Theory of Semiconductor Devices
(반도체 소자 이론)

Chapter 14. Light Emitting Diodes

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Light Emitting Diodes

✓ LIGHT EMITTING DIODE (LED)

▪ Basically p-n junction that are designed to produce light via a process called electroluminescence.

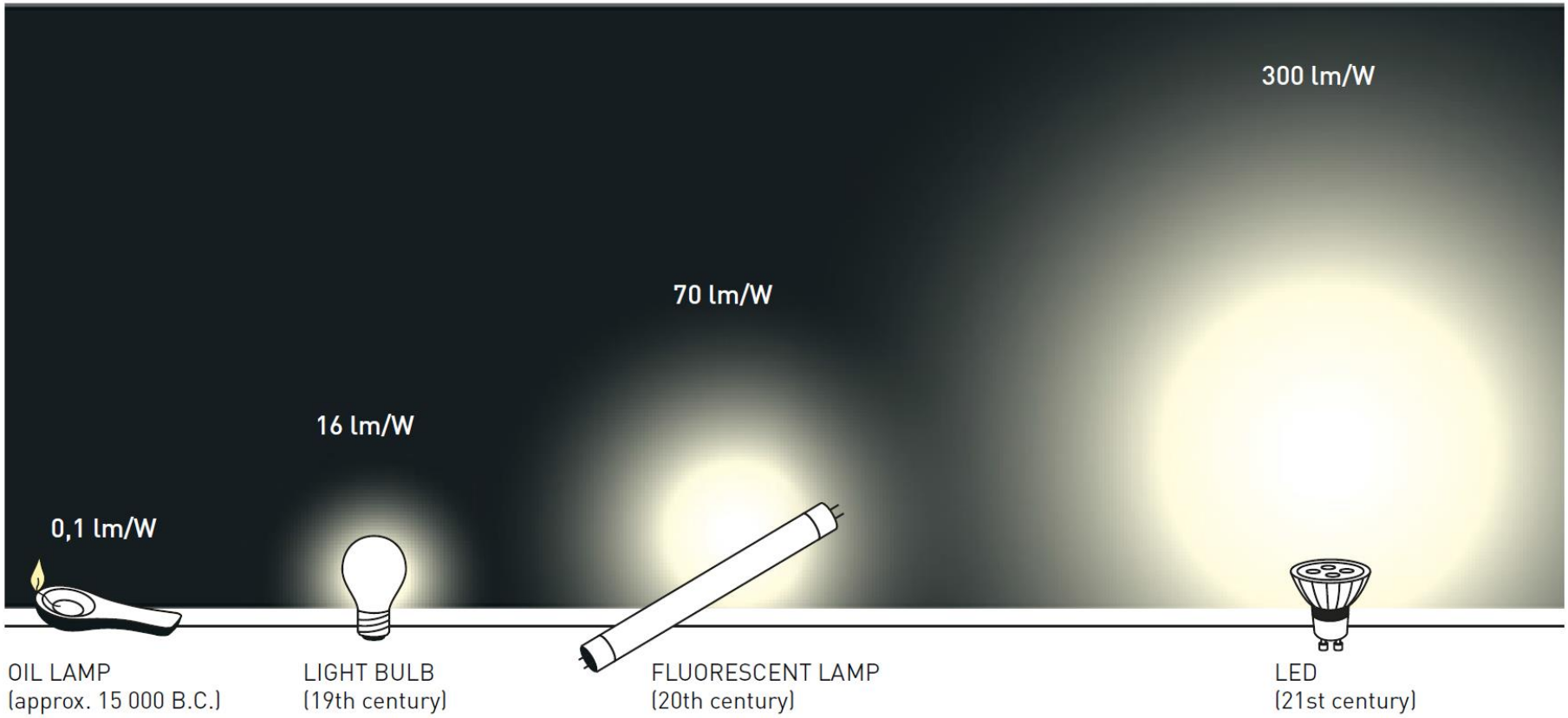
✓ ELECTROLUMINESCENCE

▪ The radiative recombination of injected minority carriers (electrons and holes) in and near the semiconductor p-n junction.

✓APPLICATION OF LED

- In & outdoor display
- Traffic signal
- Automobile indicator
- Solid state lighting
- Agriculture

Light Emitting Diodes



- **40 % electricity savings (261 TWh) in USA in 2030 due to LEDs**

→ **Eliminates the 30+ (1000 MW) power plants by 2030**

→ **Avoids generating ~185 million tons of CO_2**

Light Emitting Diodes

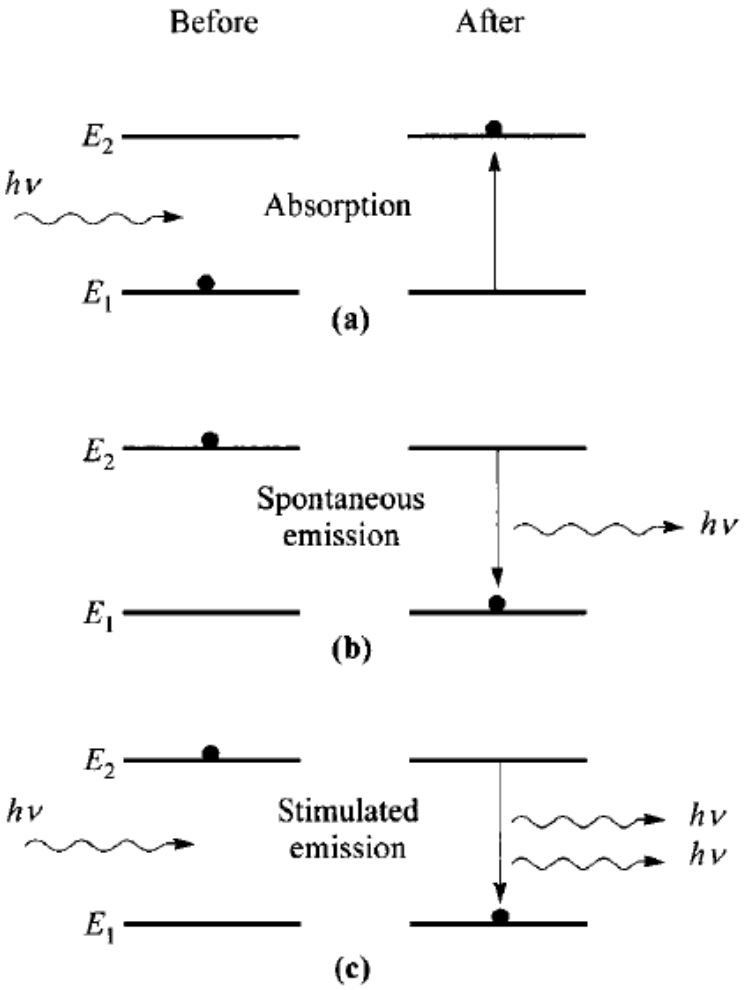


Fig. 3 The three basic optical processes between two energy levels. The black dot indicates the state of the electron. The initial state is at the left; the final state, after the process has occurred, is at the right.

Light Emitting Diodes

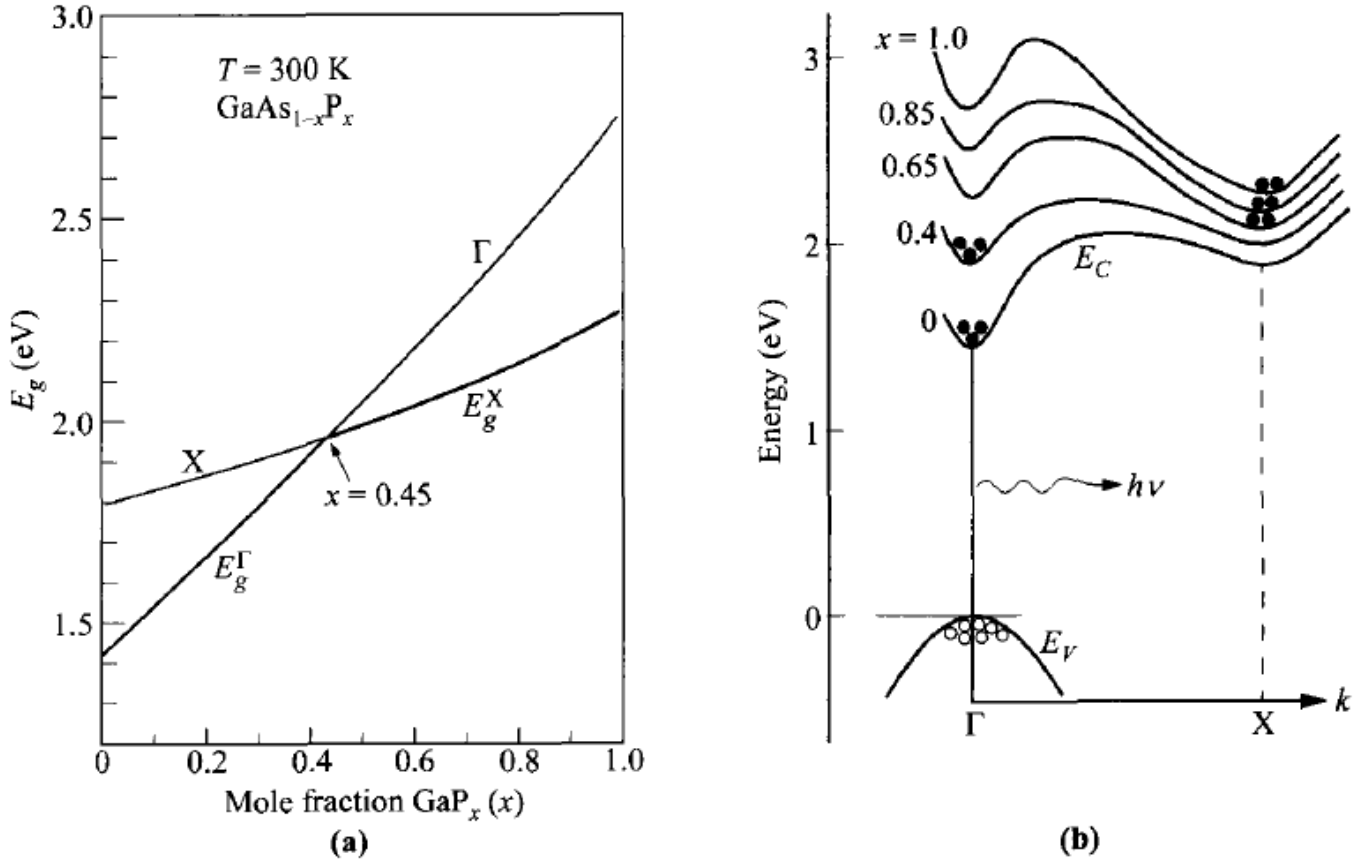
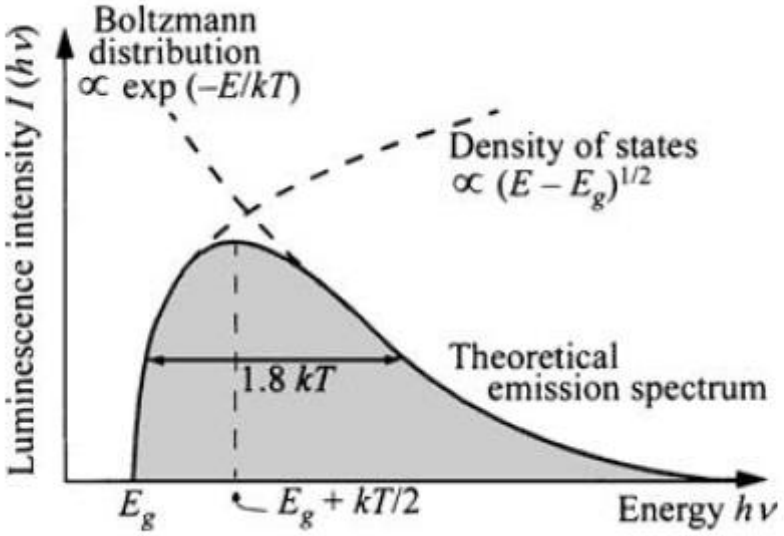
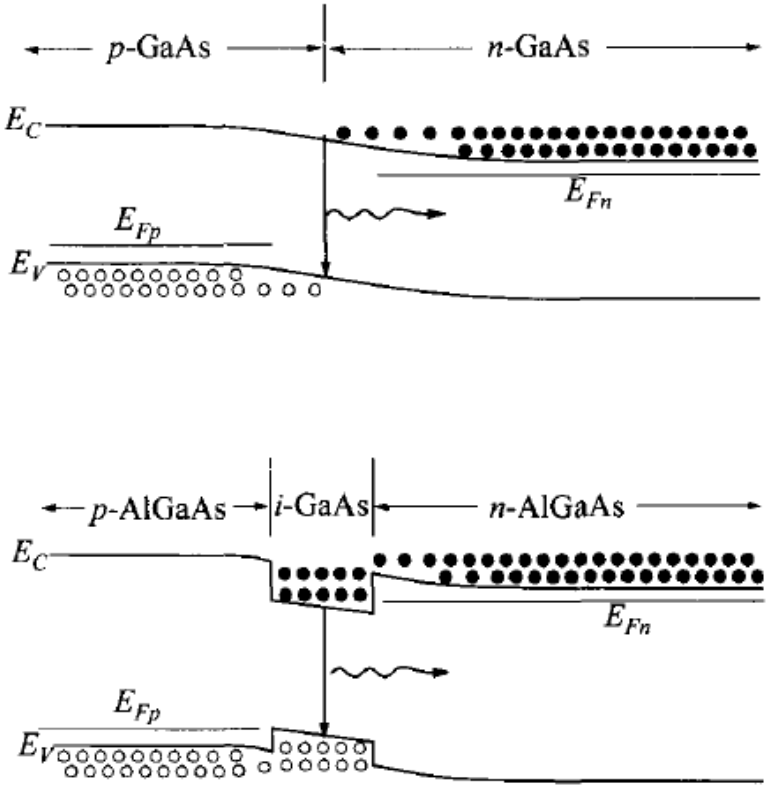


