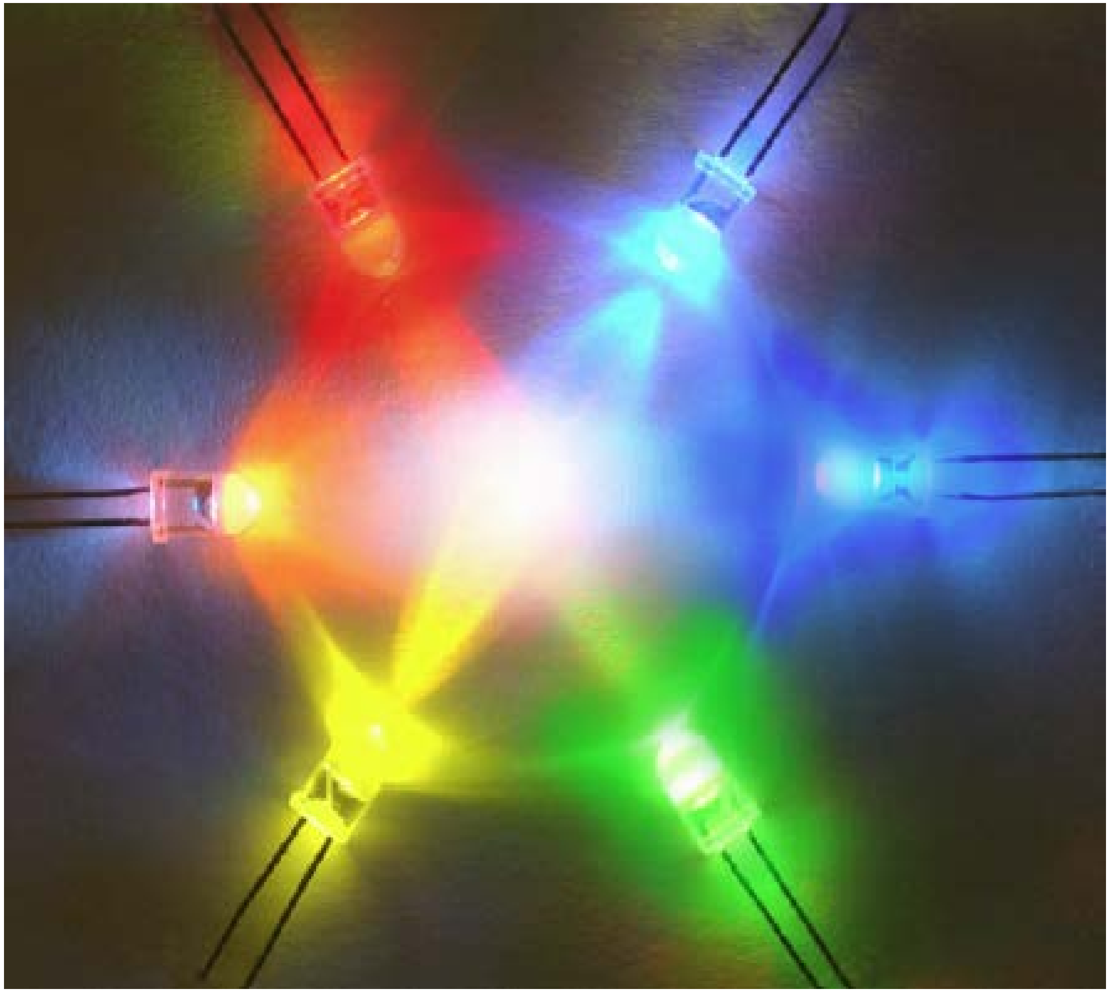
Light Emitting Diodes

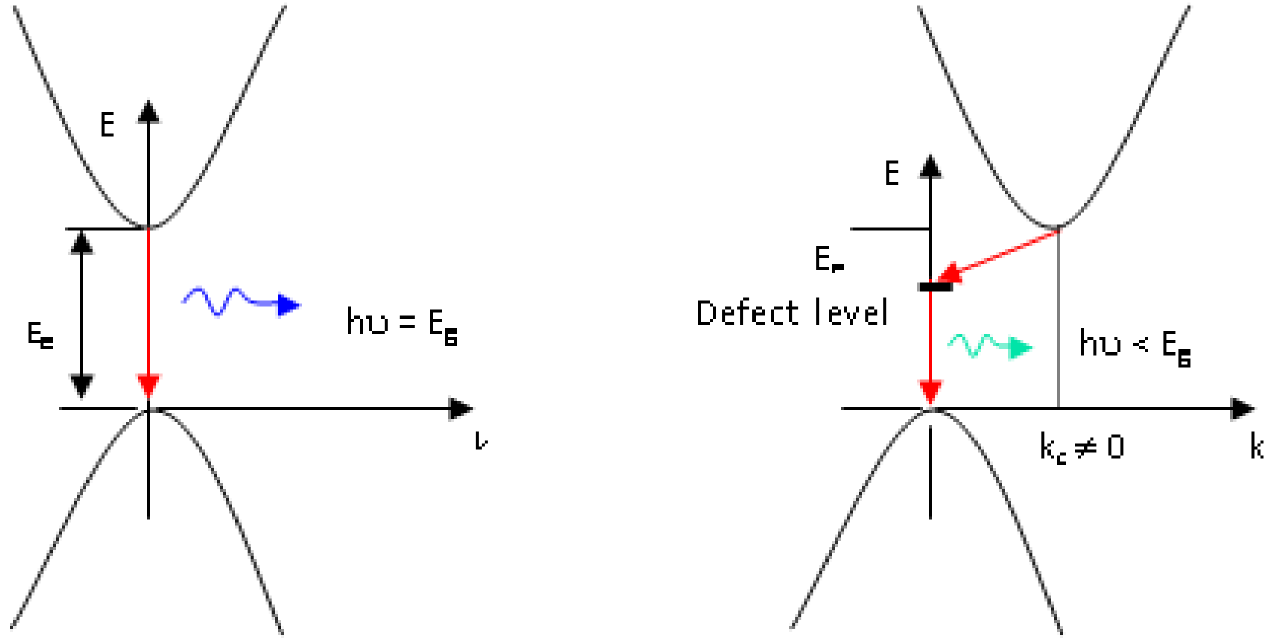


WWW.LIGHTEMITTINGDIODES.ORG

OPTI 500 A FALL 2012, LECTURE 8

Light Emission from Semiconductor

- Spontaneous radiative transition in direct bandgap semiconductors generate light ~ $E_c - E_v = h\nu$



(a) Direct Bandgap (b) Indirect Bandgap

Fig. 1. E - k diagram of direct and indirect bandgap semiconductors

- Direct Bandgap – GaAs and most III-V compounds (not GaP)
- Indirect Bandgap – diamond (B- doped diamond is a semiconductor), Ge, Si SiC
- Injected electrons and holes in direct bandgap semiconductors p-n junction diodes recombine radiatively in the transition region between p- and n-sides.

