McGill University
Montreal, Canada
January 11, 2013

A Revolution in Lighting: Light-Emitting Diodes

E. Fred Schubert

Rensselaer Polytechnic Institute, Troy, New York, USA

1

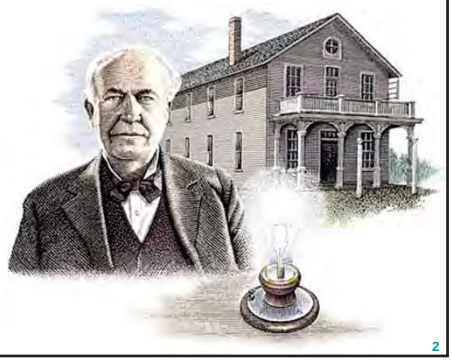
The beginnings of lighting

- In 1879, Thomas A. Edison demonstrated a light bulb with a C (carbon) filament that burned for 40 hours.

Gas light

Edison's light bulb

Thomas A. Edison

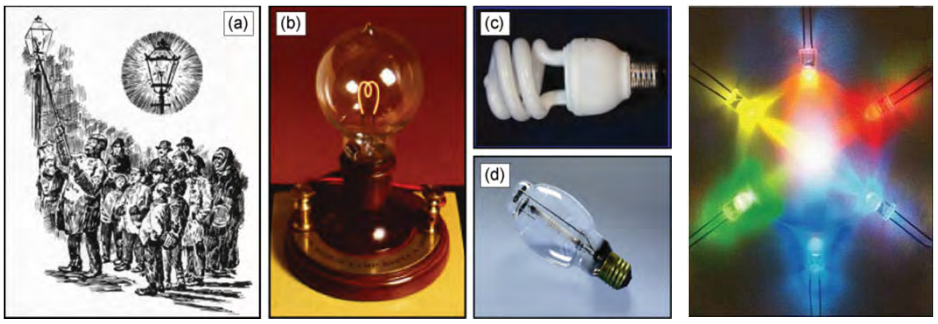


Pictures from Thomas Edison National Historical Park

2

Solid-state lighting technologies and figures of merit

Lighting technologies



Figures of merit for new LED lighting

Quantity	Edison ~1900	LEDs 2013	
▪ Luminous source efficiency	1.5	150	lm/W
▪ Luminous flux	10	1000	lm
▪ Color rendition capability (CRI)	yellow-orange	> 90	-
▪ Color temperature	2000	3000 – 6000	K
▪ Lifetime	40	100 000	hrs
▪ Cost	~30	~30	$

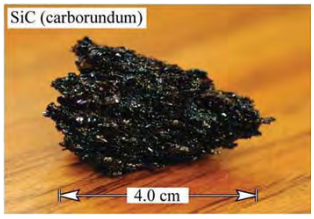
3

History of LEDs

4

First LED – SiC – Round, 1907

- Henry Joseph Round (1881 – 1966)
- 1907: First observation of electroluminescence
- 1907: First LED (SiC)
- SiC, carborundum, an abrasive material



A Note on Carborundum.

To the Editors of Electrical World:

SIRS:—During an investigation of the unsymmetrical passage of current through a contact of carborundum and other substances a curious phenomenon was noted. On applying a potential of 10 volts between two points on a crystal of carborundum, the crystal gave out a yellowish light. Only one or two specimens could be found which gave a bright glow on such a low voltage, but with 110 volts a large number could be found to glow. In some crystals only edges gave the light and others gave instead of a yellow light green, orange or blue. In all cases tested the glow appears to come from the negative pole, a bright blue-green spark appearing at the positive pole. In a single crystal, if contact is made near the center with the negative pole, and the positive pole is put in contact at any other place, only one section of the crystal will glow and that the same section wherever the positive pole is placed.

There seems to be some connection between the above effect and the e.m.f. produced by a junction of carborundum and another conductor when heated by a direct or alternating current; but the connection may be only secondary as an obvious explanation of the e.m.f. effect is the thermoelectric one. The writer would be glad of references to any published account of an investigation of this or any allied phenomena.

