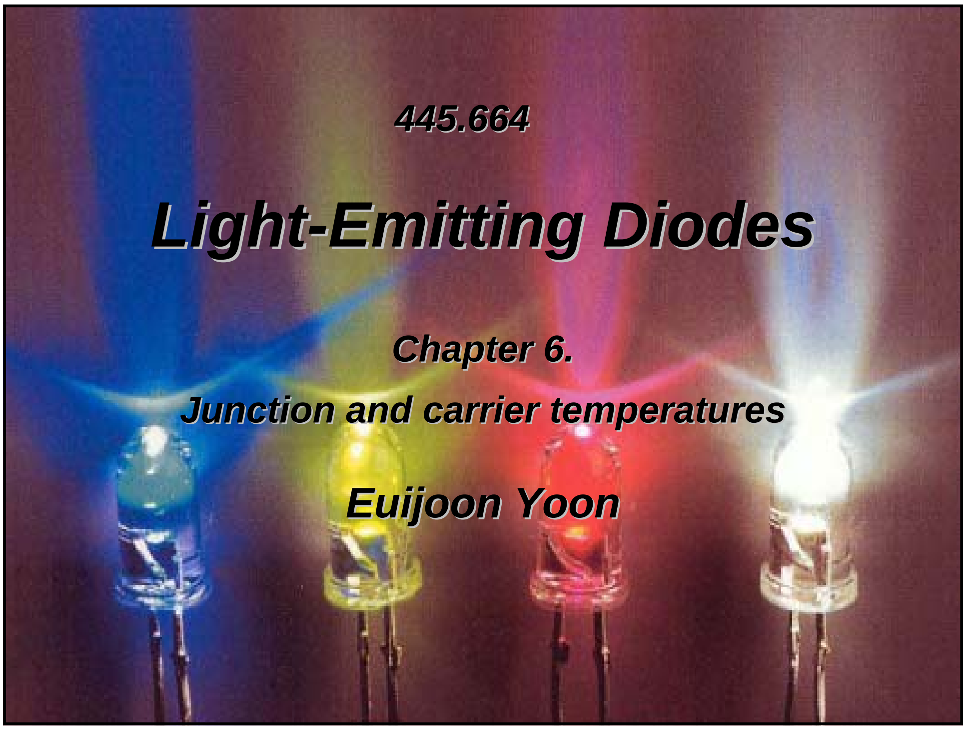

Junction temperature

- *Junction temperature : temperature of the active region crystal lattice*
- *Why relevant?*

1. IQE depends on junction temperature

2. Shortening of device life time caused by high temperature

3. Degradation of the encapsulant by heat

→ *It is desirable to know the relation of junction temperature vs. drive current*

- *Heat generation : contacts, cladding layers, active region*

  Low current : heat generation in parasitic resistances of contacts and cladding layer is small (I^2R)

  High current : contribution of parasitics becomes important and dominated

Carrier temperature and high-energy slope of spectrum

- *High energy part of the emission*
  : Boltzmann distribution of carriers

$$I \propto \exp(-h\nu / kT_C)$$

$$\frac{d(\ln I)}{d(h\nu)} \propto \frac{-1}{kT_C}$$

-Carrier temperature increases along with the carrier level

- Upper limit of the carrier temperature

Exponential dependence of the emission intensity on energy

Carrier temperature can be directly inferred from the slope

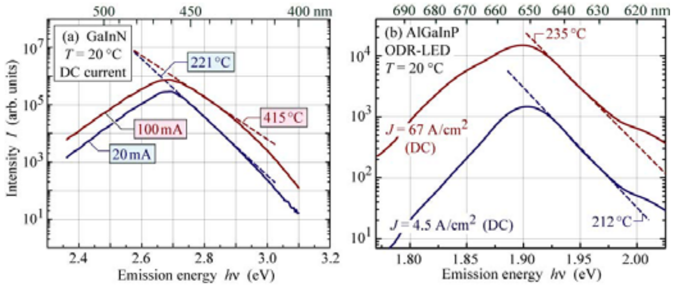

Fig. 6.1. Carrier temperatures in (a) GaInN blue and (b) AlGaInP red LEDs inferred from the high-energy slope of emission spectrum. Due to the alloy-broadening effect, the measured carrier temperatures overestimate the true carrier temperature (after Chhajed *et al.*, 2004; Gessmann *et al.*, 2003).