Light Emission from Semiconductors

- Silicon Carbide semiconductor [Ref: E. Fred Schuber "Light-Emitting Diodes" Second Edition, Cambridge University Press, Cambridge, 2006]

  - 1907 First observation of light from carborandum crystallites – SiC abrasive powder – Yellow light

  - Point contacts 10 – 110 V

  - 1960 High quality crystals p-n junction diodes, emission – 430/475 nm

  - SiC – indirect bandgap material

  - Low efficiency

Light Emission from Semiconductors

- Gallium Arsenide
  - Single crystal films
  - Infrared emitter
- Gallium Arsenide Phosphide
  - Red/orange/yellow/green with isoelectronic N dopant
- Gallium Nitride
  - Blue/violet/ultraviolet emission using metal semiconductor contacts
  - Difficulty producing p-type doping at the early stages
  - Electron beam irradiation and post deposition anneal of Mg doped films contributed to p-type activation

Light Emission from Semiconductors

- Aluminum Nitride/Gallium Nitride/Indium Nitride
  - Alloying above systems a suitable bandgap could be produced enabling almost any color from UV – Red

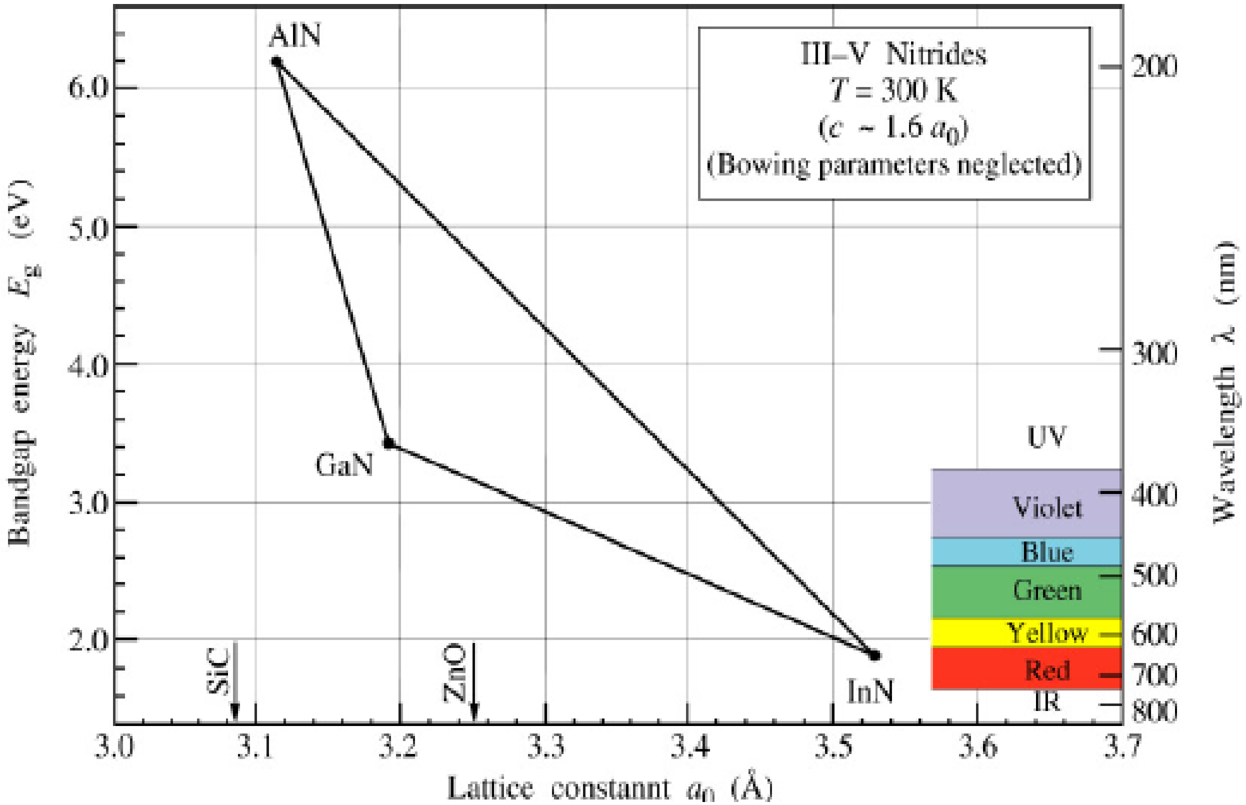


Fig. 2. Bandgap as a function to alloy composition/lattice constant
GaN(3.4 eV) + InN/AlN => E_g = 1.9 – 6.2 eV (λ = 652 – 200 nm)
[Ref: Schubert, 2006]