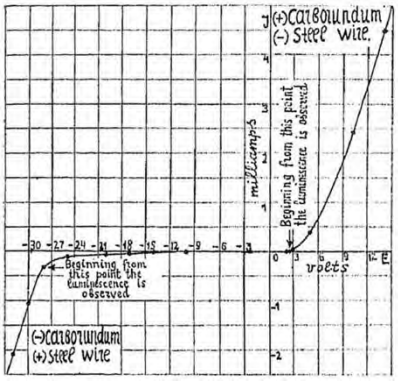
NEW YORK, N. Y. H. J. ROUND.

Henry Joseph Round

5

LED – SiC – Lossev, 1924

- Oleg V. Lossev (1903 – 1942)
- Brilliant scientist who published his first paper at age of 20 years
- First detailed study of electroluminescence in SiC
- Luminescence is no heat glow (incandescence)
- Similarity to vacuum gas discharge

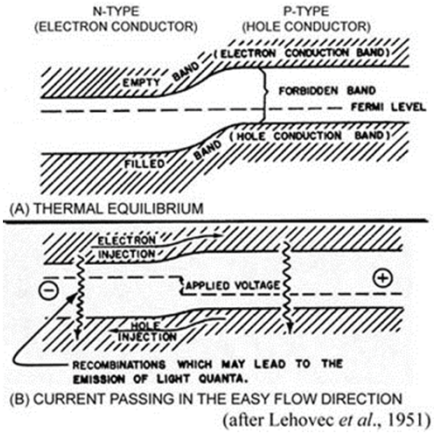


Oleg V. Lossev

6

1951 Kurt Lehovec 1958 Otto Folberth 1962 Nick Holonyak

- Kurt Lehovec: Injected minority carriers are origin of p-n electroluminescence
- Otto Folberth: Inventor of GaAsP pn-junction devices
- Nick Holonyak: First coherent (visible) light from GaPAs junctions



First correct explanation of light emission from LEDs (Lehovec et al., 1951)

Kurt Lehovec

Otto Folberth

Nick Holonyak Jr.

7

1972 GaPAs yellow LEDs 1980s HB AlGaInP LEDs

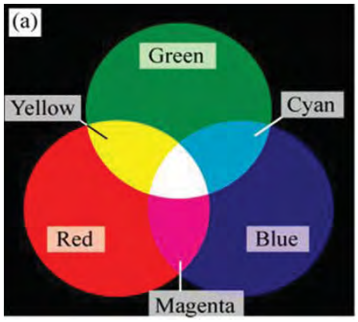
- GaPAs Yellow and red LEDs
- AlGaInP: First high-brightness LED material system
- Suited for outdoor applications

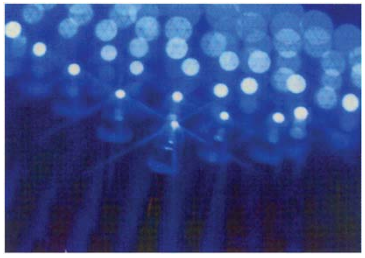
8

1989: Blue LEDs

- Blue: The elusive color
- Without blue: No white
- Without blue: No displays (TV and cell phones)
- Isamu Akasaki et al., Meijo University, Japan