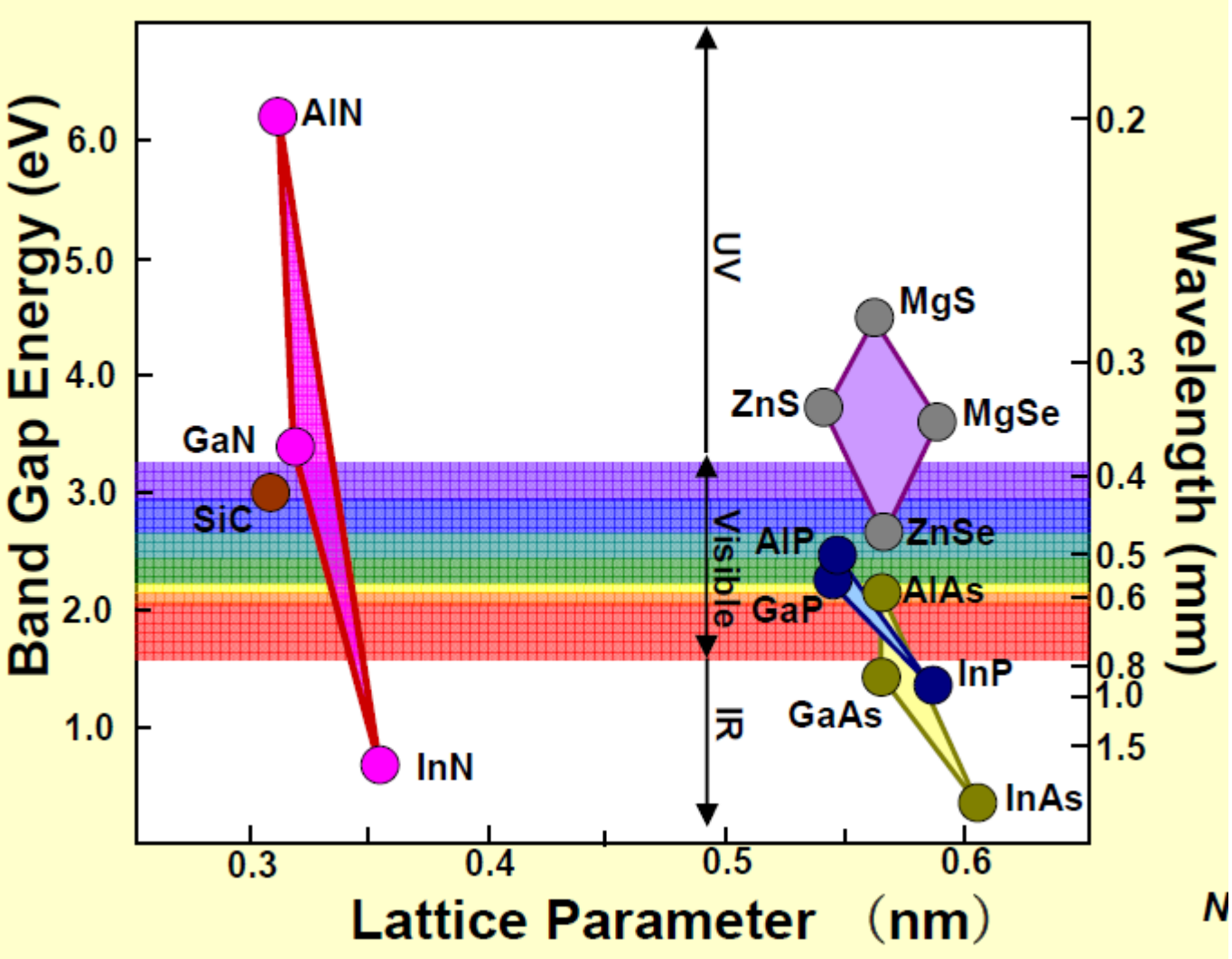
Fig. 4 (a) Composition dependence of the direct and indirect bandgap for $GaAs_{1-x}P_x$. (After Ref. 4.) (b) Energy-momentum diagram for $GaAs_{1-x}P_x$. (After Ref. 5.)

Light Emitting Diodes

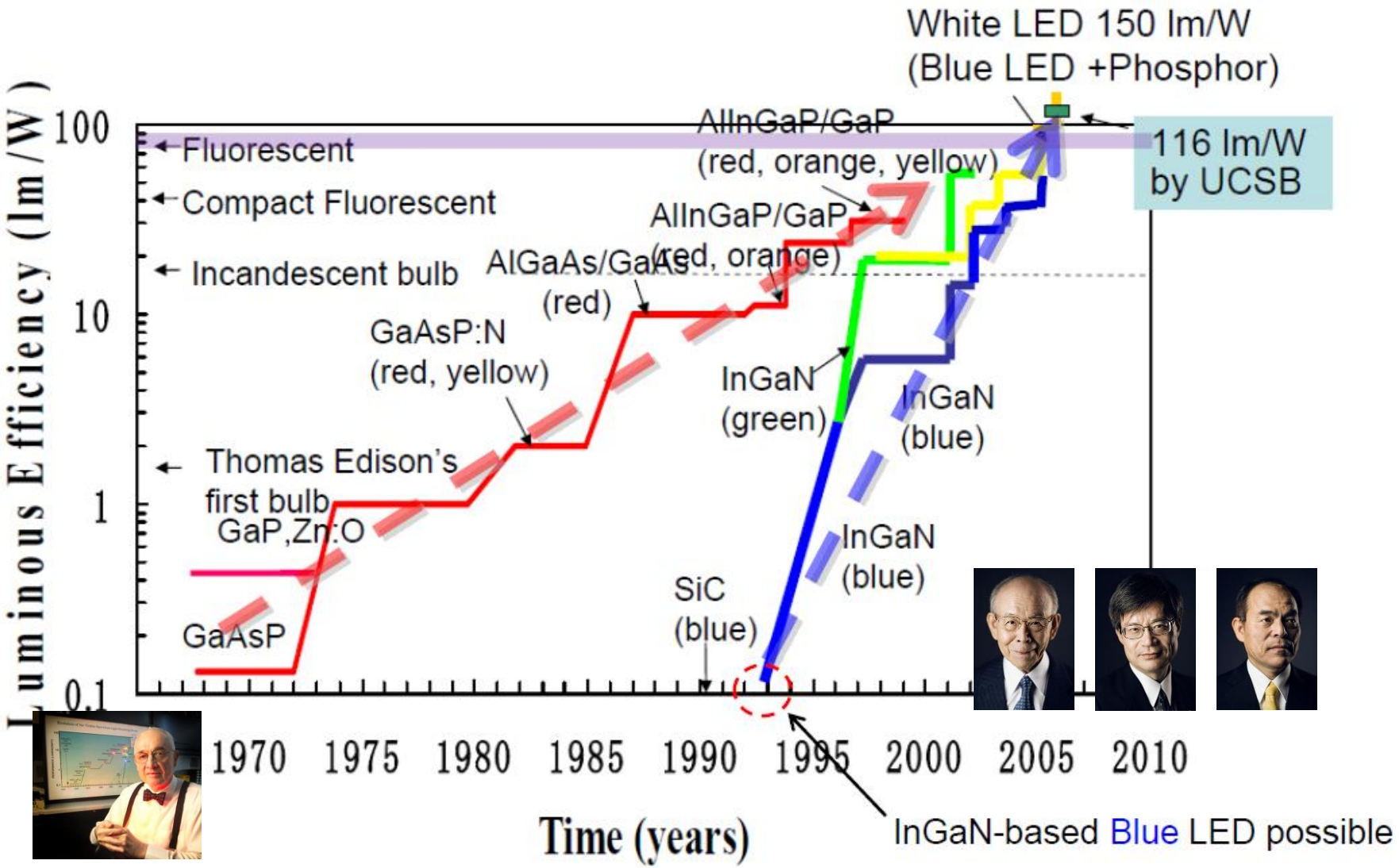




Light Emitting Diodes



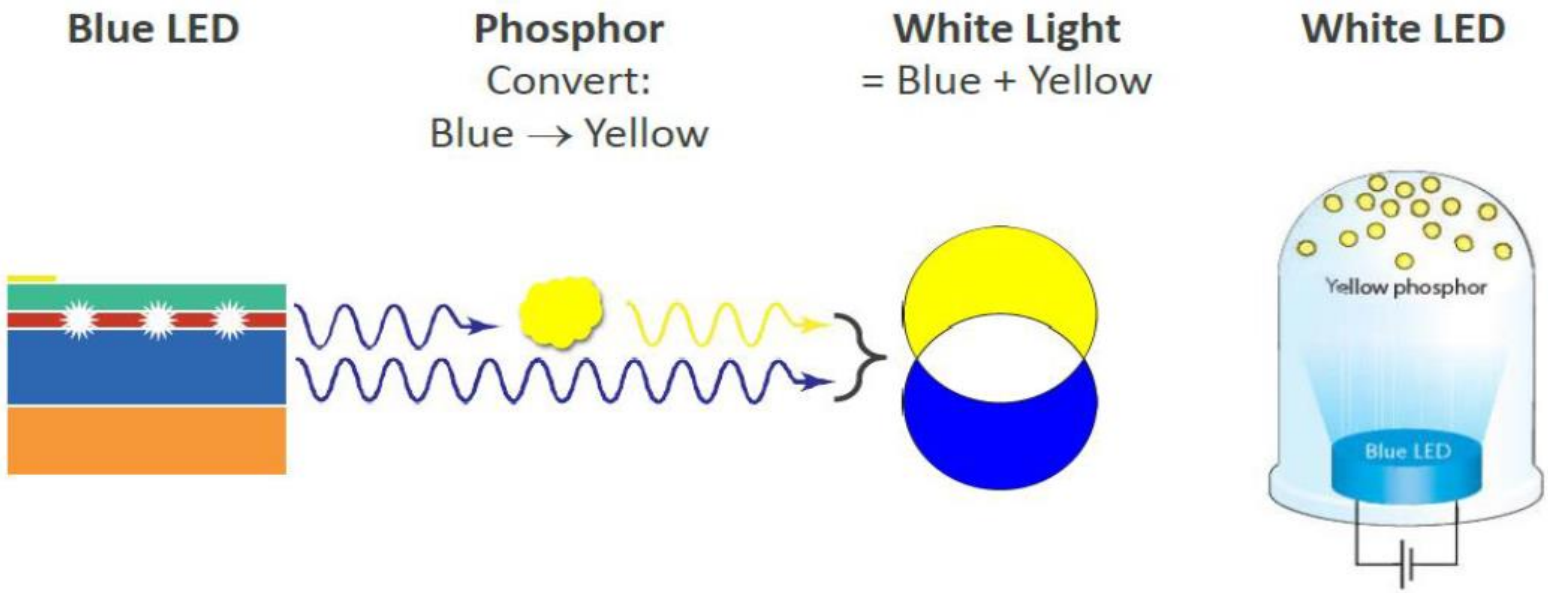
Light Emitting Diodes



Light Emitting Diodes

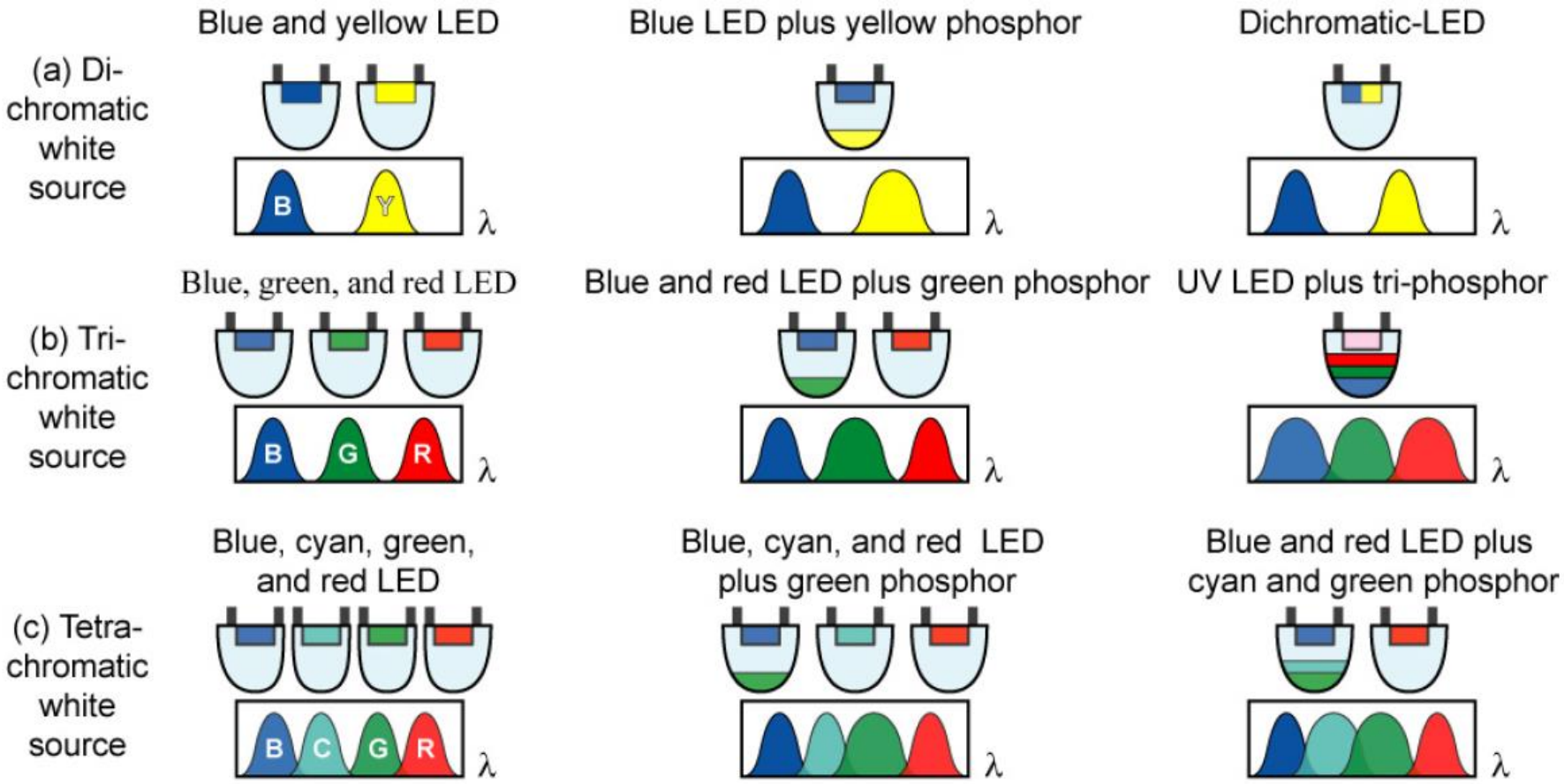
White Light: Blue + Other colors (red, yellow, green)

Other Colors: Convert Blue LED Light to Yellow using Phosphor.