LED Structures

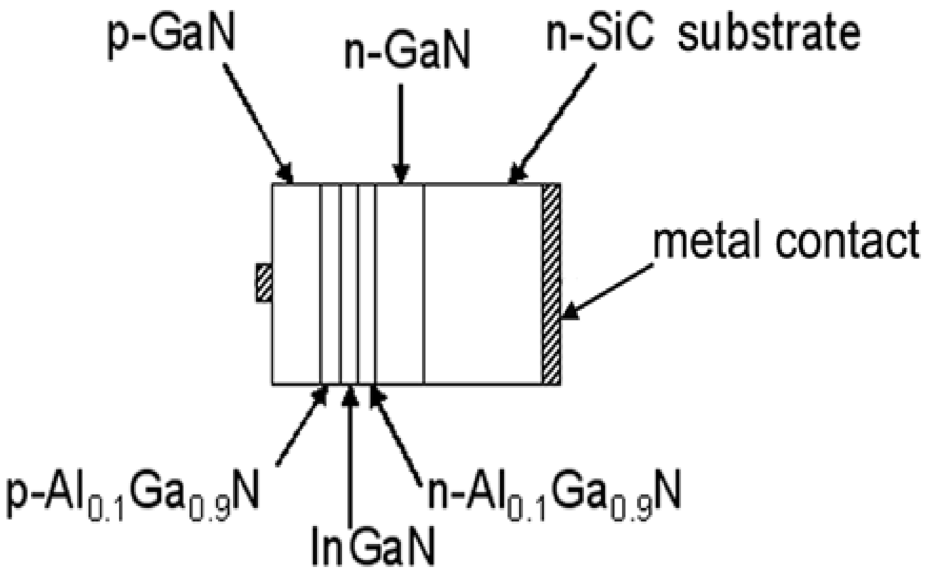
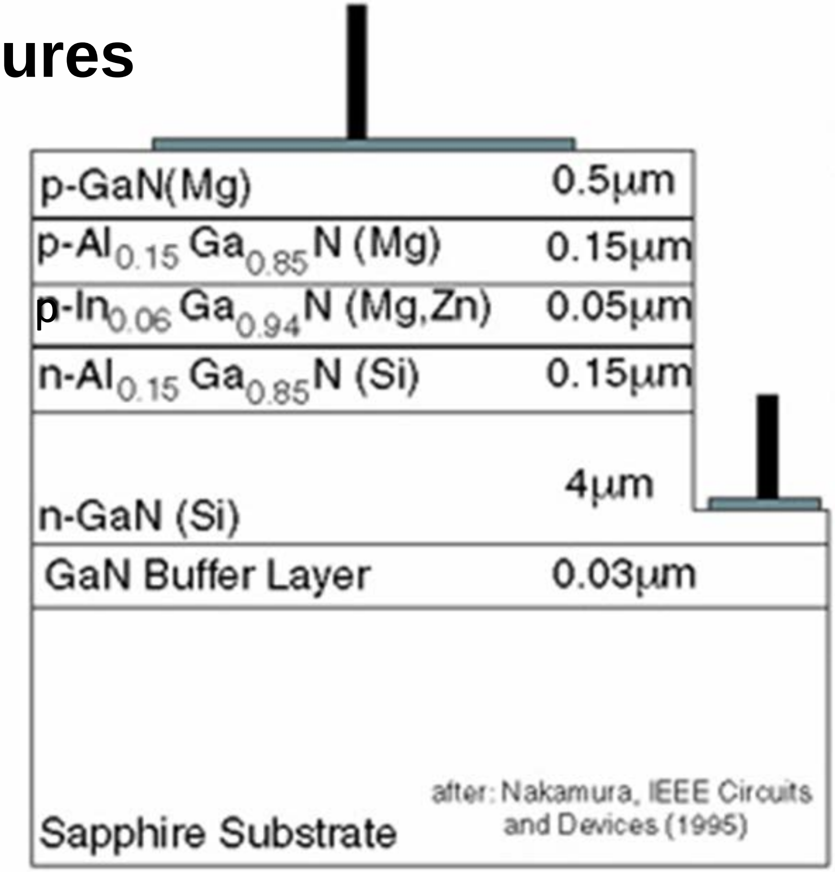


Fig. 3. Schematic of a blue emitting LED [Kong et al., Mat. Res. Soc. Proc. 395, 903 (1996)