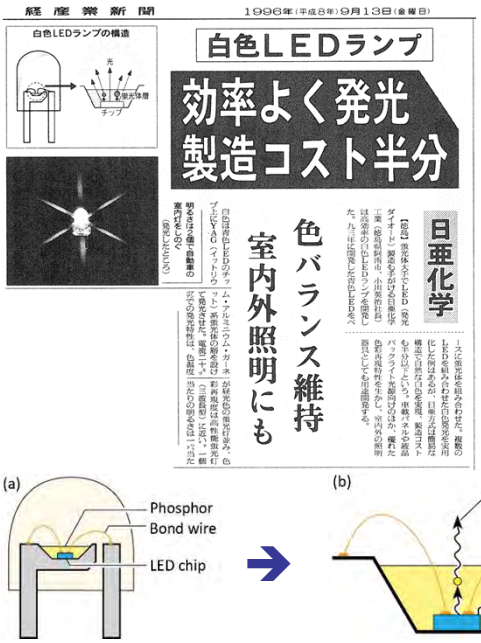
Isamu Akasaki





9

1996: White LEDs



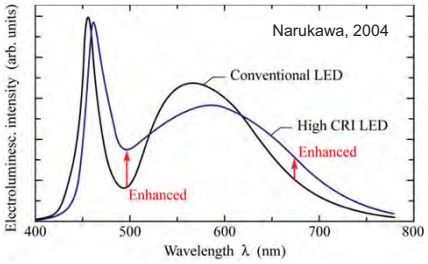
- Japanese Nikkei Newspaper
- September 13, 1996
- “White LED lamp”
- Lifespan 50 000 hrs predicted, 10 x longer than fluorescent lamps and 100 x longer than incandescent lamps

Shuji Nakamura

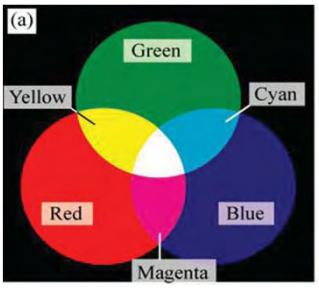
10

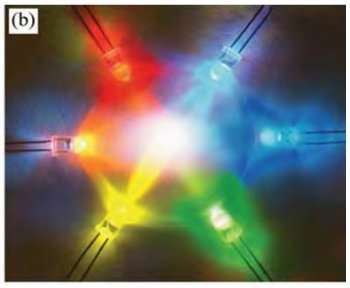
2000: Vision for solid-state lighting

- Jeffrey Tsao and colleagues of US Sandia National Laboratories
- Vision for solid-state lighting:
  Very large energy savings are possible by LED lighting (Solid-state lighting)



Jeff Tsao





Multiple light-emitting diodes

11

Additional milestones in LED technology development

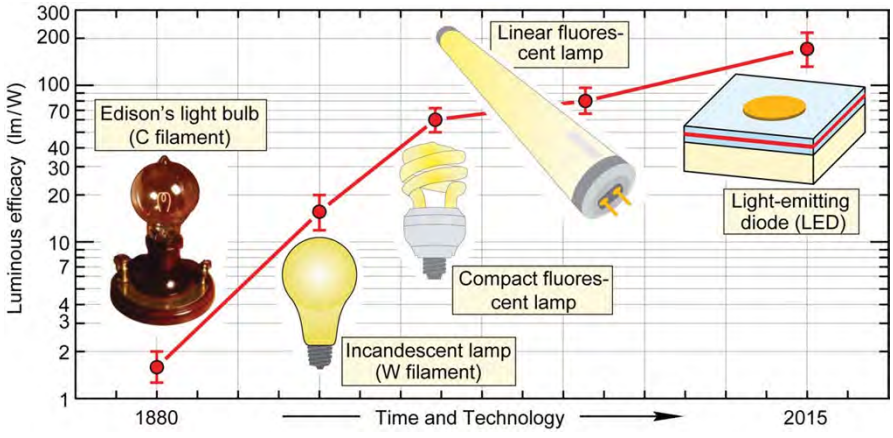
- 1994: Candela-class InGaN/AlGaN blue LEDs (Nakamura et al.)
- 1995: High-brightness InGaN green LEDs (Nakamura et al.)
- 1996: First white LED; 5 lm/W; 50 000 hours lifetime (Nichia Company)
- 1997: Polarization fields in GaN and related materials (Bernardini et al.)
- 1998: Crystallographic wet chemical etching of GaN (Stocker at al.)
- 1999: Fabrication of thin-film InGaN light-emitting diode membranes by laser lift-off (Wong et al.)
- 2000: Nitride semiconductors free of electrostatic fields for efficient white light-emitting diodes (Waltereit et al.)
- 2000: Vision for Solid-State Lighting (Tsao et al.)
- 2004: Increase in the extraction efficiency of GaN-based light-emitting diodes via surface roughening (Fujii et al.)
- 2005: Introduction of the concept of “Smart Lighting” (Schubert and Kim)
- 2005: Remote phosphor configuration (Kim et al.)
- 2010: Retrofit lamps based on LEDs (all major LED manufacturers)
- 2011: 100 lm/W efficiency at high currents (XM-L XLamp, Cree Company)

