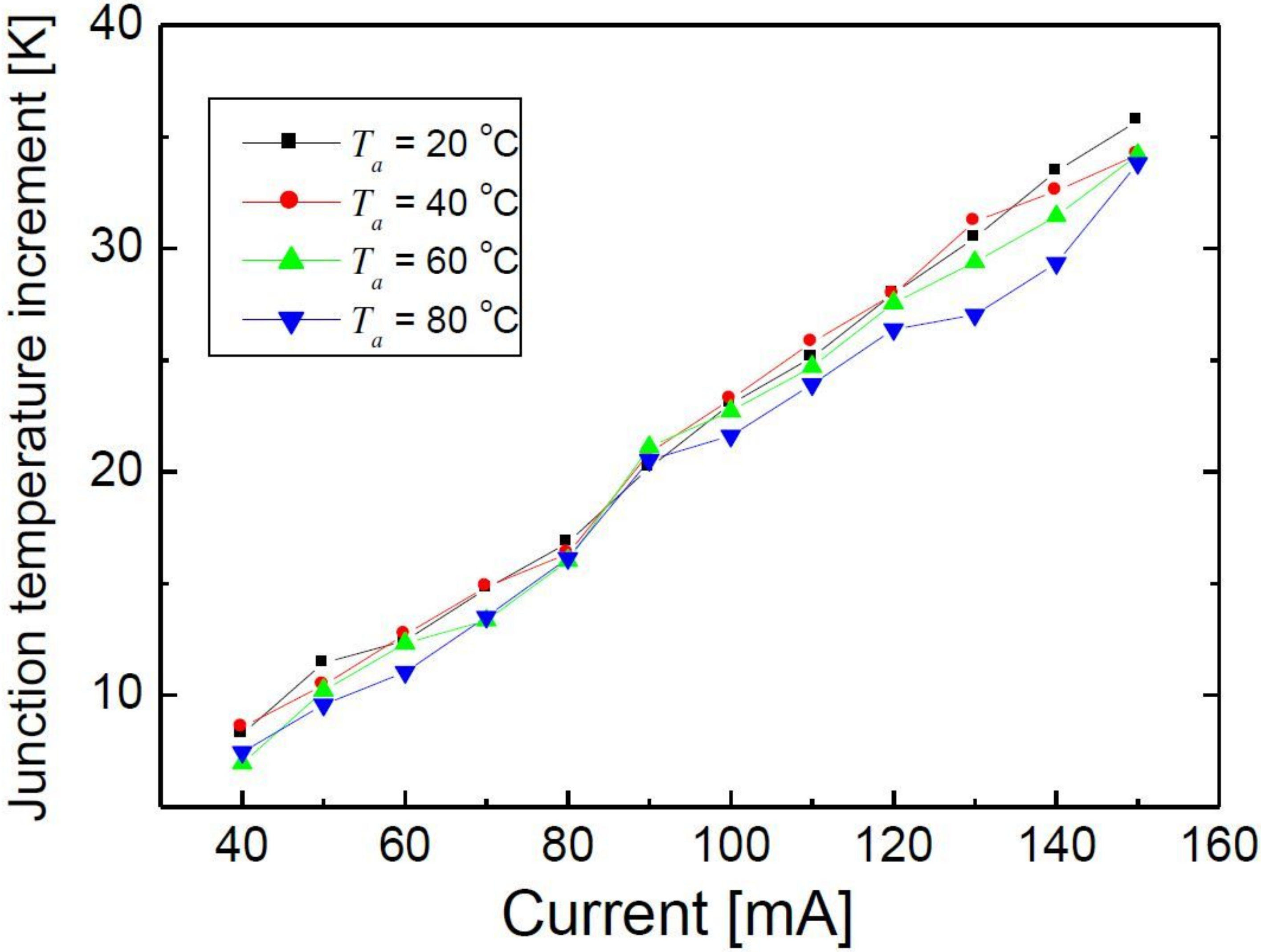


Figure 5

ΔTj as a function injection current for Ta of 20, 40, 60, and 80 oC.