Single quantum well structure on sapphire substrate

Schematic Band Diagrams for LED Structures

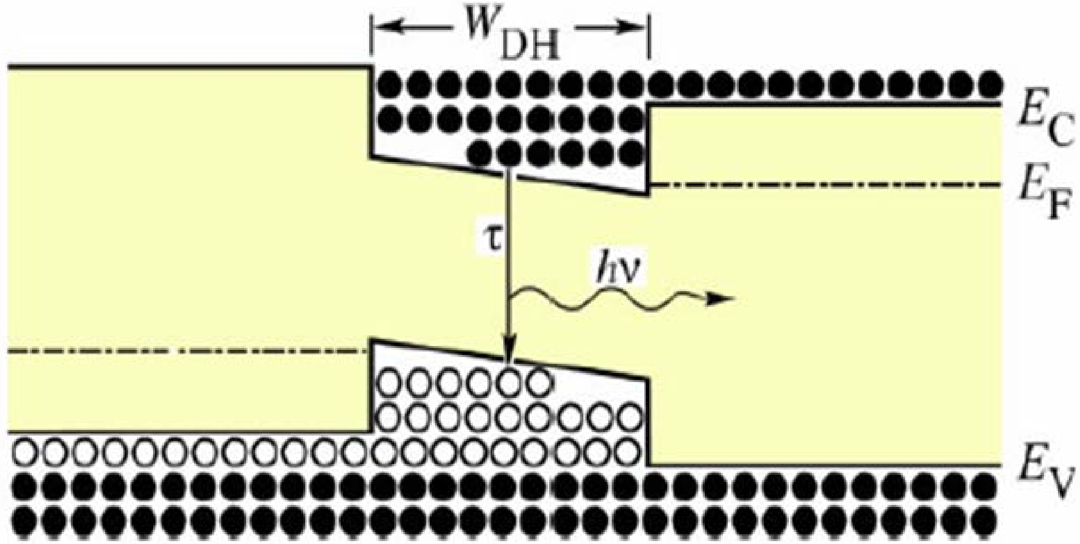


Fig. 4. Double heterojunction structure

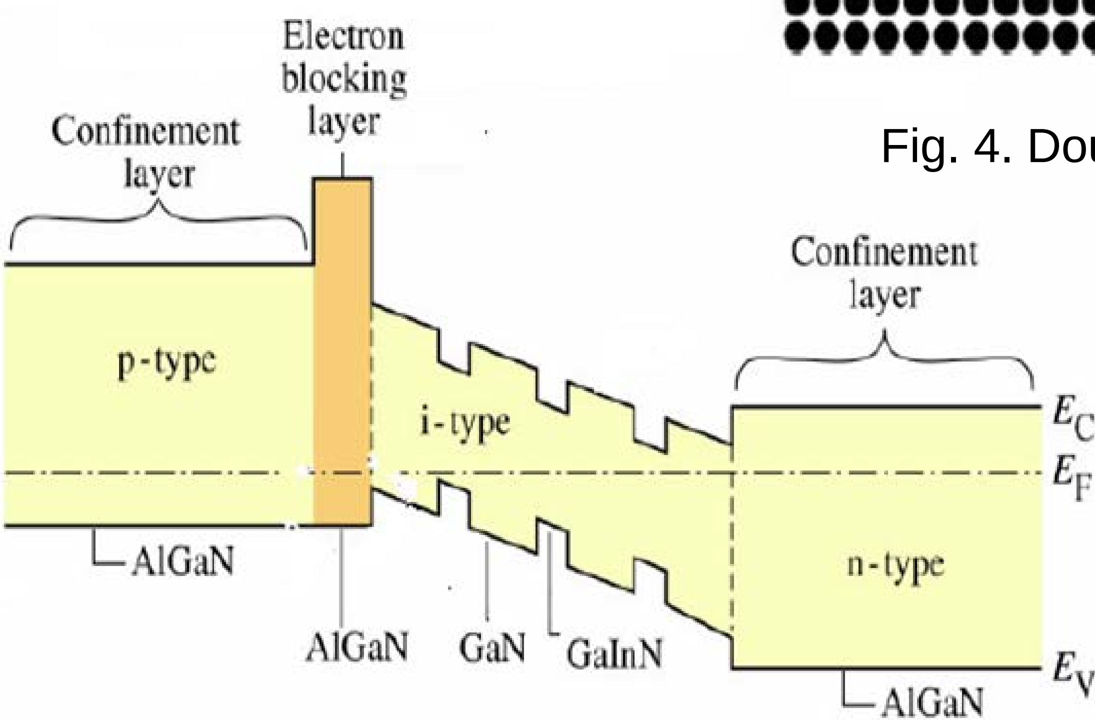


Fig. 5. Multiple Quantum well LED structure [Schubert, 2006]

Fabrication

- Metallorganic Chemical Vapor deposition [Ref: S. Nakamura, S. Pearton and G. Fasol, “The Blue Laser Diode: The Complete Story, Second edition, Springer-Verlag, Berlin, 2000].

- Heteroepiaxial deposition on sapphire or 6H-SiC substrates 6H-SiC provides a better lattice match also provides back metal contact

- Indium content in the active layer varied to obtain desired color emission, Zn introduced as a dopant

Electrical Characteristics

- Diode forward current

  - $I_f = I_0$ (eqV/nkT –1),

- I_0 is the saturation current,

  - $I_0 = (qD_p n_i^2)/(N_D L_p) + (qD_n n_i^2)/(N_A L_n)$,

Where:

- q = electronic charge,

- D_p and D_n = hole and electron diffusion coefficient,

- n_i = intrinsic carrier concentration,

- L_p and L_n = hole and electron diffusion length, and

- n = ideality factor, determined from a semilogarithmic plot

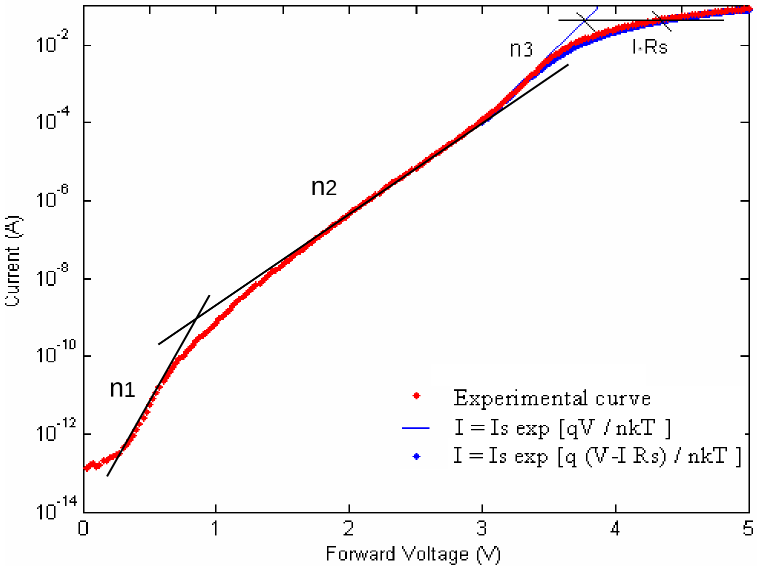
  - $n = (q/kT)(V_2 – V_1)/(\ln I_2 – \ln I_1)$

- n = 1, for an ideal diode, forward current is controlled by carrier diffusion

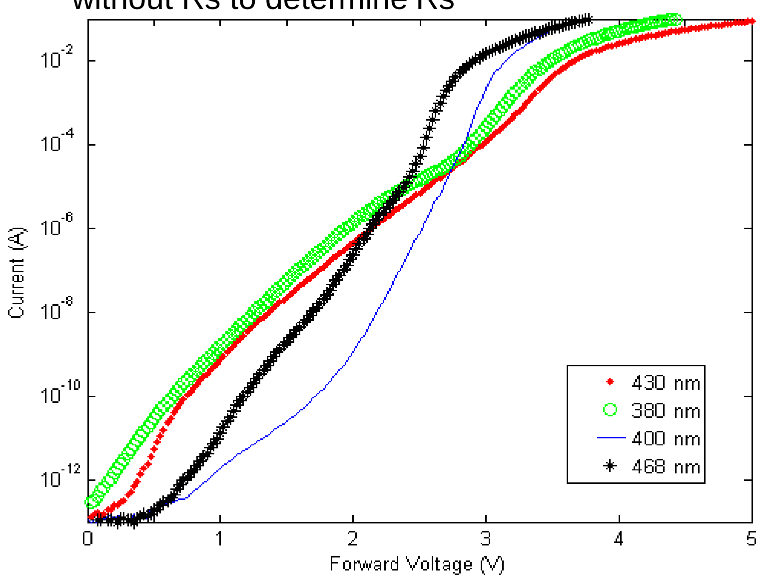
- n = 2, forward current is dominated by SRH recombination process.