12

Promise of Solid-State Lighting

13

Promise – Evolution of efficiency of LEDs

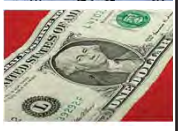


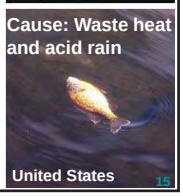
J. K. Kim *et al.* Opt. Express **16**, 21835 (2008)

14

Promise – Quantification of benefits

- **Energy benefits**
  - 22 % of electricity used for lighting
  - LED-based lighting can be **20** × more efficient than incandescent and **5** × more efficient than fluorescent lighting
- **Environmental and economic benefits**
  - Reduction of **CO_2** emissions, a **global warming gas**
  - Reduction of **SO_2** emissions, **acid rain**
  - Reduction of **Hg** emissions by coal-burning power plants
  - Reduction of hazardous **Hg** in homes
- **Financial benefits**
  - Electrical energy cost reduction, but also savings resulting from less pollution, global warming





15

Promise – Quality of light and color rendition

Incandescent lamp

CFL

LED

Low CRI illumination source

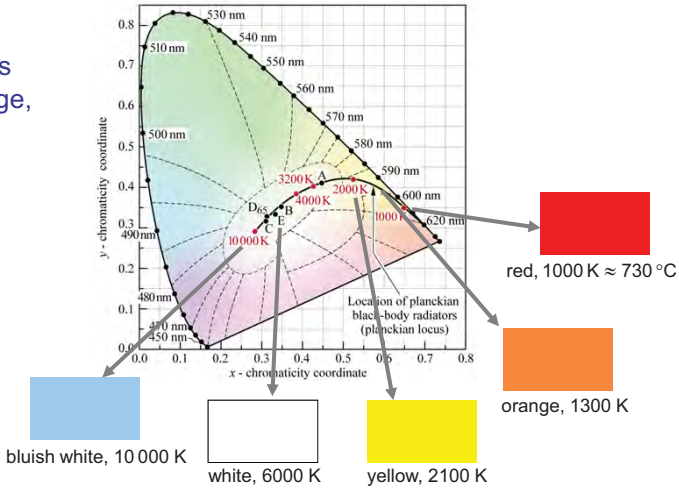
High CRI illumination source

16

Promise – Color Temperature

As temperature increases, hot objects glow in the red, orange, yellow, white, and bluish white

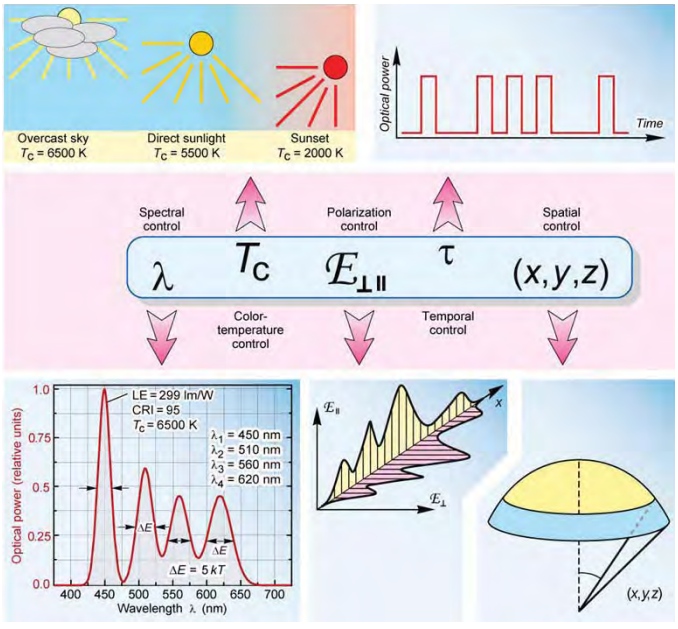
Example: Red-hot horseshoe



- Hot physical objects exhibit heat glow (incandescence) and a color
- Planckian radiator = Black, physical object with temperature *T*
- Color temperature = Temperature of planckian radiator with same location in chromaticity diagram