- **Nichia Corp. (1996): Commercialization white LED using InGaN DH blue LED**
- **Nobel prize (2014) → Akasaki, Alamo, Nakamura : "for their invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light source"**

Light Emitting Diodes



www.lightemittingdiodes.com

Light Emitting Diodes

Internal, extraction, external, and power efficiency

$$\eta_{int} = \frac{\#\text{ of photons emitted from active region per second}}{\#\text{ of electrons injected into LED per second}} = \frac{P_{int} / (h\nu)}{I / e}$$

$$\eta_{extraction} = \frac{\#\text{ of photons emitted into free space per second}}{\#\text{ of photons emitted from active region per second}}$$

$$\eta_{ext} = \frac{\#\text{ of photons emitted into free space per sec.}}{\#\text{ of electrons injected into LED per sec.}} = \frac{P/(h\nu)}{I/e} = \eta_{int}\ \eta_{extraction}$$

$$\eta_{power} = \frac{P}{IV}$$

Light Emitting Diodes

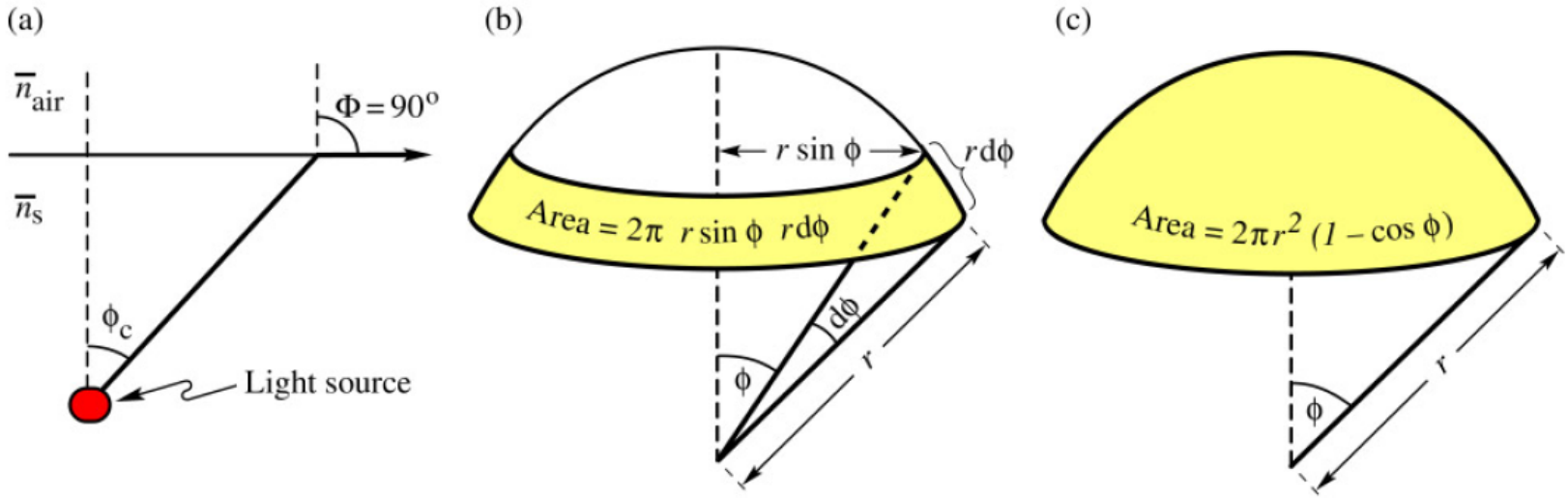


Fig. 5.3. (a) Definition of the escape cone by the critical angle ϕ_c. (b) Area element dA. (c) Area of calotte defined by radius r and angle ϕ_c.

- Total internal reflection occurs inside LED chip
- Light escape cone defined my critical angle for total internal reflection

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Light Emitting Diodes

$$\frac{P_{escape}}{P_{source}} \approx \frac{1}{2}\left[1 - \left(1 - \frac{\phi_c{}^2}{2}\right)\right] = \frac{1}{4}\,\phi_c{}^2$$

- ϕ_c = critical angle of total internal reflection
- Problem: Only small fraction of light can escape from semiconductor

$$\frac{P_{escape}}{P_{source}} = \frac{1}{4}\,\frac{\bar{n}_{air}{}^2}{\bar{n}_s{}^2}$$

- Above equation gives < 10 % extraction efficiency for typical III-V semiconductors

Light Emitting Diodes

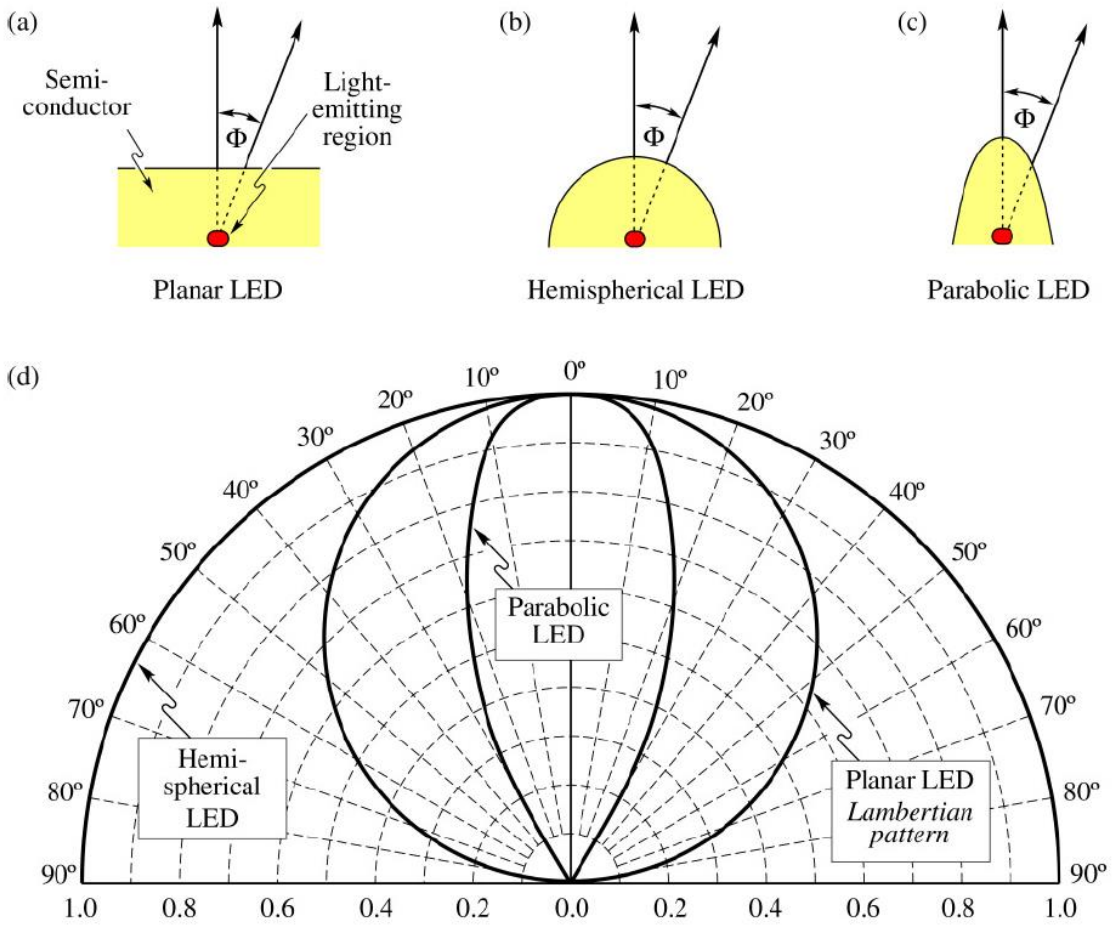
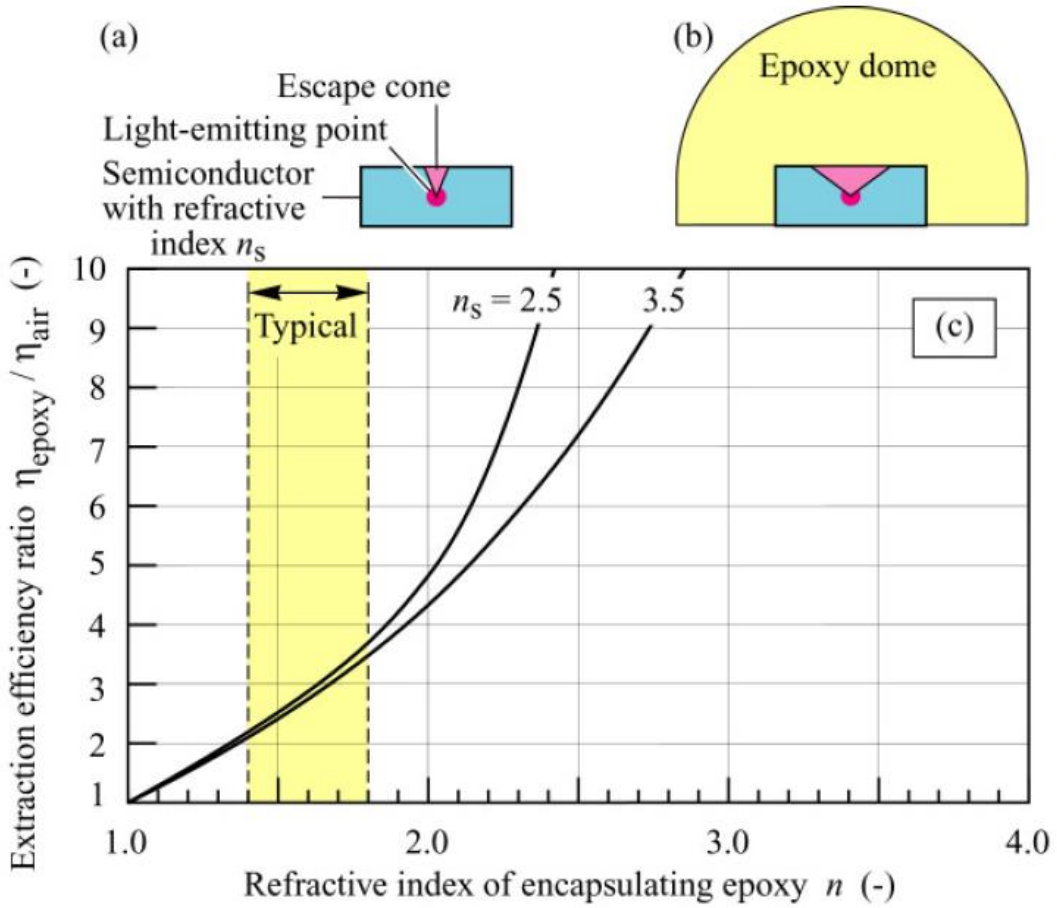


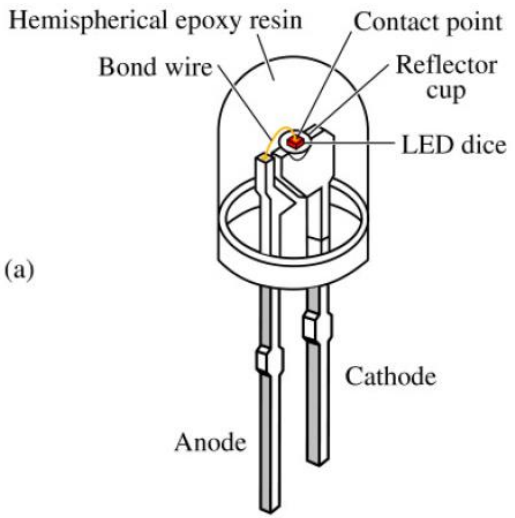
Fig. 5.5. Light-emitting diodes with (a) planar, (b) hemispherical, and (c) parabolic surfaces. (d) Far-field patterns of the different types of LEDs. At an angle of $\Phi = 60°$, the Lambertian emission pattern decreases to 50 % of its maximum value occuring at $\Phi = 0°$. The three emission patterns are normalized to unity intensity at $\Phi = 0°$.

- Die shaping can change emission pattern
- "Natural" LED has a planar surface

www.lightemittingdiodes.com

Light Emitting Diodes





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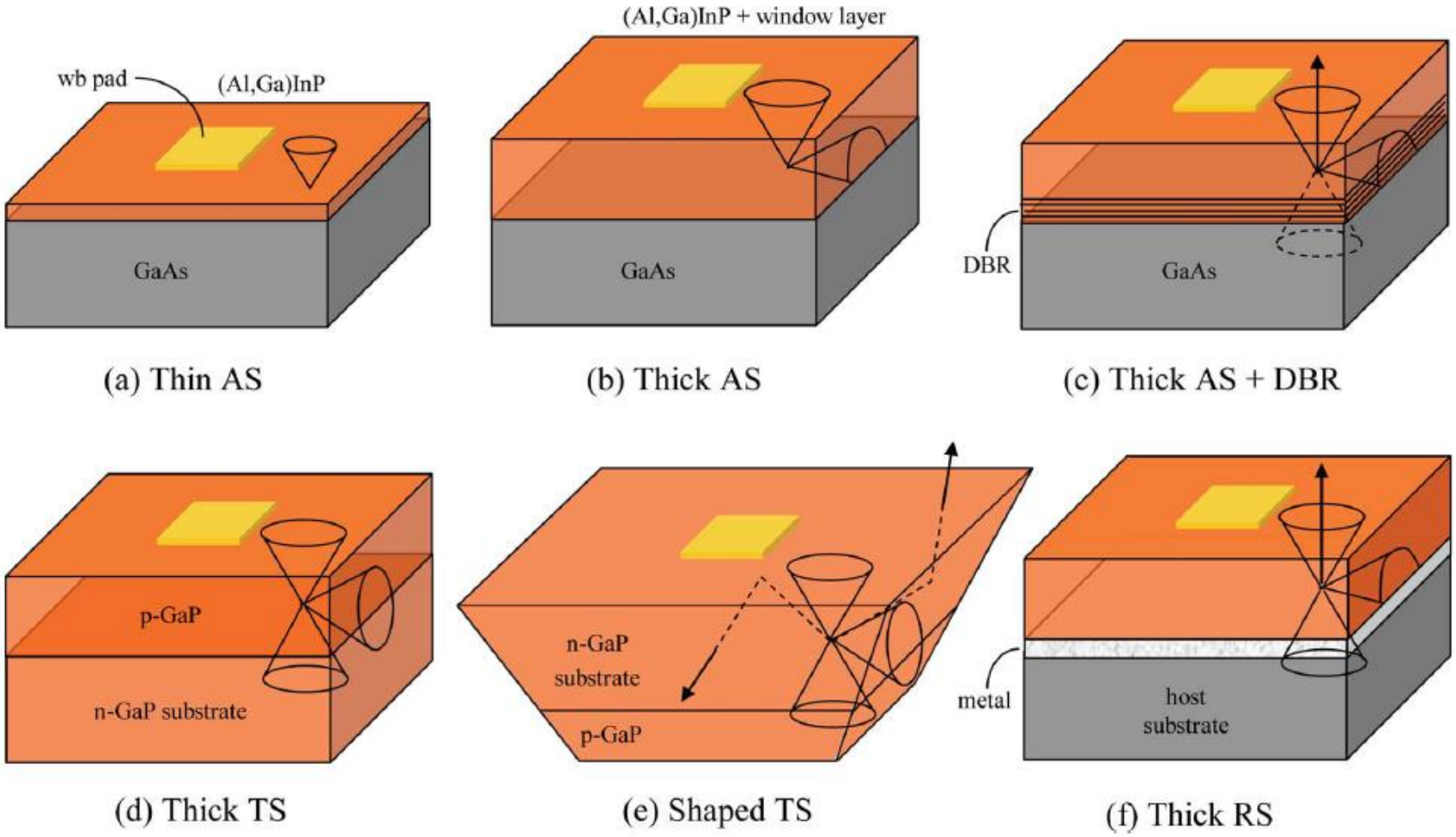
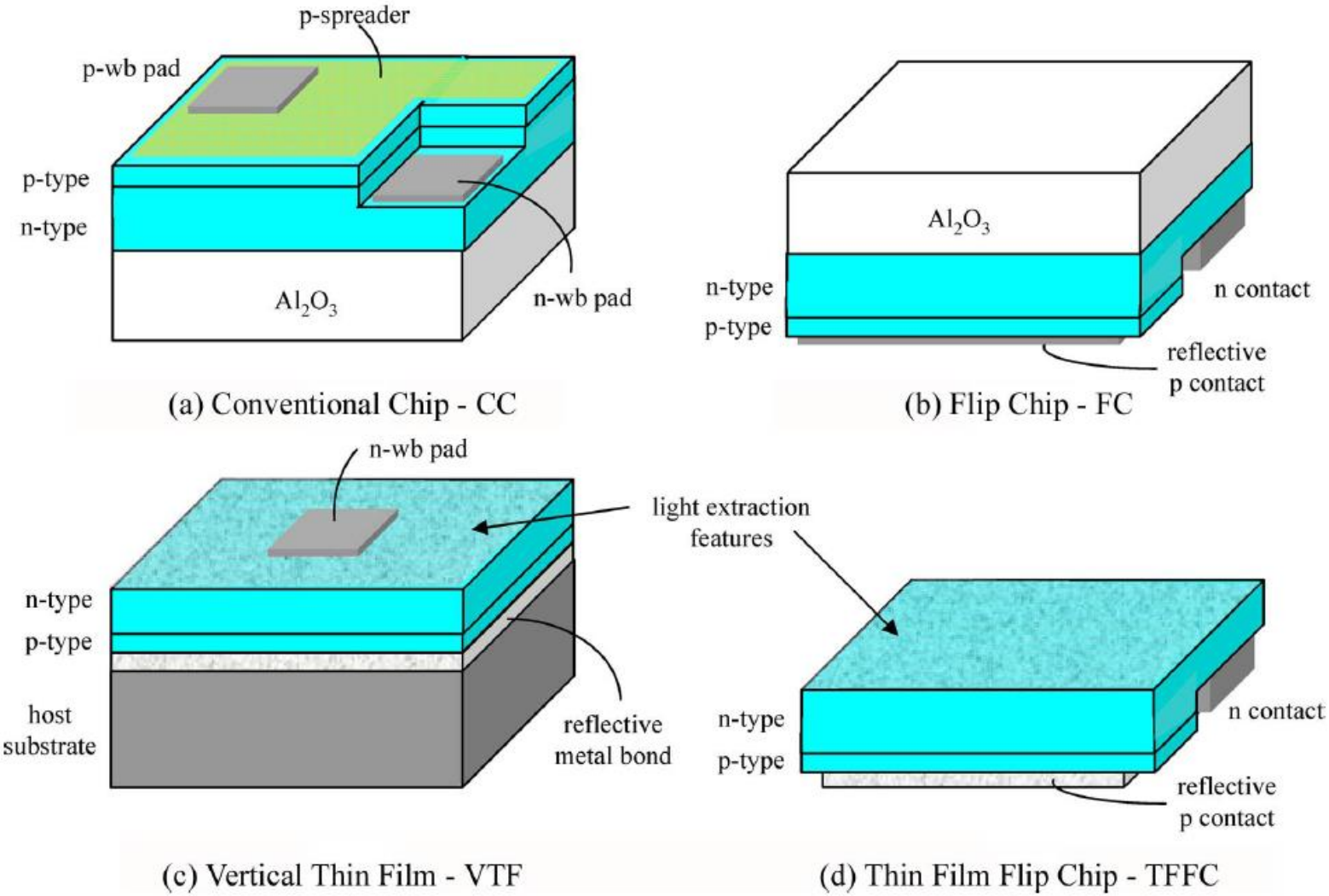