Experimental Results

I-V measurements



(a) Semi-log plot of 430nm LED showing linear regimes & corresponding 'n' & the fit with Rs & without Rs to determine Rs



(b) Semi-Logarithmic plots of all LEDs

Diode Forward current relationship,

$$I = I_s \exp [q (V - I R_s) / nkT]$$

I_s - Saturation current, n - ideality factor

n = 1, diffusion current

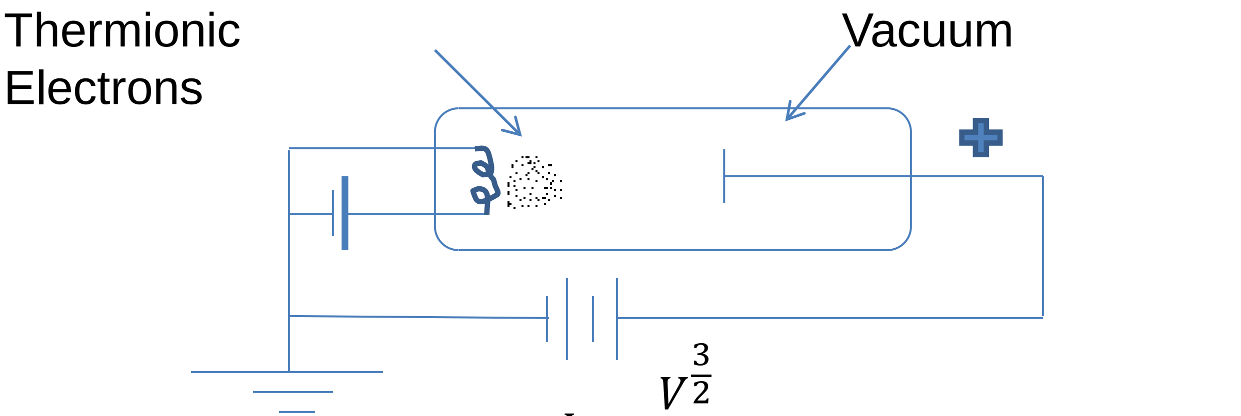
n = 2, recombination current

n > 2, Space Charge Limited

Table: Reverse current, Optical turn-on voltage, forward voltage for 20 mA of drive current, Series Resistance and Ideality factor

LED (nm)	I_r at -1V (A)	V_{OTO} (V)	V_f at 20 mA (V)	R_s (Ω)	Ideality factor (n3) Voltage range (V)
380	1.64x10-11	3.19	3.65	7.63	4.51 (2.80<V<3.35)
400	1.11x10-12	2.74	3.27	5.19	2.05 (2.80<V<3.05)
430	2.51x10-12	2.98	3.90	13.63	4.94 (3.10<V<3.55)
468	1.90x10-13	2.47	3.07	7.29	2.00 (2.40<V<2.70)