17

Promise – Beyond "Replacement Paradigm"



Controllable light sources enable fundamentally new applications

18

Future Generation of Lighting

Solid-State Light Sources Getting Smart

E. Fred Schubert and Jong Kyu Kim

More than a century after the introduction of incandescent lighting and half a century after the introduction of fluorescent lighting, solid-state light sources are revolutionizing an increasing number of applications. Whereas the efficiency of conventional incandescent and fluorescent lights is limited by fundamental factors that cannot be overcome, the efficiency of solid-state sources is limited only by human creativity and imagination. The high efficiency of solid-state sources already provides energy savings and environmental benefits in a number of applications. However, solid-state sources also offer controllability of their spectral power distribution, spatial distribution, color temperature, temporal modulation, and polarization properties. Such "smart" light sources can adjust to specific environments and requirements, a property that could result in tremendous benefits in lighting, automobiles, transportation, communication, imaging, agriculture, and medicine.

The history of lighting has taken several rapid and often unexpected turns (*1*). The first commercial technology for lighting was based on natural gas that served thousands of streets, offices, and homes at the end of the 19th century. As a result of the competition from Edison's incandescent lamp, gaslights were strongly improved by the use of mantles soaked with the rare-earth compound thorium oxide, which converted the gas flame's heat energy and ultraviolet (UV) radiation into visible radiation. Ultimately, however, the gaslights shown in Fig. 1 were displaced by incandescent light bulbs first demonstrated in 1879. Fluorescent tubes and compact fluorescent

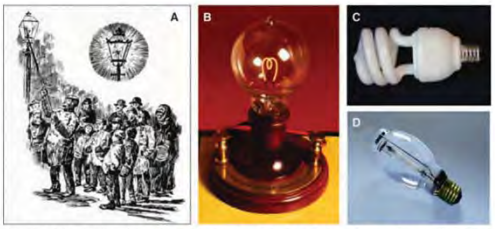


Fig. 1. (A) 1880s illustration of the nightly illumination of a gaslight with a thorium oxide–soaked mantle. (B) Replica of Edison's lamp. (C) Contemporary compact fluorescent lamp. (D) High-pressure sodium lamp.

gases (CO_2), emission of acid rain–causing SO_2, and mercury pollution. Solid-state lighting could cut the electricity used for lighting, currently at 22%, in half. Although tremendous energy savings have already materialized [e.g., traffic lights that use light-emitting diodes (LEDs) consume only one-tenth the power of incandescent ones], there is a sobering possibility that energy savings may be offset by increased energy consumption: More wasteful usage patterns, abundant use of displays, and an increase in accent and artistic lighting may keep the use of electricity for lighting at its current level [11% in private homes, 25% in commercial use, and 22% overall (*3*)].

Several promising strategies to create white light with the use of inorganic sources, organic sources, and phosphors are shown in Fig. 2, energy incurred when converting a 250-nm UV photon to a photon of the visible spectrum. The efficiency of incandescent lamps is limited to about 17 lm/W by the filament tem-

- Beyond "Replacement"
- "Smart" Lighting
- New opportunities for a better world

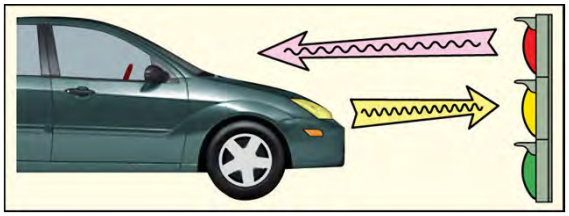
(*Science Magazine*, May 2005)