Light Emitting Diodes



Light Emitting Diodes

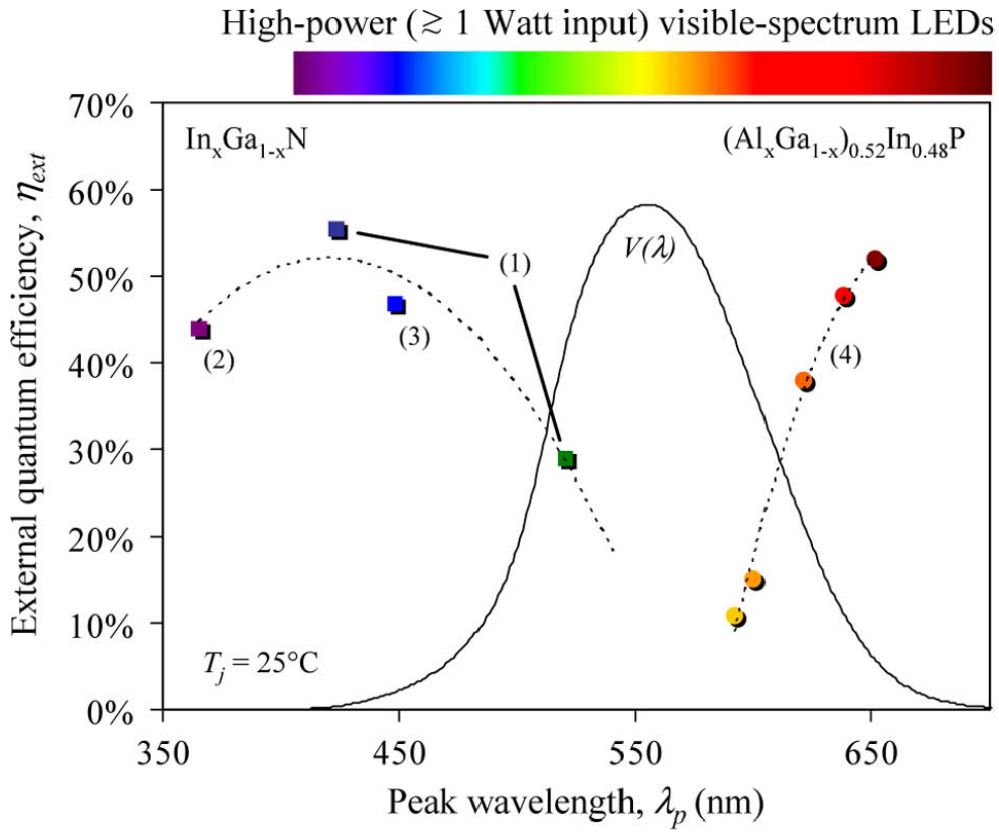
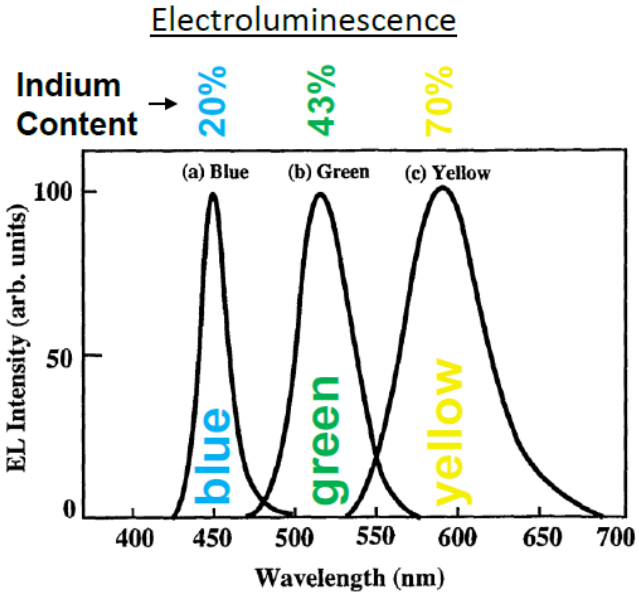


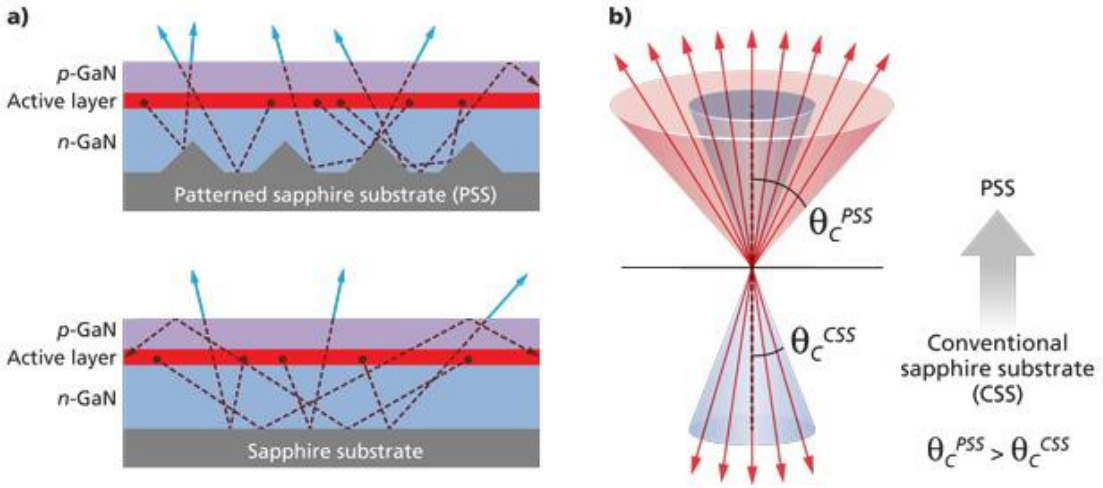
Fig. 2. State-of-art external quantum efficiencies for high-power visible-spectrum LEDs ($T_j = 25$ °C): (1) InGaN TFFC LEDs, 350 mA (this paper); (2) InGaN VTF LED, 1000 mA [42]; (3) InGaN CC LEDs employing patterned substrates [35]; and (4) Production performance, AlGaInP TIP LEDs [9], Philips Lumileds Lighting Co., 350 mA. $V(\lambda)$ is the luminous eye response curve from CIE. Dashed lines are guides to the eye.

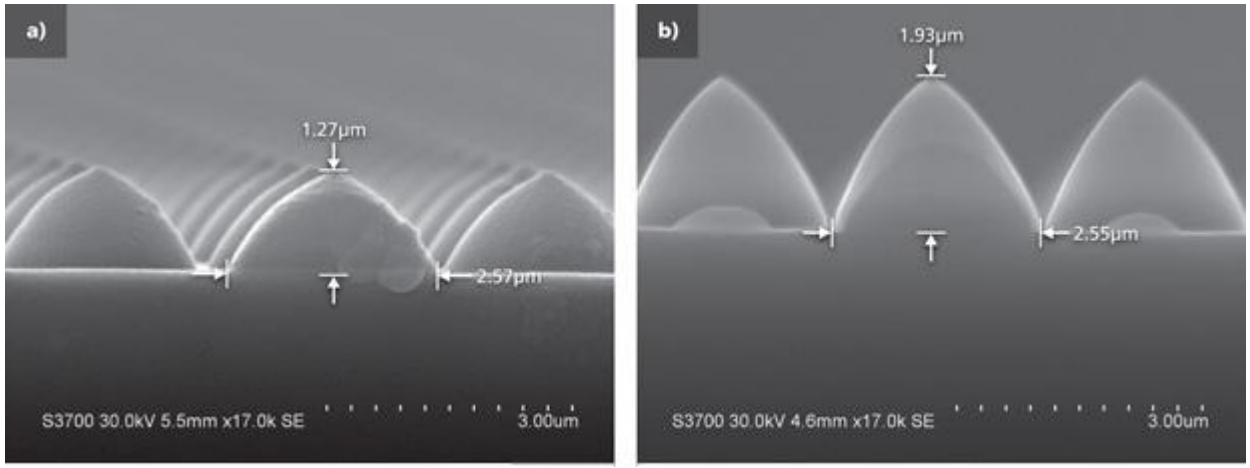


- **Highly strained InGaN layer**
- **High internal piezoelectric field**

Light Emitting Diodes

- **Microstructures for efficient light extraction**

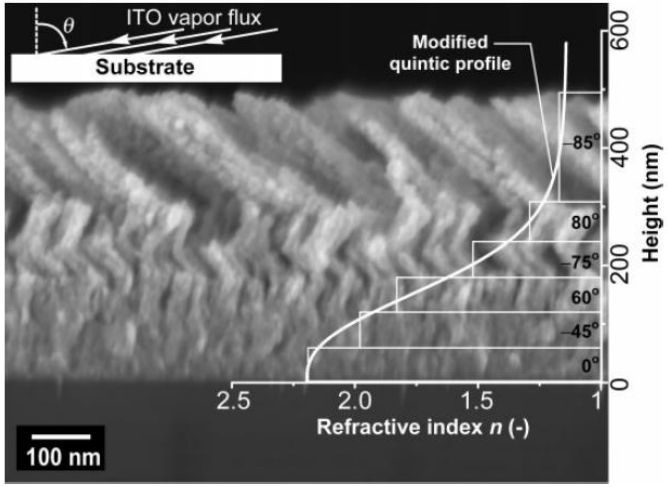


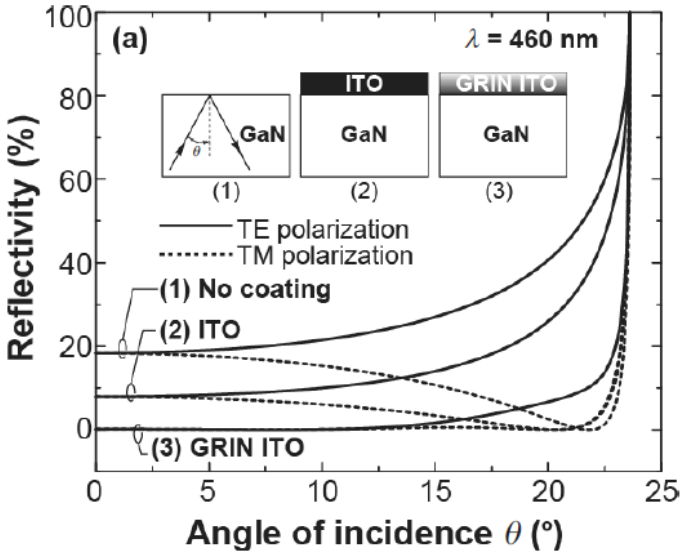


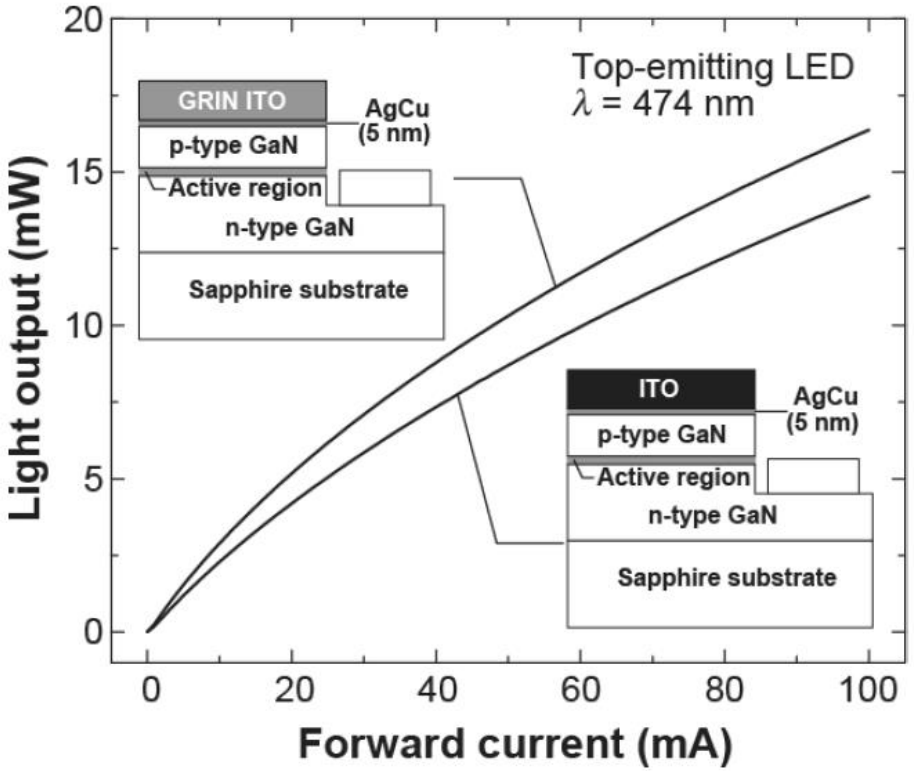
- **Rubicon Tech. (2014)**

Light Emitting Diodes

- **Nanostructures for efficient light extraction**





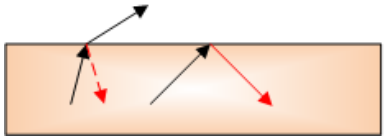


- **RPI (2007)**

Light Emitting Diodes

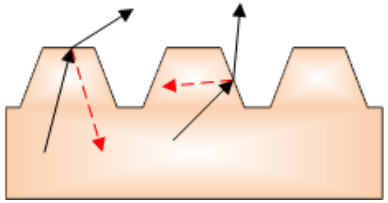
- **Combination of Micro-/nano-structures**