Space Charged Limited Current



$$J \propto \frac{V^{\frac{3}{2}}}{L^2}$$

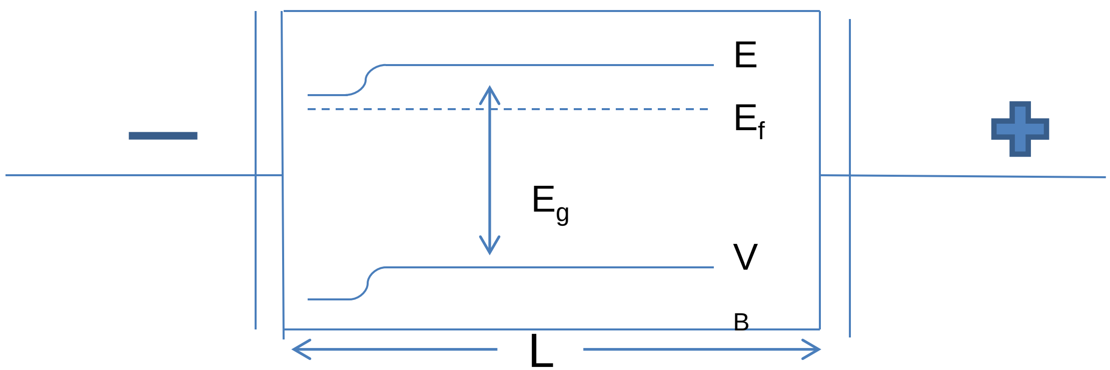


Figure b) Insulator

$$J \propto \frac{V^2}{L^3}$$

Space Charge Limited Current

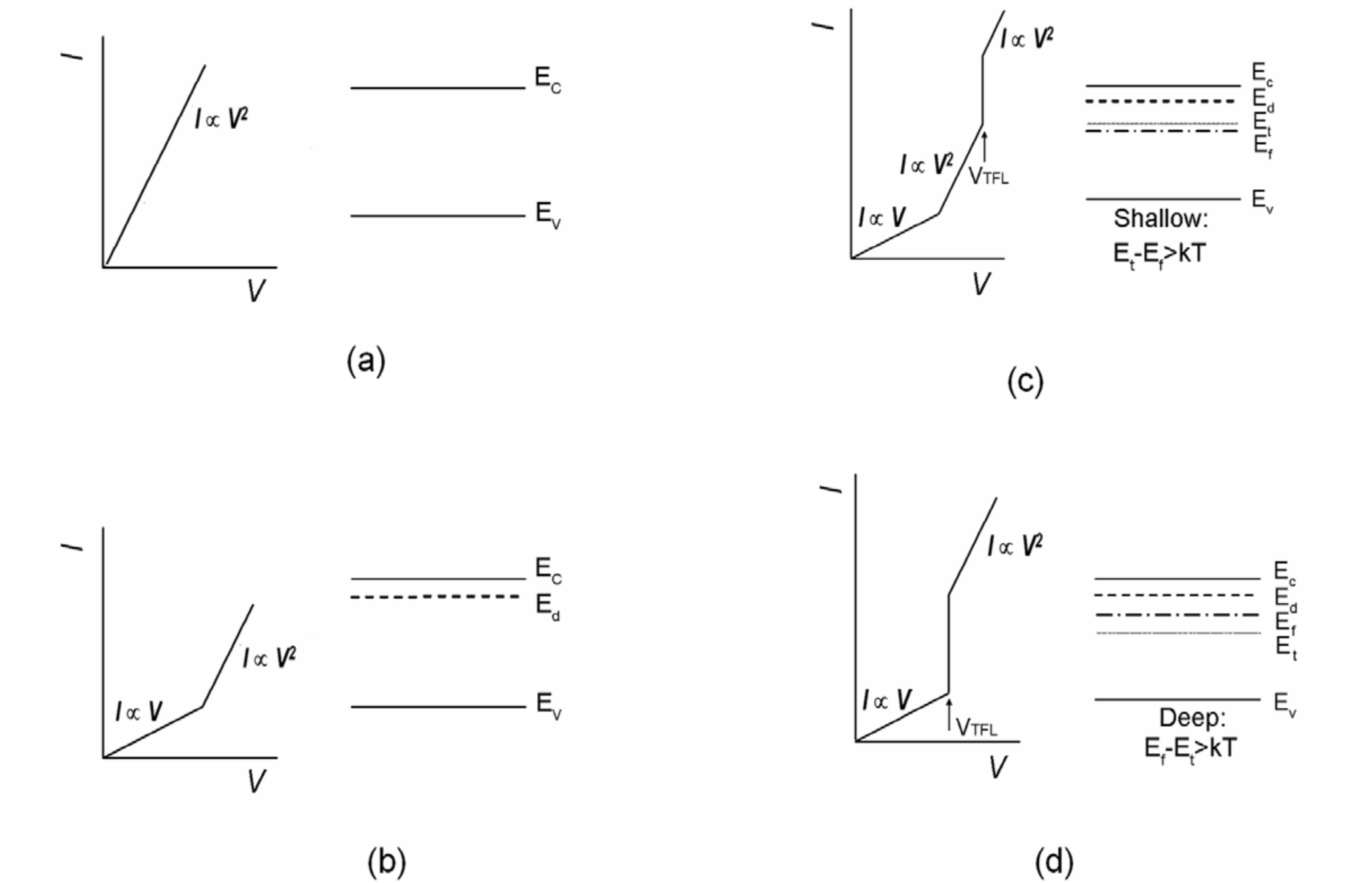


Fig. Schematic space charge limited current (SCLC) I-V characteristics. (a) Ideal insulator, (b) Insulator with thermally generated carriers, (b) insulator with thermally generated carriers, (c) Insulator with “shallow” traps, and (d) Insulator with “deep” traps.

Space Charge Limited Current

- For insulators free from any trapping states
  - $J_{Sclc} \propto V^2$
- Approximate expression for SCL current
  - $Jsclc \sim \varepsilon\varepsilon_0\mu(V^2/L^3)$,
- [$Q = CV$, $J = Q/t$, $C = \varepsilon\varepsilon_0/L$, $t = L/v$. $v = \mu E$, and $E = V/L$,

An exact expression for the SCL current will have a numerical factor of 9/8

- thermally generated carriers, n_o
  - $J_{th} = qn_o\mu\ (V/L)$.
- When J_{th} => J_{Sclc}, J approaches ohmic to, $J \propto V^2$, at
  - $V_x = qn_oL^2/\varepsilon\varepsilon_o$
- In the presence of deep traps
  - $Q(V_{TFL}) = qp_{t0}L$
  - $V_{TFL} = qp_{t0}L^2/\varepsilon\ \varepsilon_0$
- where p_{t0} is the density of unoccupied traps, alternatively traps occupied by holes

[Ref: M. A. Lampert and P. Mark, “Current Injection Solids”, Academic Press, New York, (1970)].

Space Charge Limited Current

- $J(2V_{TFL})/J(V_{TFL}) \sim p_{t0}/n_0$;

- p_{t0} may be determined from the experimentally determined V_{TFL},

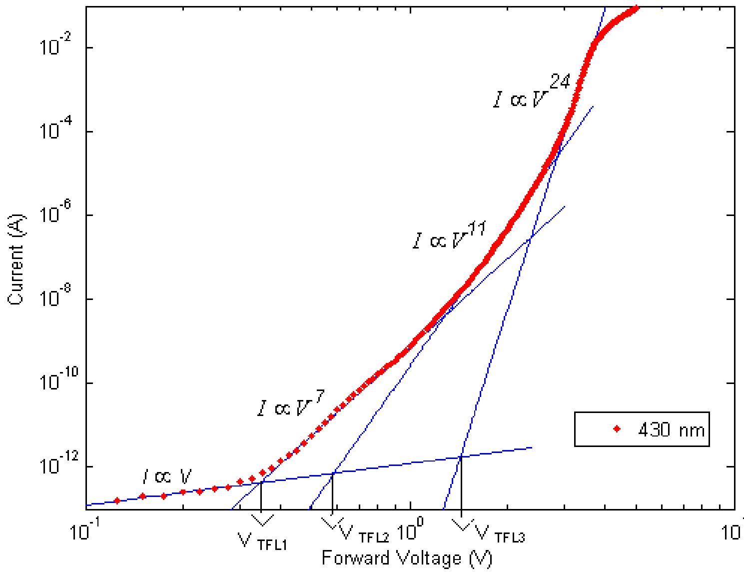
- $n_{0,}$ from the observed $J(2V_{TFL})/J(V_{TFL})$ ratio.

- From n_0, the effective Fermi level, E_f (the quasi-Fermi level), can be calculated from

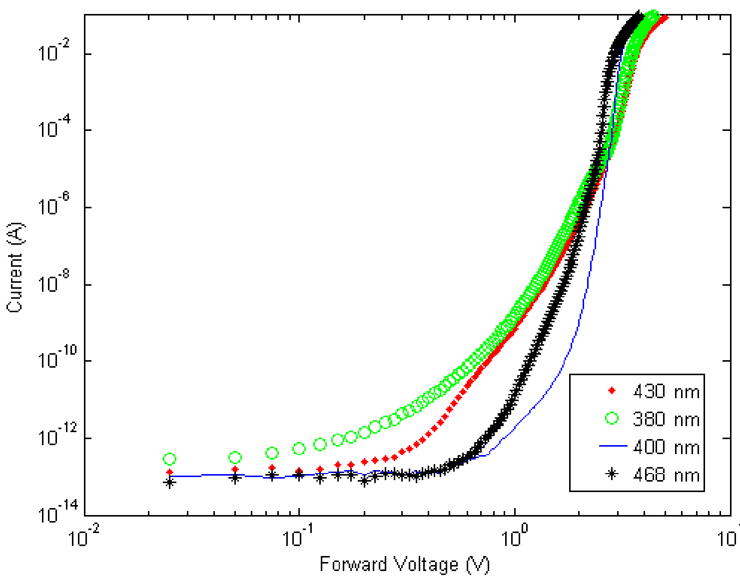
$$n_0 = N_c \exp\left[-(E_c - E_f) / kT\right].$$