19

Promise – Beyond "Replacement Paradigm"

Controllable light sources will enable a wealth of new functionalities

- Example: Communicating lights

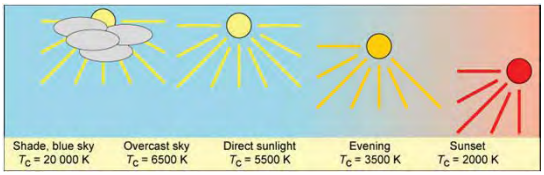


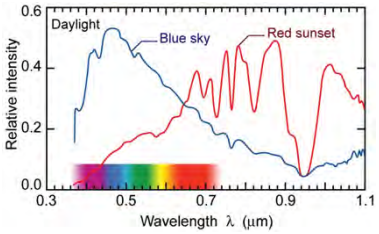
20

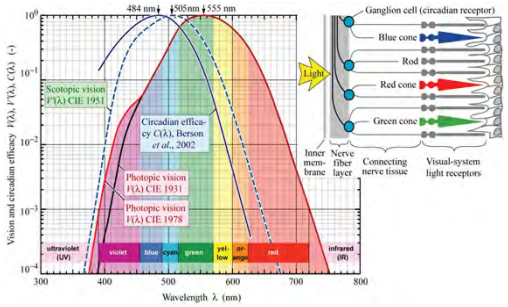
Promise – Beyond "Replacement Paradigm"

Controllable light sources will enable a wealth of benefits

- Example: Circadian lights





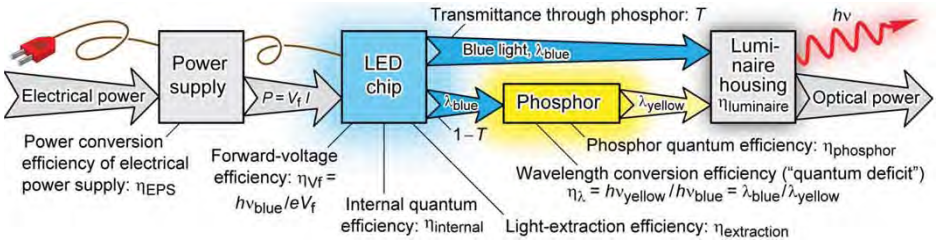


21

Challenges

22

Efficiency of LED



J. K. Kim *et al.* Opt. Express **16**, 21835 (2008)

- **Light-extraction efficiency**
  - Innovation in materials ➔ Materials with tunable refractive index
- **Internal quantum efficiency**
  - Innovation in devices ➔ The efficiency droop in LEDs

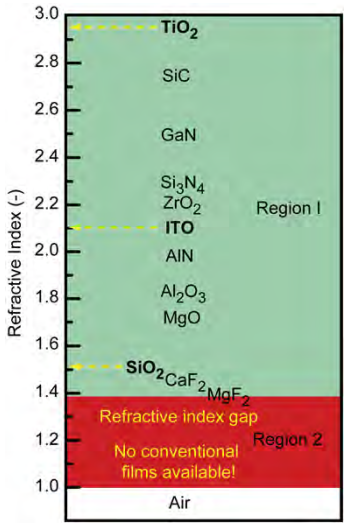
23

Materials with tailorable refractive index

24

Refractive Index = *n*

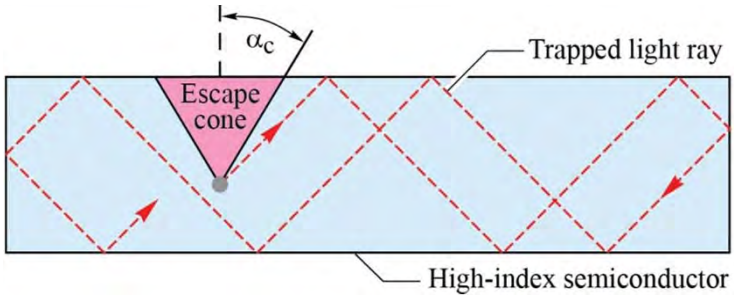
Isaac Newton



- Isaac Newton: Refraction experiments
  - Water, alcohol, glycerin
  - ➔ Optical density ➔ Refractive index
- Refractive index: Power of refraction
- Refractive index: Speed of light
- v_{phase} = speed of light in vacuum / n = c / n
- Dense materials $n \geq 1.39$:
  SiO_2 (n = 1.46); MgF_2 (n = 1.39)