(i) Flat surface



Fresnel reflection (FR)
Total internal reflection (TIR)

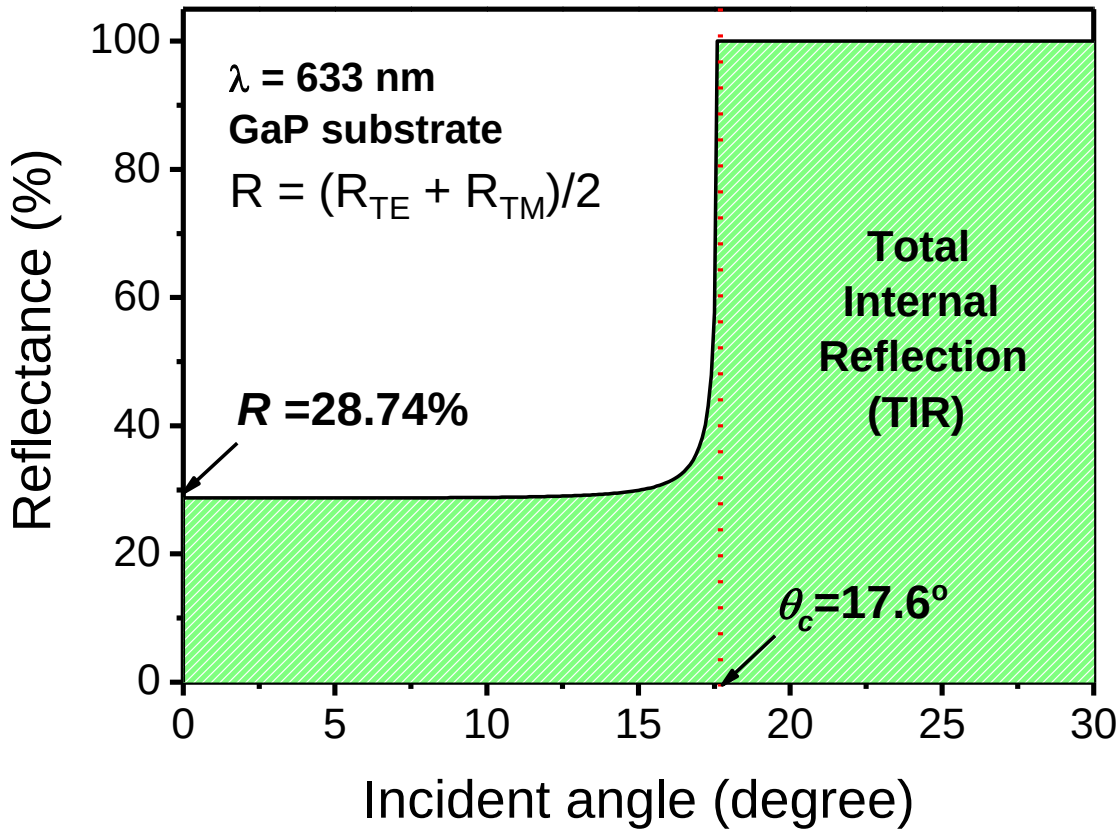
(ii) Micro-structure (MS)



Reducing TIR
Difficult to control FR

----→Fresnel reflection
——→ Total internal reflection

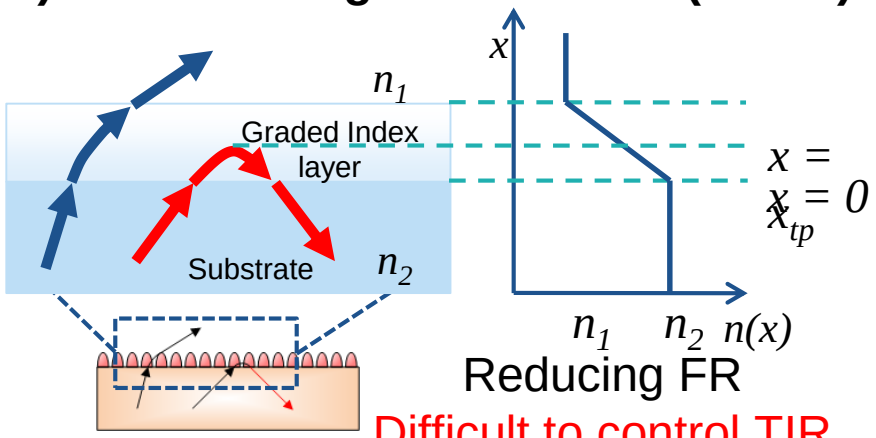
Angle dependent reflectance



At least ~30 % reflection occurs at any incident angle!!

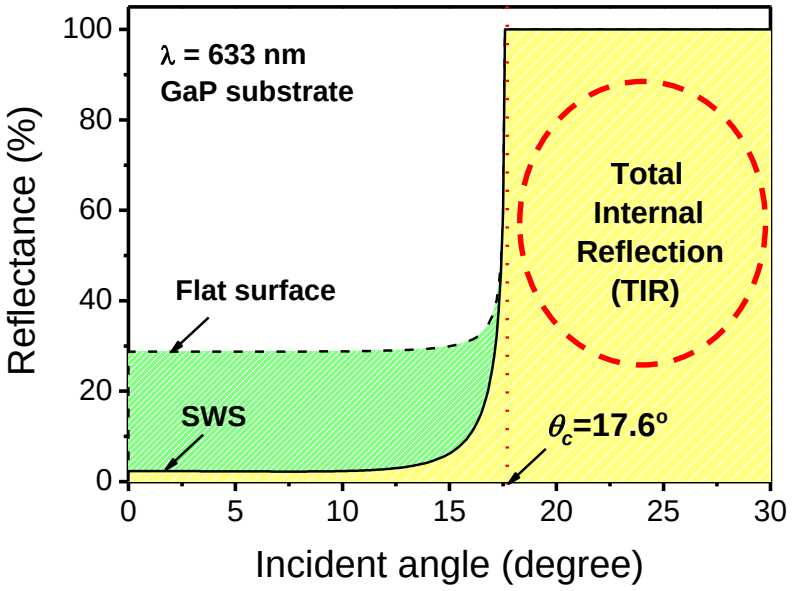
Light Emitting Diodes

(iii) Subwavelength Structures (SWSs)

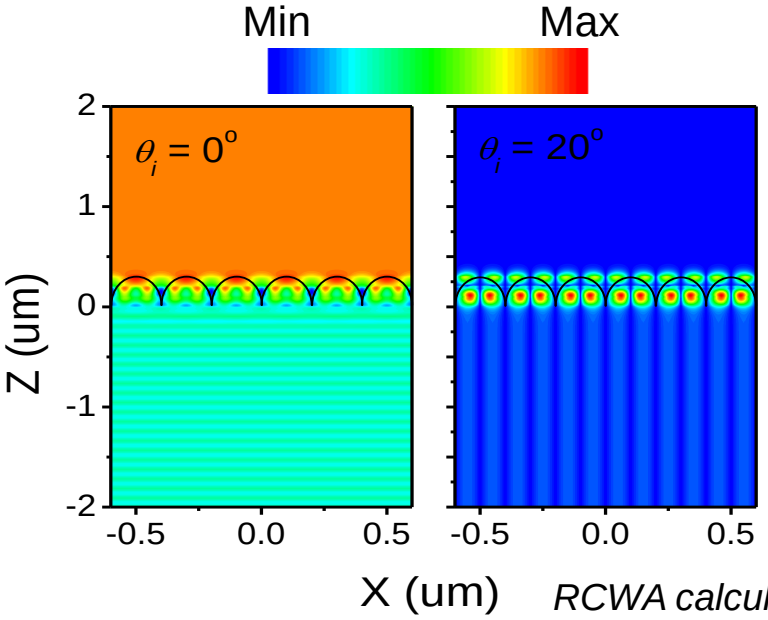


Reducing FR

Difficult to control TIR



Electric field intensity distribution



RCWA calculation

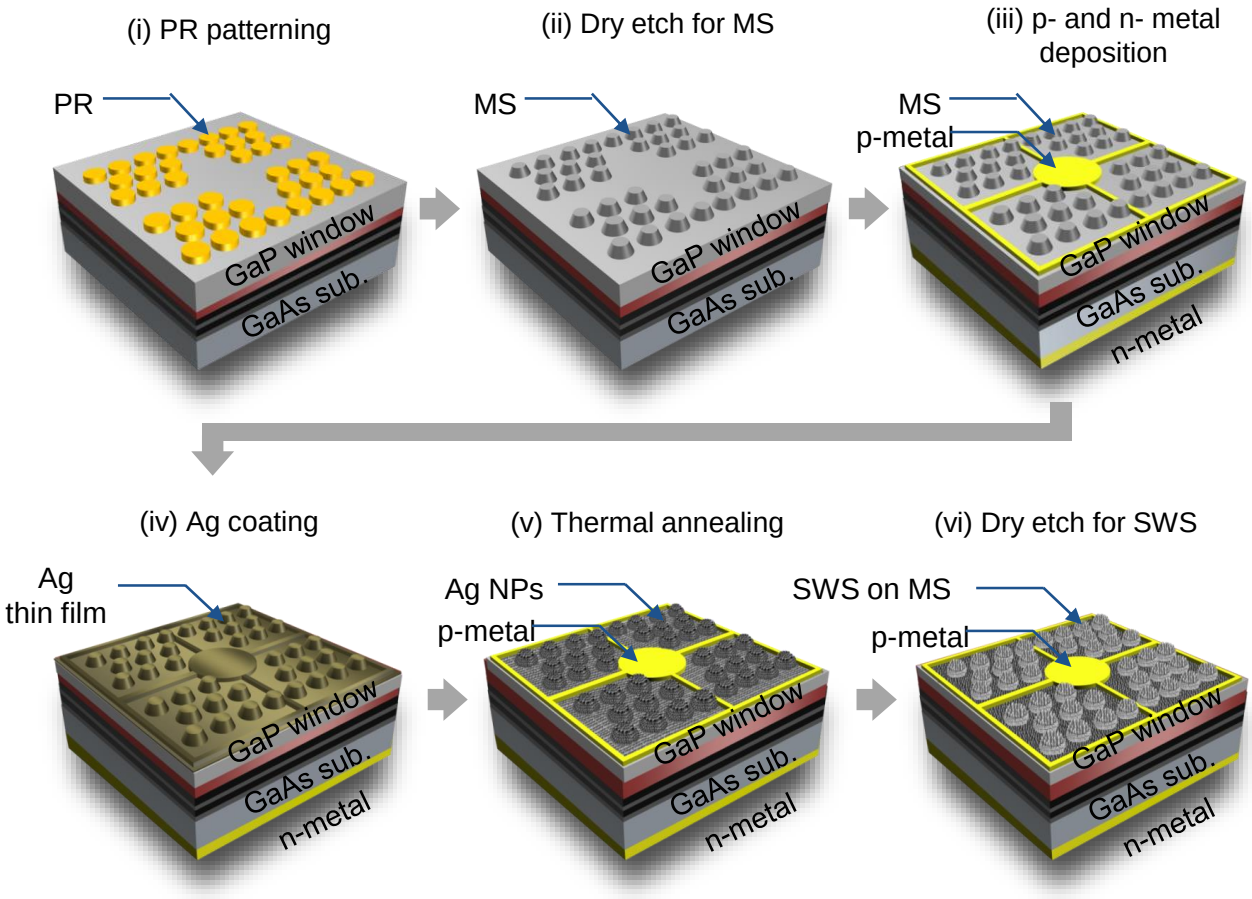
The electric field cannot penetrate the SWS region at above critical angle!

LED with SWSs or graded layer

- 24.3% (J. K. Kim et al., Adv. Mater 2008)
- 26.4% (Y. M. Song et al., OE 2009) red LED
- 31% (Y.-C. Lee et al., APL 2009)
- 30.2% (Y. M. Song et al., APL 2010) blue LED

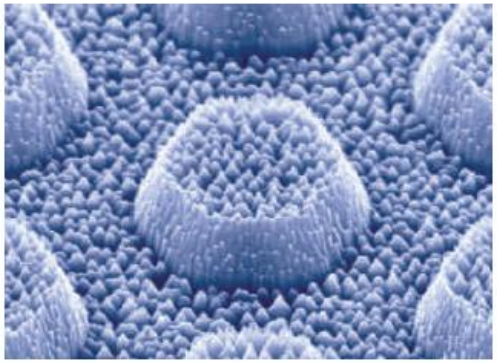
➡ **~30% limitation**

Light Emitting Diodes



Improving LED output

Opt. Express **19,** A157–A165 (2011)



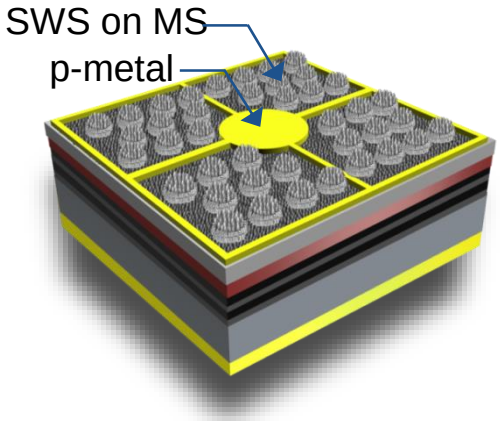
High-refractive-index LEDs often suffer from low extraction efficiency because of Fresnel reflection and total internal reflection losses. Fabricating microstructures on the surface of an LED is an efficient way of improving its efficiency, but achieving this while also reducing reflection losses has proved to be a significant challenge. Young Min Song and co-workers from South Korea have now developed a bioinspired fabrication technique that uses antireflective subwavelength structures on top of microstructures to dramatically improve the potential light output powers of an LED. They first formed hexagonally patterned microstructures with diameters of 2 μm and thicknesses of 600 nm by dry etching

Opt. Express (2011)