- E_f is the approximate position of the deep trap

I-V measurements results



(a) Logarithmic plot of 430nm diode indicating different power-low regimes



(b) Logarithmic plots of all LEDs

Trap-filled-limit voltage, $V_{TFL} = qn_{t0}w^2/\varepsilon$

Effective hole concentration in the active region,

$$p_0 = n_{t0}\, I(V_{TFL}) / I(2V_{TFL})$$

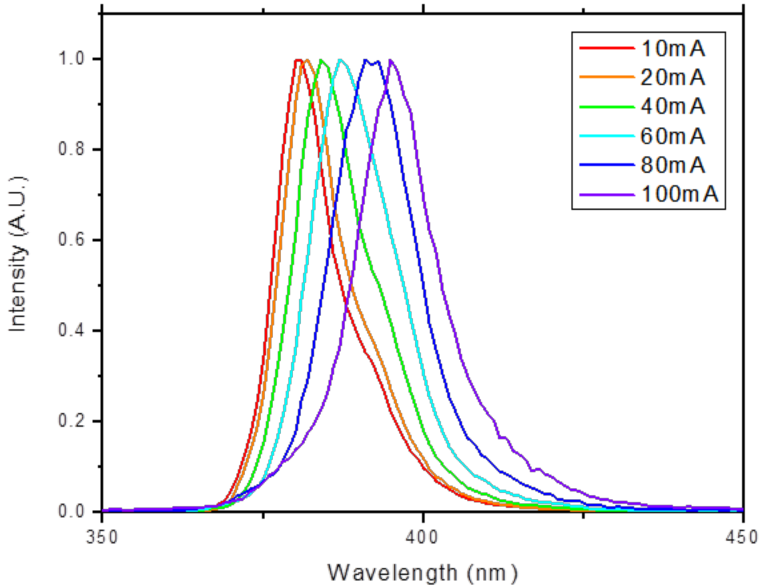
Energy level , $E_t\text{-}E_v = kT \ln [N_v/p_0]$

ε -permittivity, n_{t0}-density of unoccupied traps

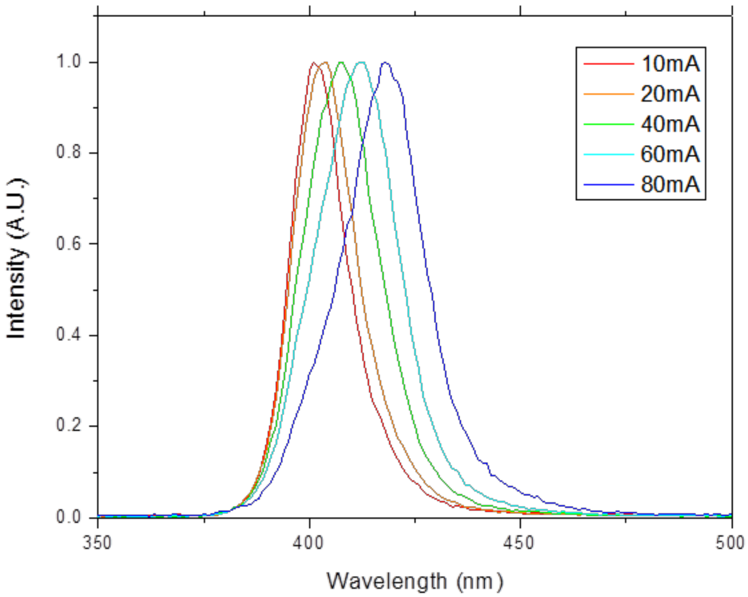
Table : Deep level state parameters

LED (nm)	V_{TFL} (V)	n_{to} (cm^{-3})	p_o (cm^{-3})	Et-Ev (eV)
380	0.27	2.63×10^{16}	7.89×10^{14}	0.26
	0.60	5.84×10^{16}	3.15×10^{13}	0.34
	1.48	1.44×10^{17}	4.61×10^{09}	0.57
400	0.75	2.66×10^{16}	3.78×10^{14}	0.28
	1.64	5.81×10^{16}	2.18×10^{06}	0.77
	1.90	6.73×10^{16}	5.72×10^{05}	0.80
430	0.35	4.35×10^{16}	2.84×10^{14}	0.29
	0.59	7.34×10^{16}	1.71×10^{13}	0.36
	1.43	1.78×10^{17}	5.50×10^{09}	0.57
468	0.75	2.86×10^{17}	2.86×10^{13}	0.35
	1.07	4.08×10^{17}	1.30×10^{11}	0.49
	1.68	6.41×10^{17}	7.66×10^{06}	0.74