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Alloy broadening

- ***Alloy broadening***

  : Semiconductor alloys exhibit substantial broadening of the emission spectrum and its high energy slope

  - Statistical fluctuation of the chemical composition in ternary and quaternary semiconductors
  (Schubert et al. 1984)

  - De-convolution of the alloy-broadening effect and kT-broadening effect

  → ***Estimation of accurate T_C***

- ***Determination of T_c using the high slope works***

  : best for binary compounds such as GaAs or InP
  (No exhibition of alloy broadening)

Junction temperature and peak emission wavelength

- ***Dependence of bandgap energy (and thus the peak emission wavelength) on temperature***

- ***Method***

Calibration measurement + **_Junction temperature measurement_**

- ***Calibration measurement : peak energy at different ambient temperature (typically 20 ~ 120 °C) with a range of pulsed currents and a duty cycle <<1***

  → ***Junction-temp. vs. emission-peak-energy for a range of current***

- ***Junction temperature measurement***
  : peak emission energy vs. DC injection current

Junction temperature and peak emission wavelength

- ***The shift of the emission energy with respect to temp is due to the fact that E_G is function of temperature***

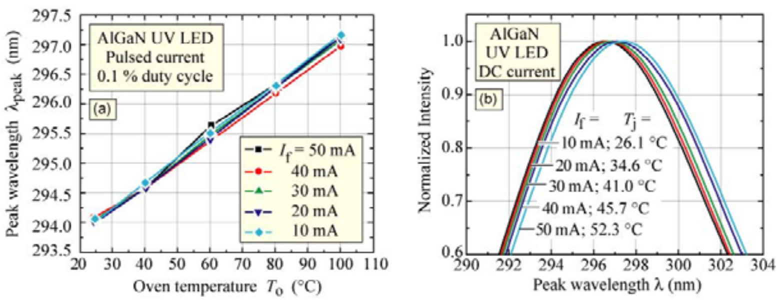

Fig. 6.2. (a) Peak emssion wavelength versus oven temperatureof an AlGaN UV LED for pulsed current injection with 0.1 % duty cycle . (b) Emssion spectra and junction temperatures for different DC currents (after Xi *et al.*, 2004).

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• ***The accuracy of the method is limited by the ability to determine the peak wavelength.***

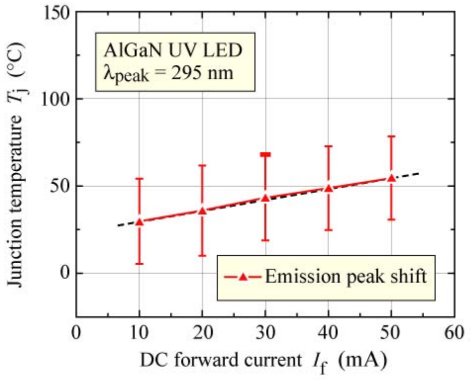

Fig. 6.3. Junction temperature inferred from emission peak energy as a function of DC injection current for a 1 mm × 1 mm deep UV LED emitting at 295 nm. The error bar stems from an uncertainty in the peak energy (after Xi *et al.*, 2004).

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Theory of temperature dependence of diode forward voltage

$$J = J_S\left(e^{eV_f/(n_{ideal}kT)} - 1\right) \qquad J_S = e\left(\sqrt{\frac{D_p}{\tau_p}}\frac{n_i^2}{N_D} + \sqrt{\frac{D_n}{\tau_n}}\frac{n_i^2}{N_A}\right) \qquad n_i = \sqrt{N_C N_V}\, e^{-E_G/2kT}$$

$$N_C = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2}$$

For non-degenerate semiconductors and V_f>>kT/e

$$\frac{dV_f}{dT} = \frac{d}{dT}\left[\frac{n_{ideal}kT}{e}\ln\left(\frac{J_f}{J_S}\right)\right]$$