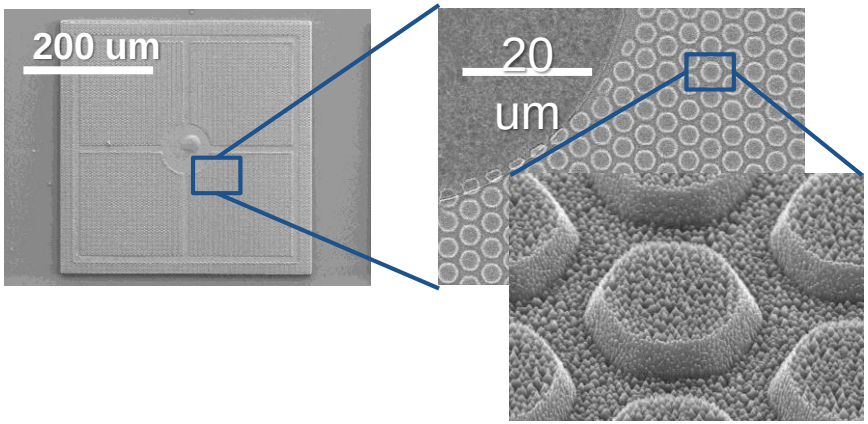
Introduced in Nat. Photonics Research Highlight (2011)

Light Emitting Diodes

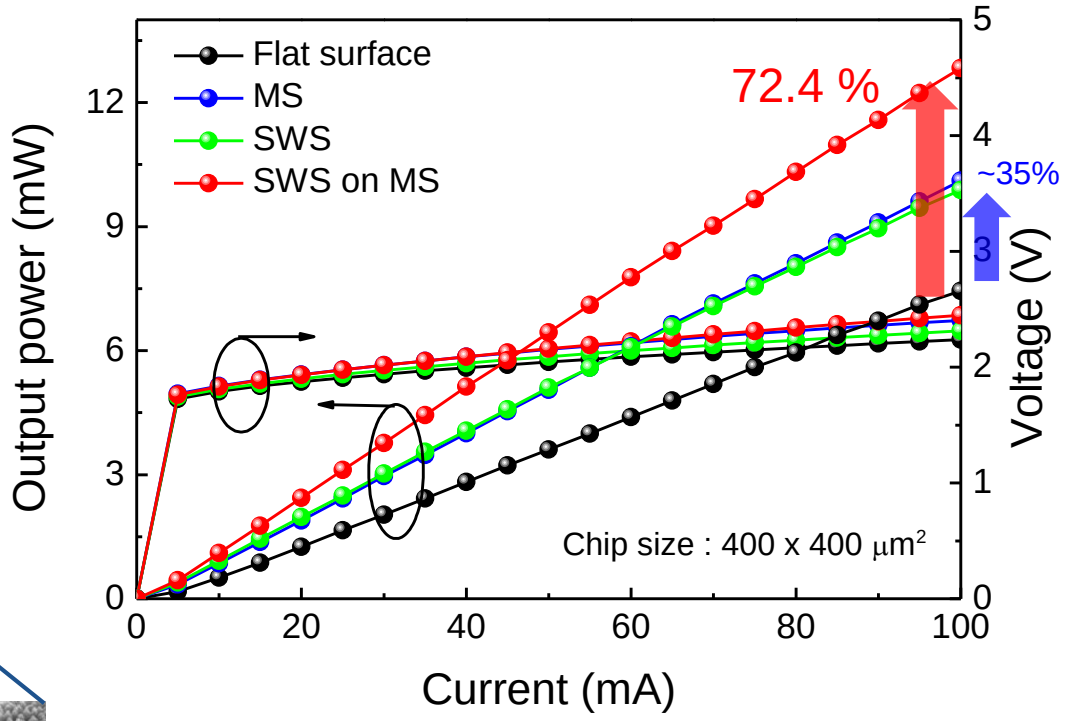
Schematic diagram for red LEDs with SWS on MS



SEM images of fabricated red LEDs with SWS on MS



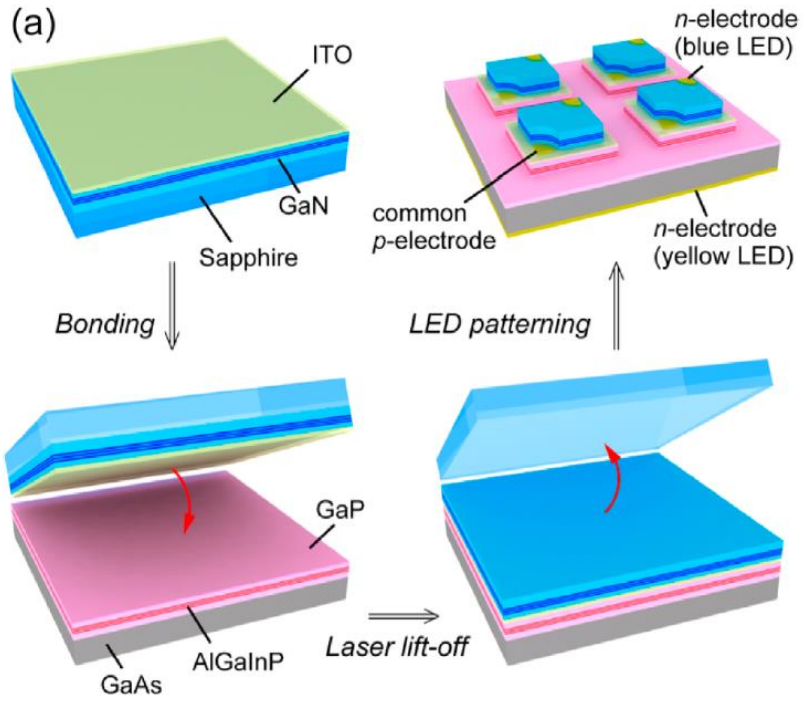
L-I-V curve for AlGaInP LEDs with SWS on MS

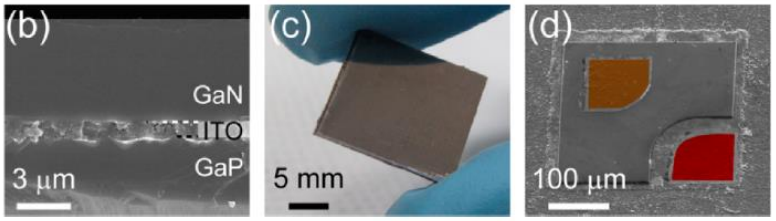


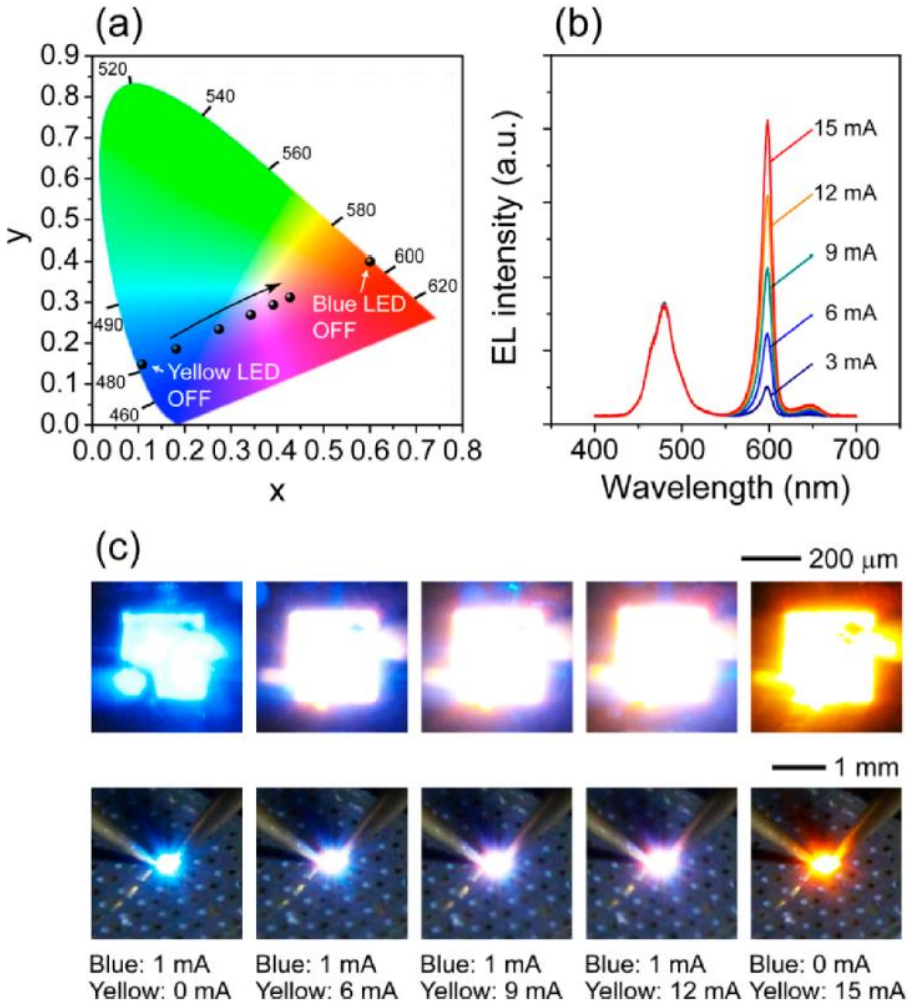
The light output power was improved by 72.4% for the LED with SWS on MS compared to the conventional LEDs