25

Light extraction



- Semiconductor ➔ High refractive index (n = 2.5)
- Air ➔ Low refractive index (n = 1.0)

- Total internal reflection ➔ "Trapped Light"
  - How can we get the light out of the semiconductor?
    ➔ Look to Nature for guidance

26

Anti-reflection coatings

- True anti-reflection (AR) coating ➔ Graded-index AR coating
- "Mother Nature" used graded-index AR coatings thousands of years ago ➔ Jellyfish
- Lord Rayleigh (1880) found that the earth's atmosphere has no reflection

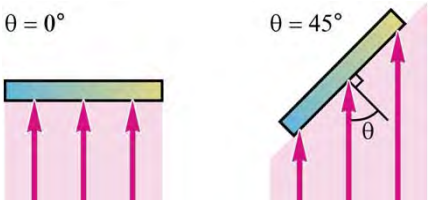
Jelly fish – Graded-index "AR coating"

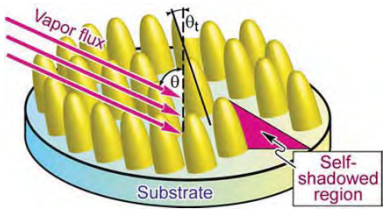
Earth atmosphere – Graded-index "AR coating

27

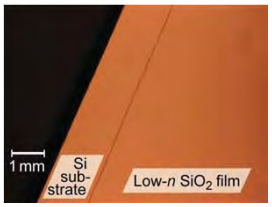
The refractive index gap: New class of materials required

- Dense materials $n \approx 1.4$: SiO_2 **($n = 1.46$);** MgF_2 **($n = 1.39$)**
- Low-*n*: refractive index $n < 1.25$
- Low-*n* films by oblique-angle evaporation

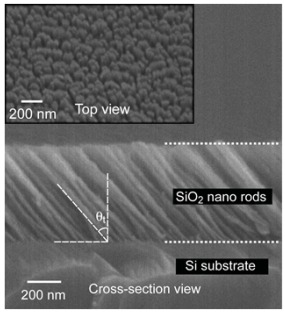




J.-Q. Xi *et al.* Nat. Photonics **1**, 176 (2007)
E. F. Schubert *et al.* Phys. Status Solid B **244**, 3002 (2007)



Optical micrograph

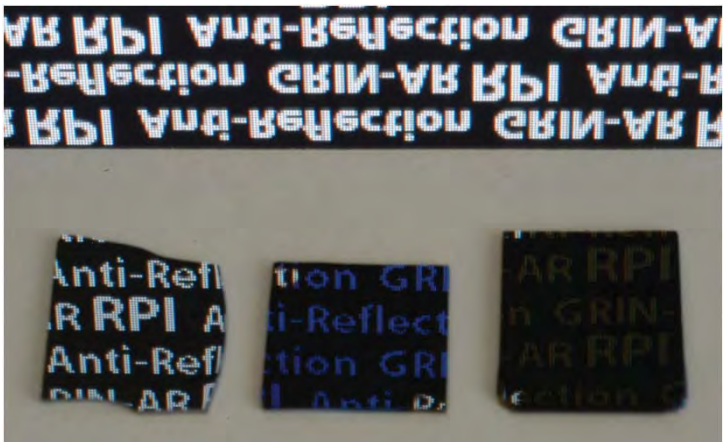


SEM

28

Anti-reflection coatings

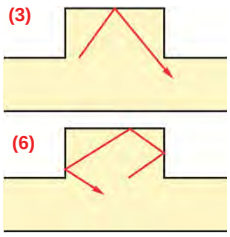
- Anti-reflection (AR) coating for broad range of angles and wavelengths