• ***Saturation current density depends on***

I. Diffusion constants of electrons & holes

II. Lifetimes of electrons & holes

III. Effective density of states at the each band edge

IV. Bandgap energy

all of which depend on the junction temperature

Experimentally -2.3 mV/K for deep-UV LED

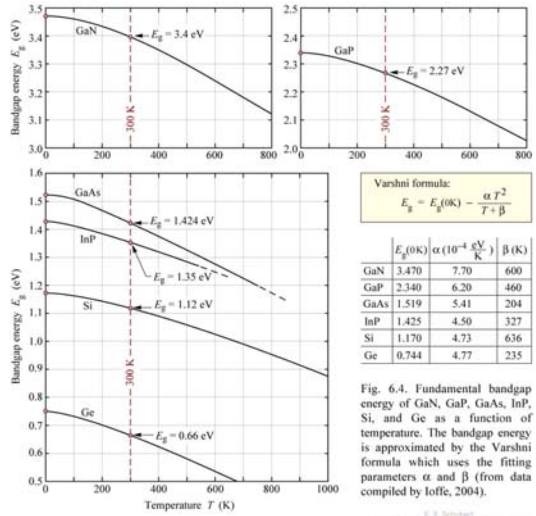
Temperature dependence of the energy gap

Varshni formula (Varshni, 1967)

$$E_g = E_g\Big|_{T=0K} - \frac{\alpha T^2}{T+\beta}$$

α and β : fitting parameters

See Table 6.1



	$E_g(0K)$	α (10^{-4} eV/K)	β (K)
GaN	3.470	7.70	600
GaP	2.340	6.20	460
GaAs	1.519	5.41	204
InP	1.425	4.50	327
Si	1.170	4.73	636
Ge	0.744	4.77	235

Fig. 6.4. Fundamental bandgap energy of GaN, GaP, GaAs, InP, Si, and Ge as a function of temperature. The bandgap energy is approximated by the Varshni formula which uses the fitting parameters α and β (from data compiled by Ioffe, 2004).

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Theory of temperature dependence of diode forward voltage

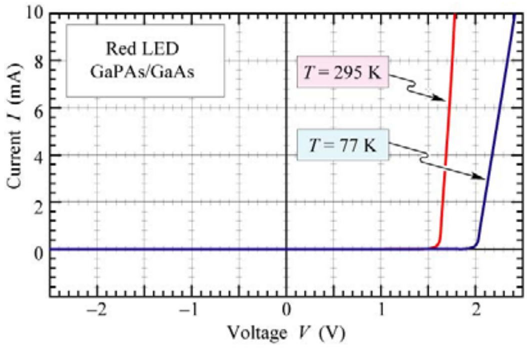

Fig. 6.5. Current–voltage characteristic of GaAsP/GaAs LED emitting in the red part of the visible spectrum, measured at 77 and 295 K. The threshold voltages are 2.0 and 1.6 V, at 77 and 300 K, respectively.

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Series resistance and V_f increase as the diode is cooled

Measurement of junction temperature using forward voltage

V_f calibration measurement under pulsed-current injection

➕

V_f measurement under DC-current injection

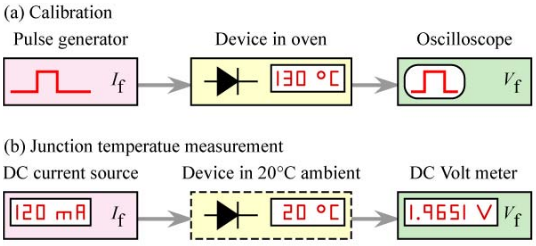

Fig. 6.6. (a) Pulsed calibration procedure establishing the forward voltage versus junction temperature (V_f vs. T_j) relation and (b) determination of junction temperature for different DC forward currents.