Light Emitting Diodes

- **Multiple color generation**

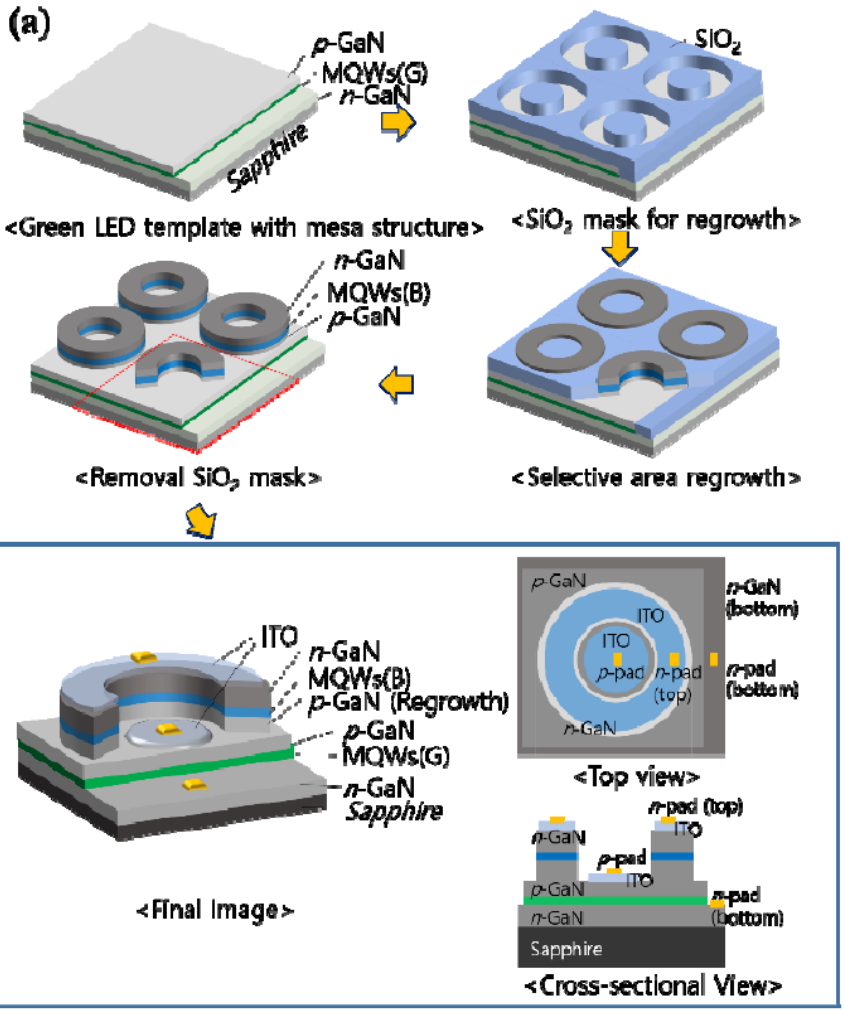


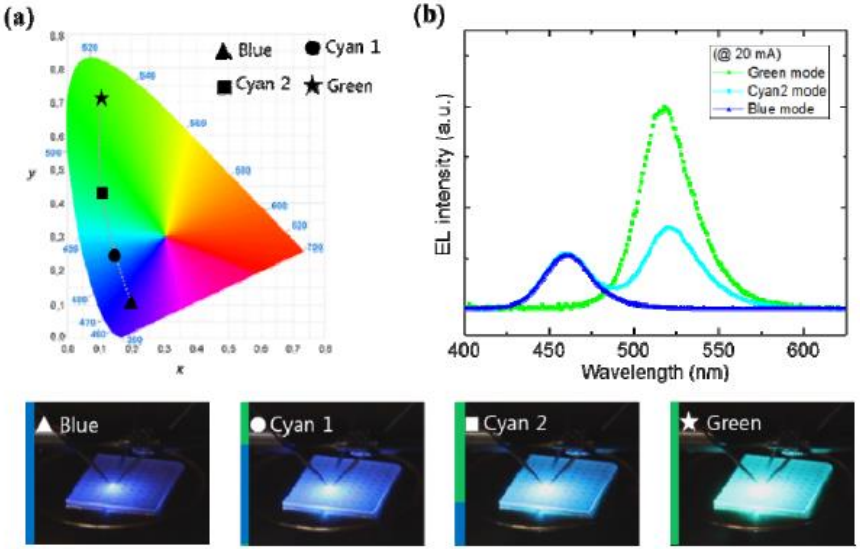




Light Emitting Diodes

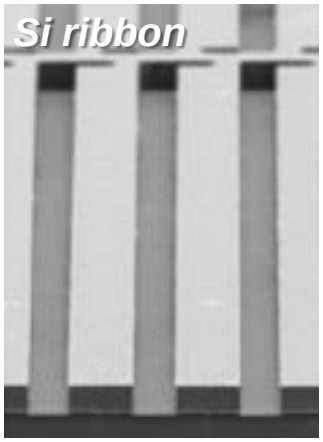
- **Multiple color generation**

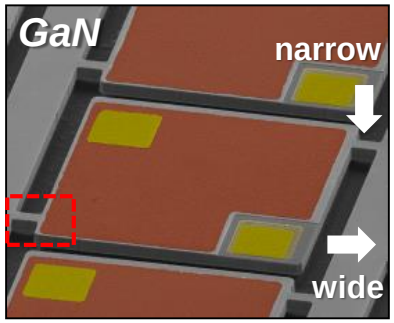


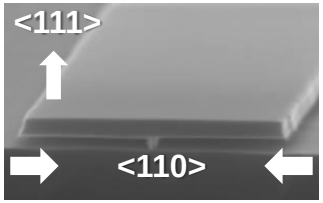


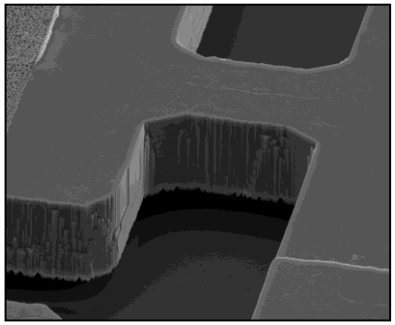
Practical approaches – Inorganic LEDs

Homogeneous Anchors

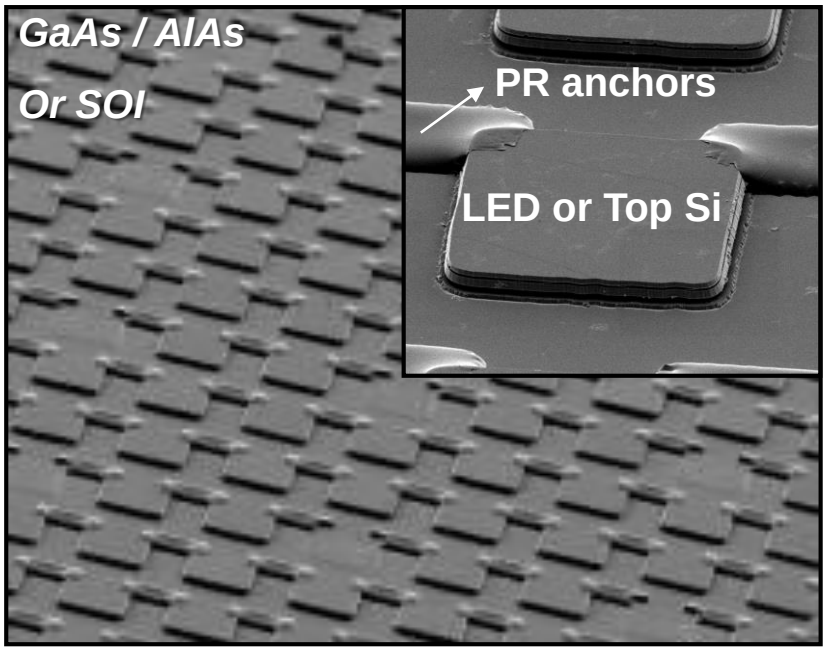




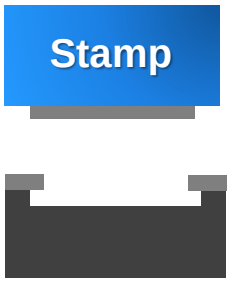


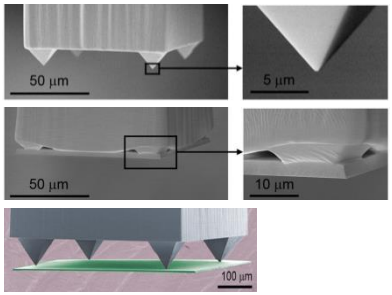


Heterogeneous Anchors

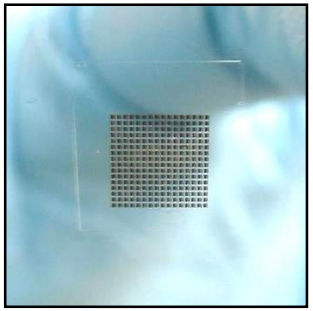


Lift-off



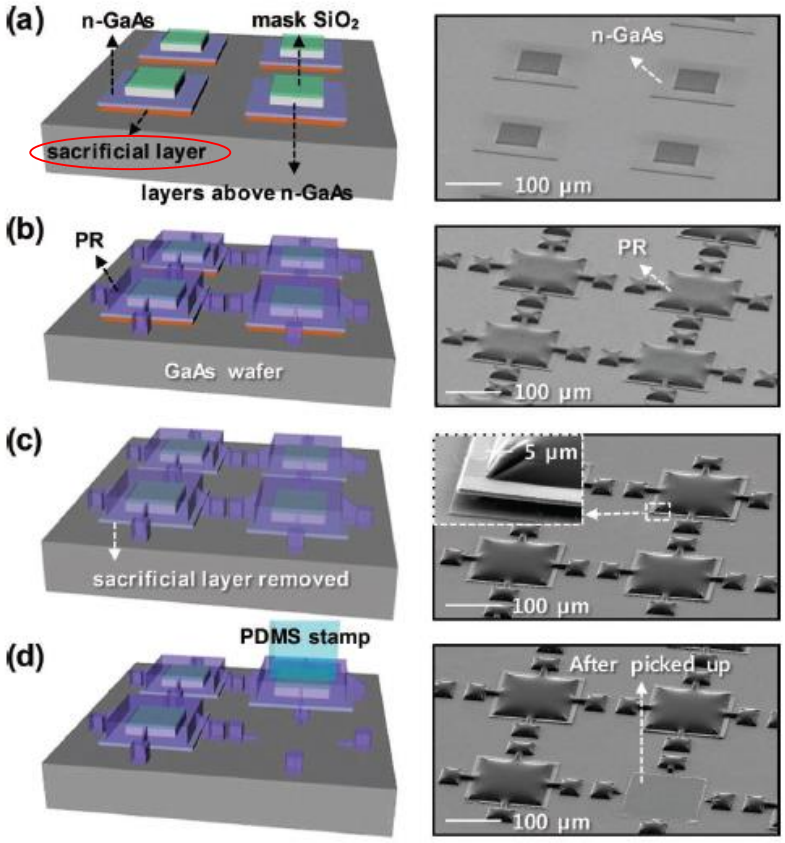


Transfer printing



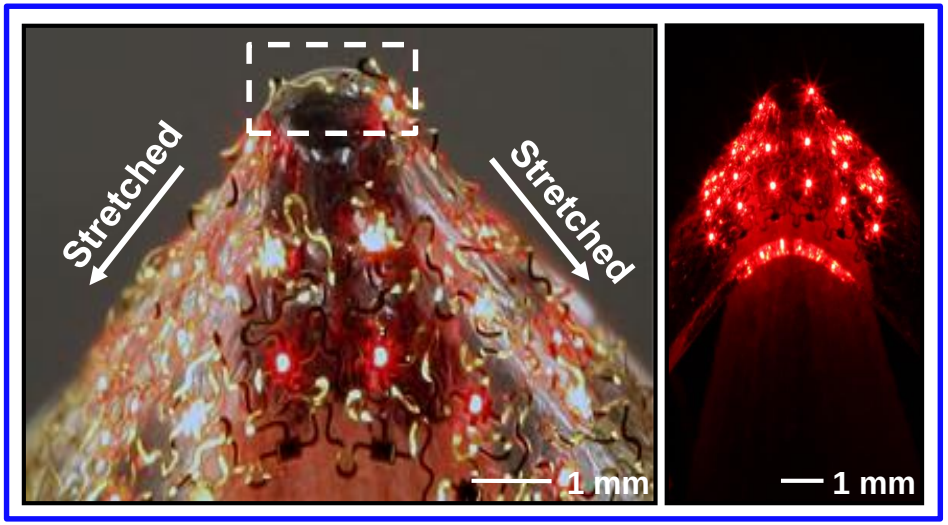
Other devices – Stretchable LEDs

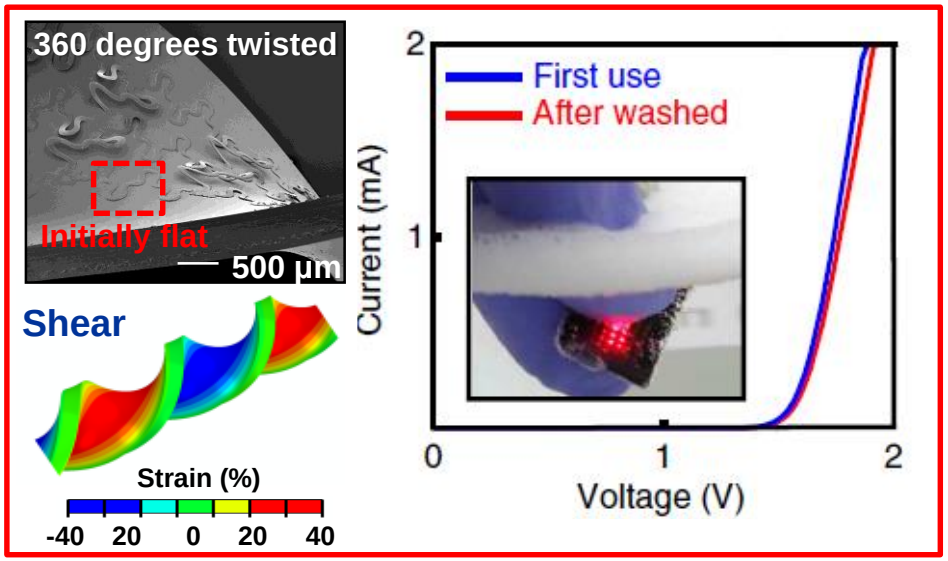
Transfer printing of ILED



Small (2012) #42

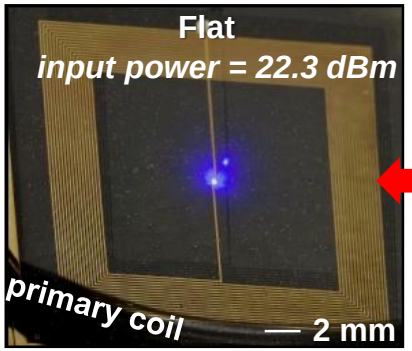
Off-plane deformation

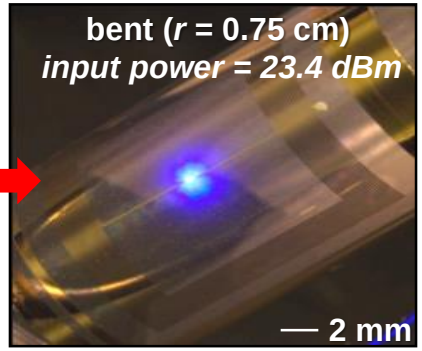




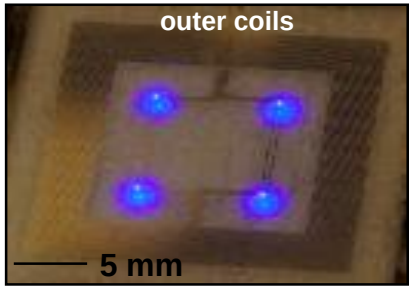
Practical approaches – Inorganic LEDs

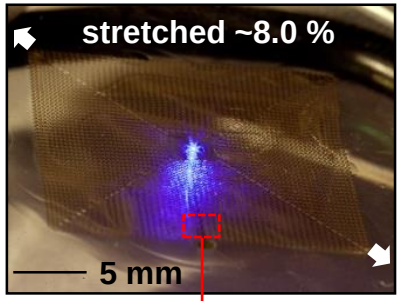
Bendable system

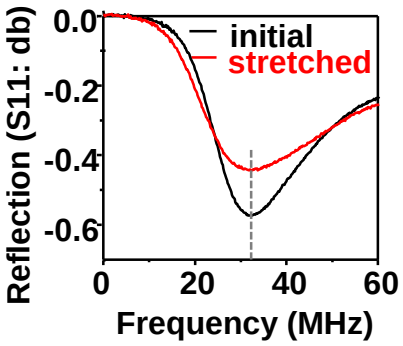


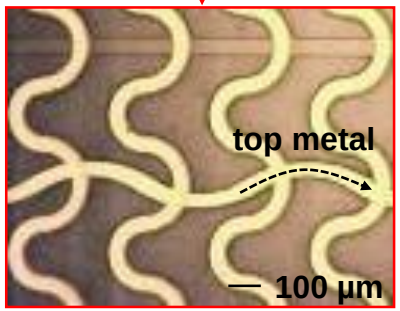


Multi-pixels and stretchable system

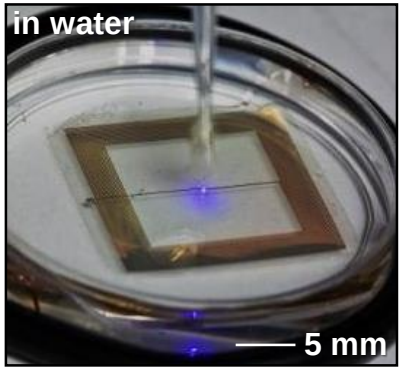


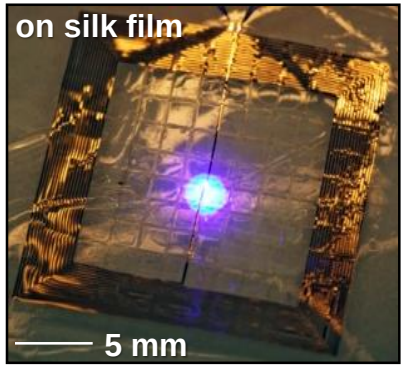


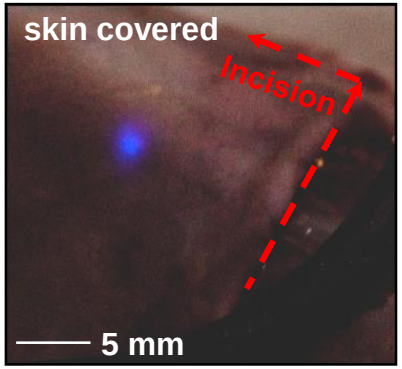