Electroluminescence Spectra



(a) LED emitting at 380 nm

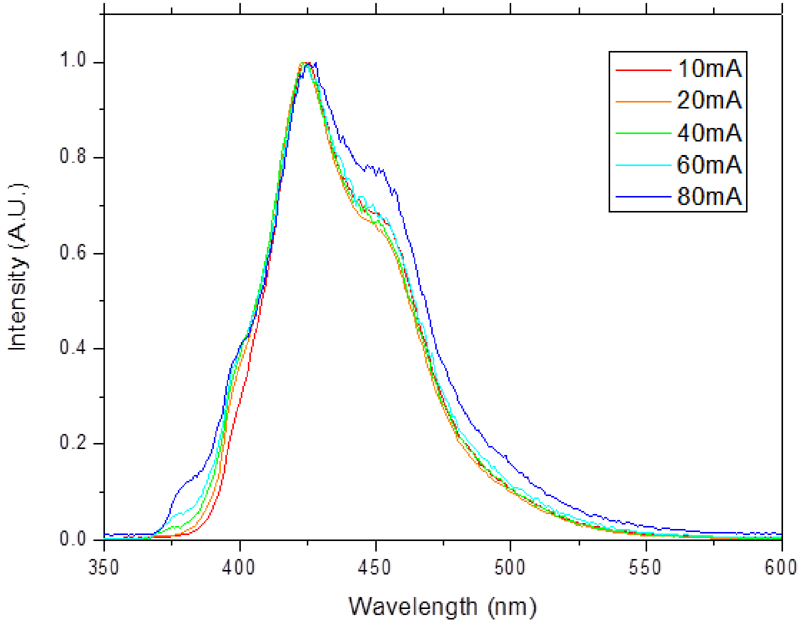


(b) LED emitting at 400 nm

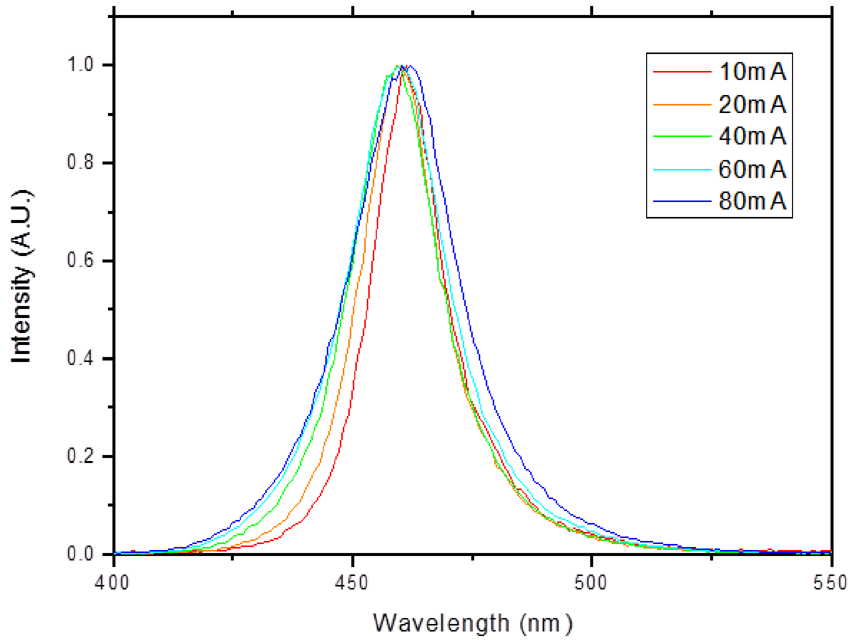
LED (nm)	Peak position (nm)	Peak shift with drive current (nm)	Radiative process/ Recombination via trap state (eV)	Comparable trap level from I-V measurement
380	381 (10 mA) Shoulder 392	395 (100 mA)	band-edge E_t-E_v = 0.010	Shallow trap ($I \propto V^2$)
400	399 (10 mA)	420 (80 mA)	band-edge	

$$\lambda = 1.24/E_g\ (\mu m)$$

Electroluminescence Spectra Results



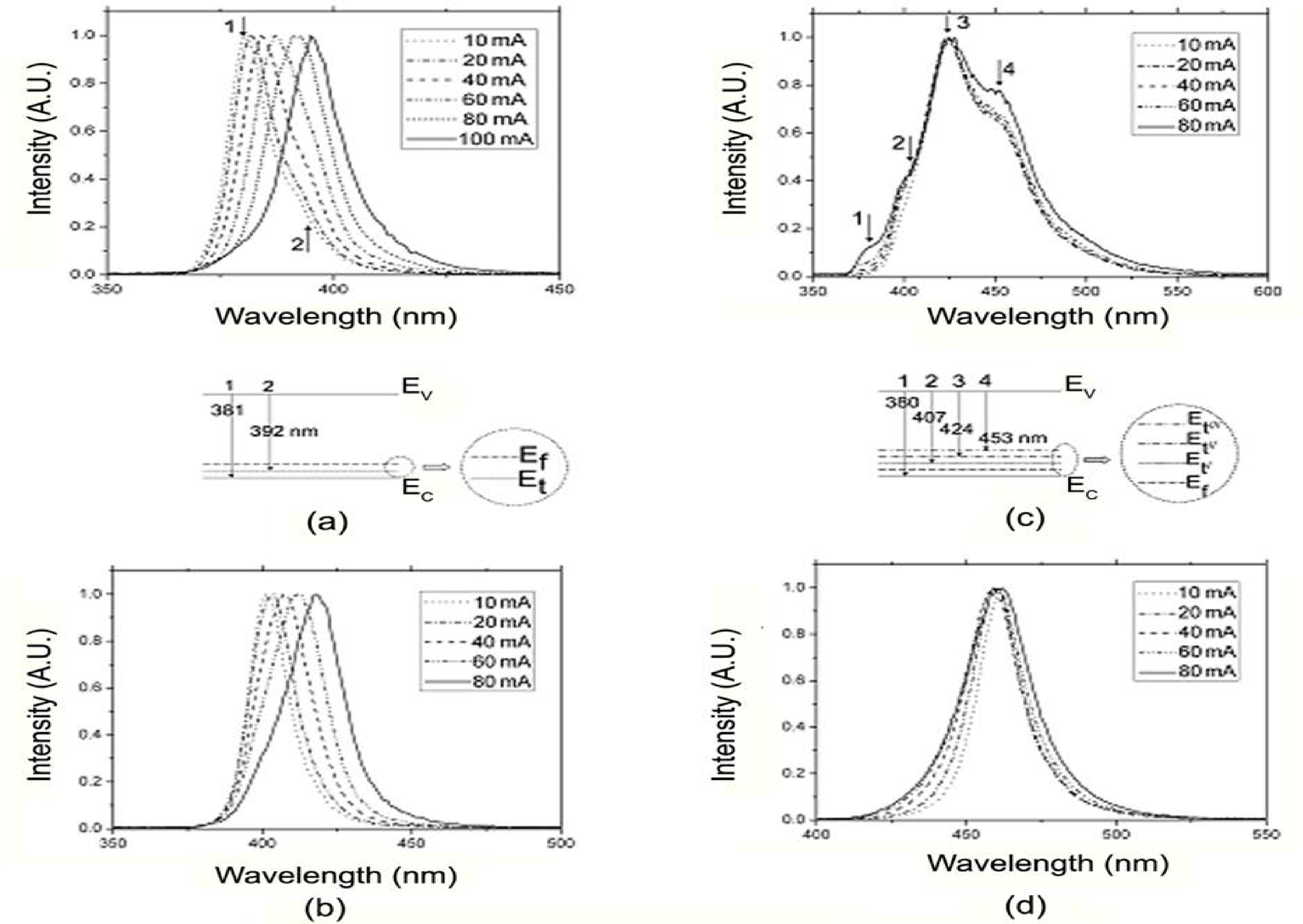
(c) LED emitting at 430 nm



(d) LED emitting at 468 nm

LED (nm)	Peak position (nm)	Peak shift with drive current (nm)	Radiative process/ Recombination via trap state (eV)	Comparable trap level from I-V measurement
430	424 (10 mA) - major 407 453 380 (80 mA)	no peak shift - - -	E_t-E_v = 0.34 E_t-E_v = 0.21 E_t-E_v = 0.52 band-edge	E_t-E_v = 0.36 E_t-E_v = 0.29 E_t-E_v = 0.57
468	459	~ no peak shift	band-edge	

Emission Spectra from Blue LEDs: Effect of Deep States in the Spectra



[Ref: Nana et al. Phys. Status Solidi **A 207**, 1489-1496 (2010)]

Summary

- Gallium indium nitride based LEDs contributed high intensity monochromatic emission over the entire visible spectral range.
- White light sources have been obtained using suitable phosphors broadening emission peaks or multiple quantum wells with varying In content.
- The material system still contain deep level states that reduce emission efficiency.
- Conduction, particularly at low biases, occur through space charge limited current.
- LED based light sources are expected to dominate the general illumination field.

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Power Point Slide Preparation

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