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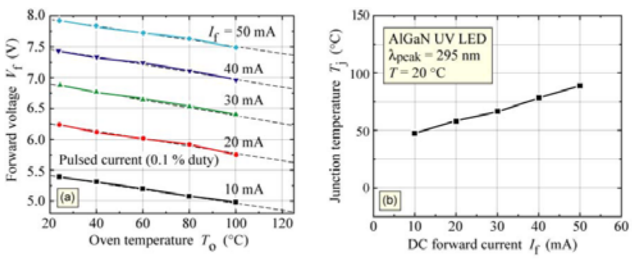
Measurement of junction temperature using forward voltage

- ***V_f calibration***
  - ***Devices in temperature controlled oven (junction temperature is known)***
  - ***Temperature range of 20 ~ 120 °C***
  - ***Pulsed mode with very small duty cycle (e. g. 0.1 %)***
  - ***Heat generated by the injection current becomes negligibly small.***



Relation between V_f and $T_{junction}$ for the I_f level of interest

Fig. 6.7. (a) Pulsed calibration measurement (duty cycle 0.1 %) and (b) junction temperature (T_j) versus DC current of an AlGaN UV LED (after Xi *et al.*, 2004)

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Measurement of junction temperature using forward voltage

- ***Junction temperature measurement***

  1. ***Room-temperature ambient***
  2. ***Series of DC current***
  3. ***Forward voltages are measured once thermal steady state has been reached.***
  4. ***Measured DC forward voltages and calibration measurement data***

→ ***Junction temperature for different current level***

- ***Accurate to within a few degrees***
- ***More accurate than the peak-wavelength method***

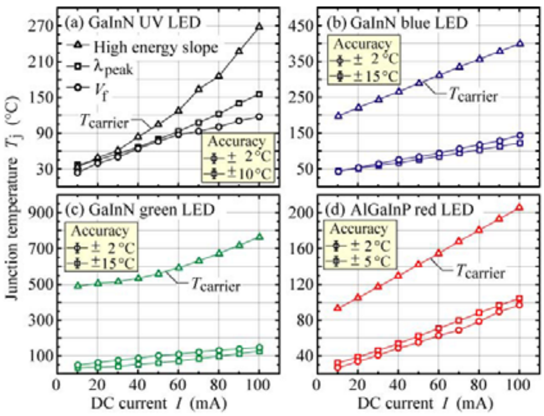

Fig. 6.8. Junction and carrier temperature of devices packaged in conventional 5 mm packages as a function of DC injection current. The measured carrier temperature over-estimates the true carrier temperature due to alloy broadening (after Chhajed *et al.*, 2004).

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Constant-current and constant-voltage DC drive circuits

- *Constant-voltage supply*
  : Battery or the rectified AC output of a transformer
  - *Two drawbacks*
    - *I. The diode current depends exponentially on the voltage,*
      → small variation in the voltage results in a large current change.
    - *II. Threshold voltage of a diode depends on temperature*
      → any temperature change results in a significant current change
- *At constant current, the emission intensity decreases with increasing temperature.*
- *A constant-voltage with series resistance can be used to reduce the temperature dependence of emission intensity*

Constant-current and constant-voltage DC drive circuits

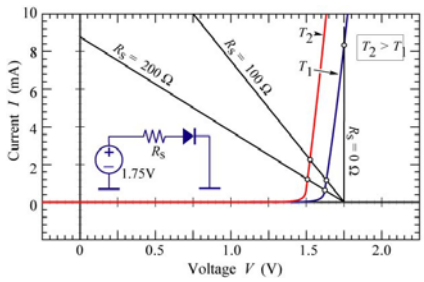

Fig. 6.9. LED drive circuit with series resistance R_S. The intersection between the diode I–V characteristics and the load lines are the points of operation. Small series resistances result in an increased diode current at high temperatures, thus allowing for compensation of a lower LED radiative efficiency.

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- *At high temperature : The emission intensity of LEDs ↓ (higher non-radiative recombination probability)*
- *Threshold voltage decreases with increasing temperature*
- *For a constant-voltage supply, diode current increases as the temperature increases.*

➡ *Series resistor can be used to compensate for the emission intensity decreases at elevated temperature*

Constant-current and constant-voltage DC drive circuits

- *The temperature dependence of LED intensity*
  : important factor for LEDs used in outdoor applications
  - ◆ *Hot summer day*
    - *Temperature and ambient light intensity are high*
    - *LED intensity drop due to high temperature*
    - *High required brightness to overcome high ambient light level*

→ *This effect can be compensated for by driving the LEDs with a higher current as the temperature increases.*

- *Constant-current drive circuit*
  - *Transistor with the LED as a load*
  - *Constant-current drive circuit does not compensate for the decrease of LED emission at elevated temperatures.*