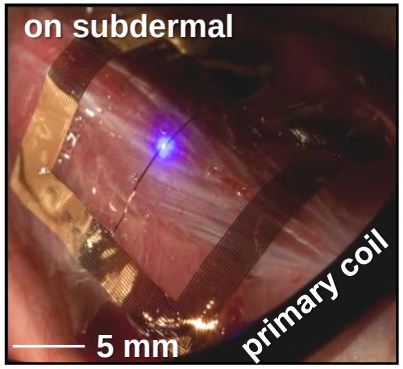


Bio-Integration



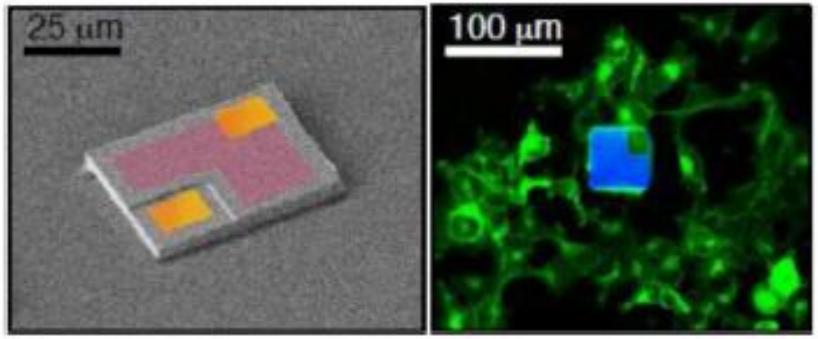


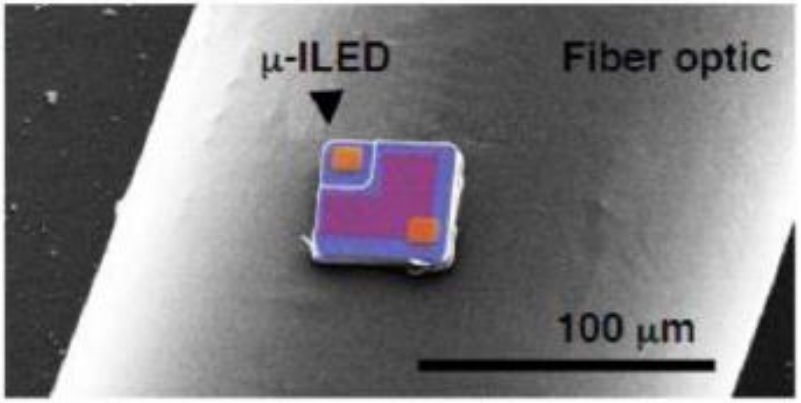




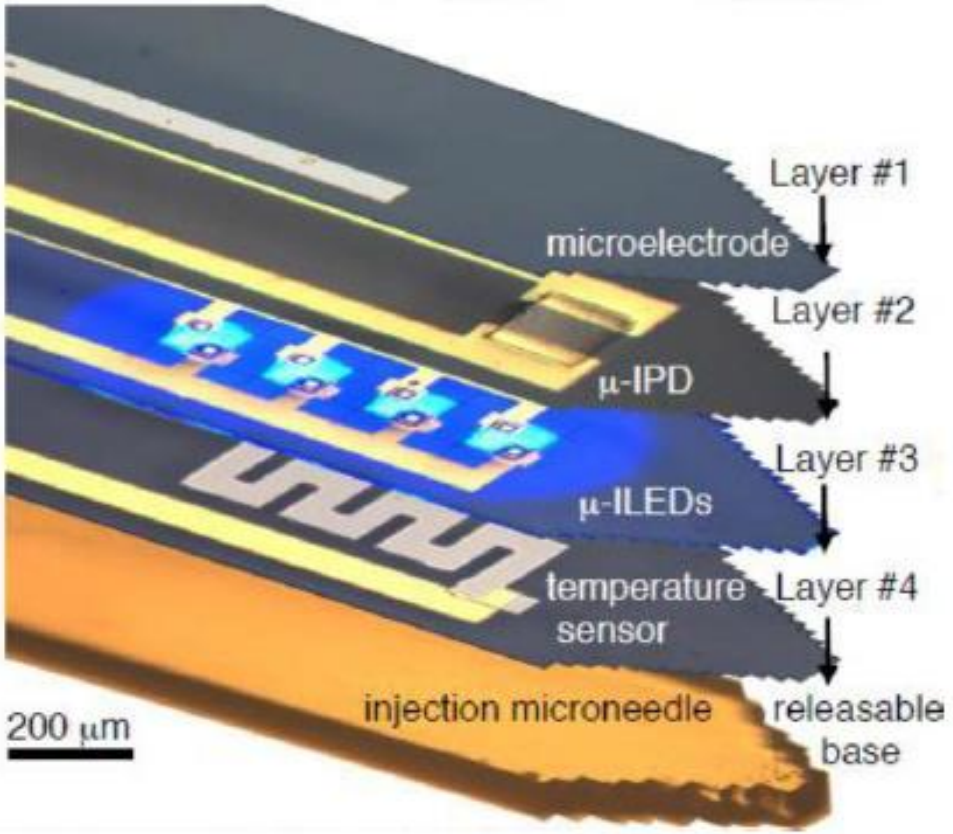
Cellular scale, tiny LEDs for implantable devices

Cellular scale LEDs





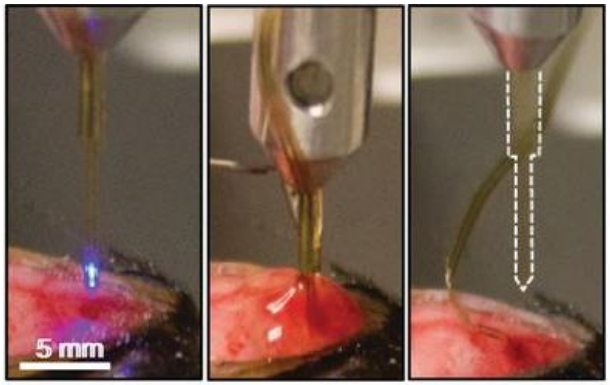
Multifunctional integrated systems

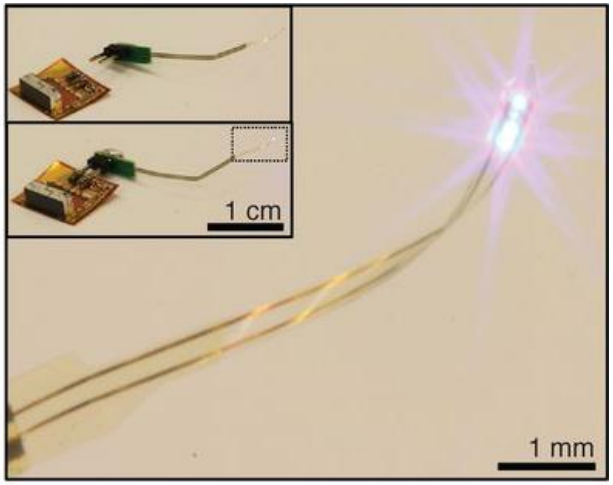


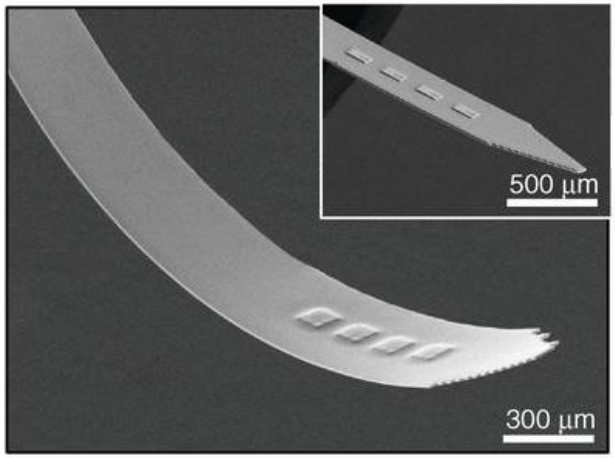
Science 340, 211 (2013) #44

Cellular scale, tiny LEDs for implantable devices

Injectable LEDs for freely moving mice

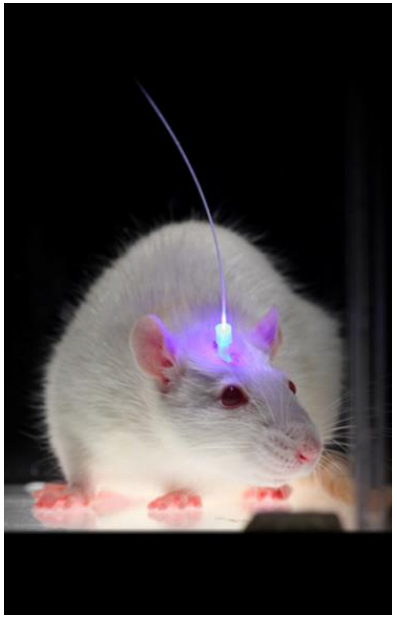






Conventional Optogenetics

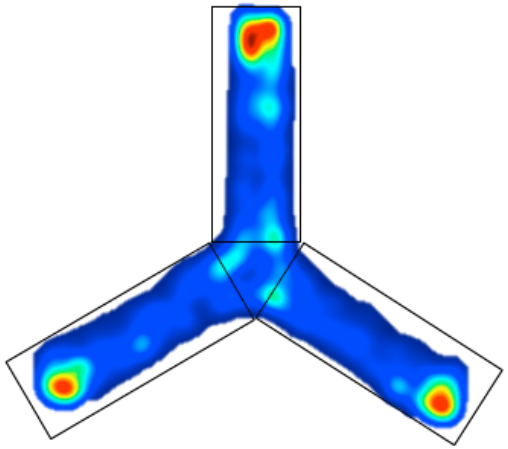
(Optical fibers)



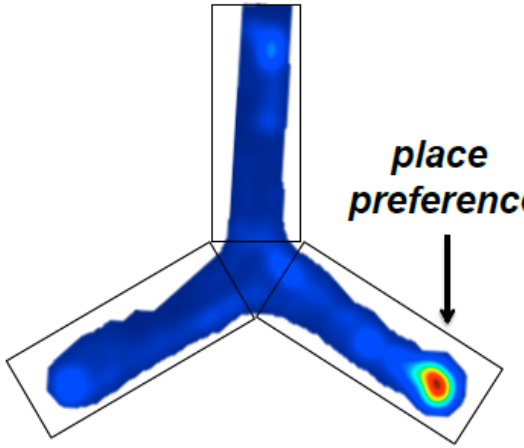
Science 340, 211 (2013)

Cellular scale, tiny LEDs for implantable devices

Maps of Location in a Y maze

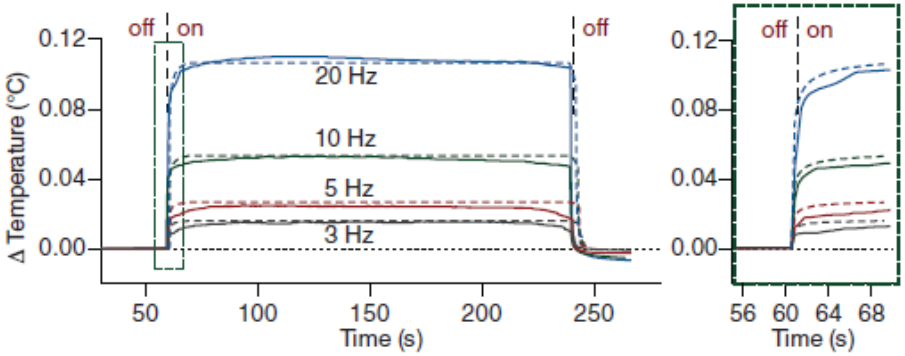


untrained

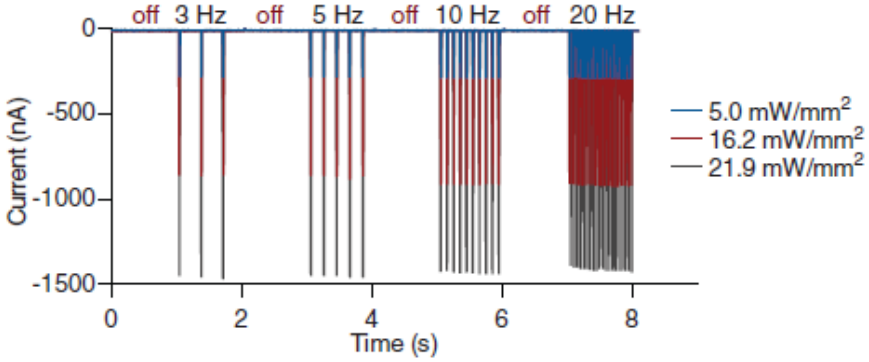


trained using injected, wireless LEDs

Temperature monitoring



Light intensity monitoring

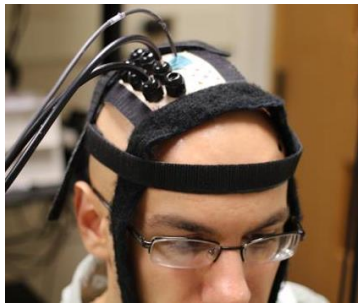


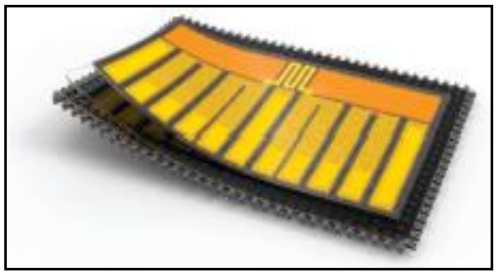
Science 340, 211 (2013)

Patch-type LEDs for Cerebral Oximetry

Epidermal optic diagnosis

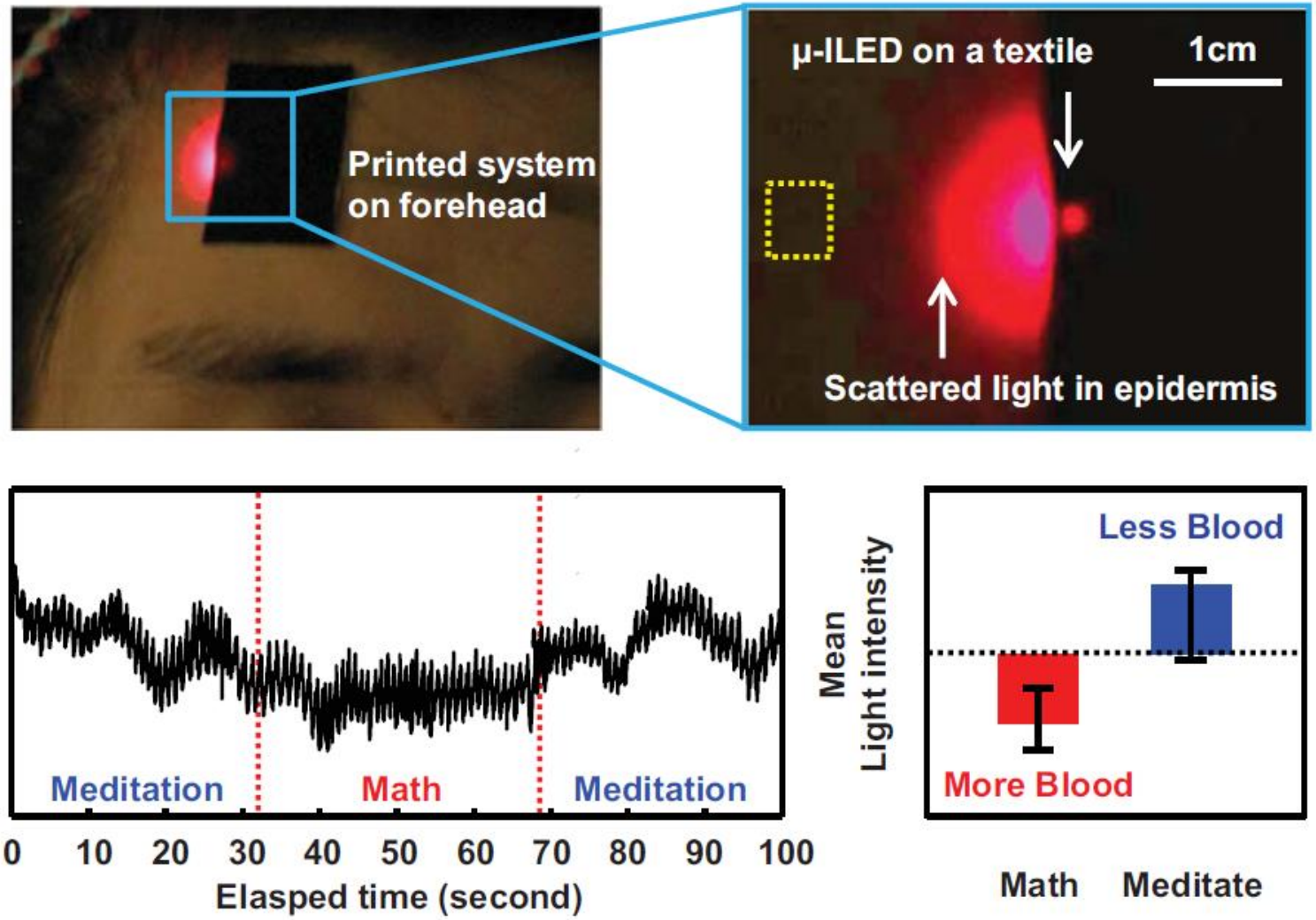
Conventional Cerebral oximetry





Nat. Comm. (2014) #53

Patch-type LEDs for Cerebral Oximetry



Nat. Comm. (2014) #53