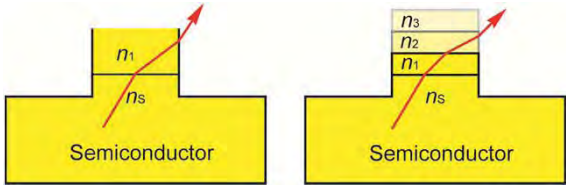


Comparison of AR coatings, 2008

29

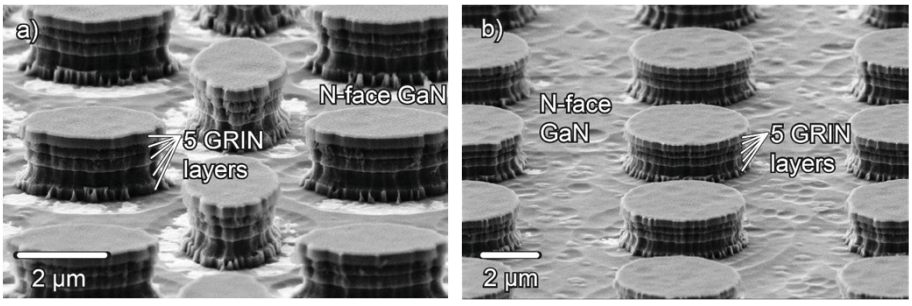
Graded-refractive-index pillar





Additional transparent layer with refractive index n_1 ($n_S > n_1 > 1$) on the pillar will result in a larger critical angle

A. N. Noemaun *et al.* J. Appl. Phys. **110**, 054510 (2011)



30

Solar cells

- Antireflection coatings for solar cells

Photovoltaic array

3 layer graded-index AR coating

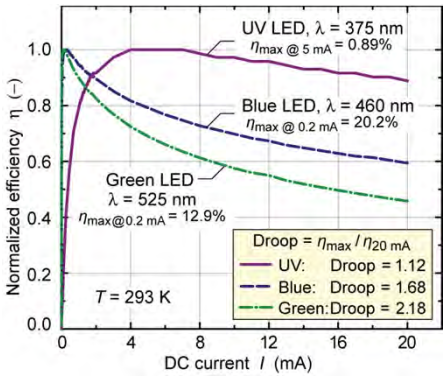
- Antireflection (AR) coatings reduce or eliminate unwanted reflections

31

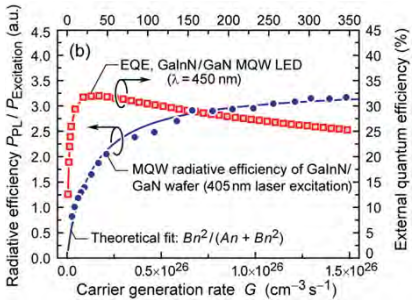
The Efficiency Droop

32

Challenges: Efficiency Droop in GaInN LEDs



- Efficiency is high, despite dislocations
- Efficiency decreases with increasing injection current
- Severe obstacle for high-power LEDs

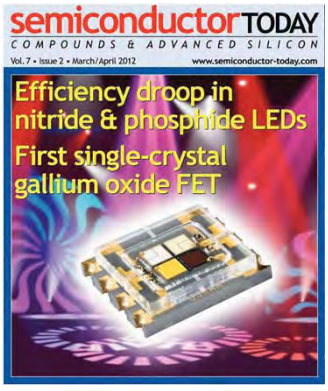


Min Ho Kim et al., 2007

33

The efficiency droop: Front-page news

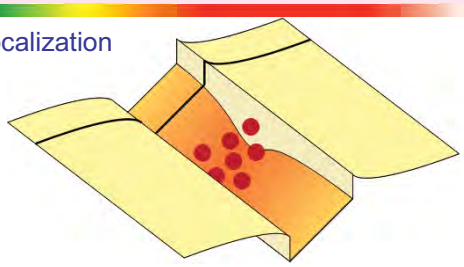
- Droop is the single largest loss mechanism in blue and white LEDs

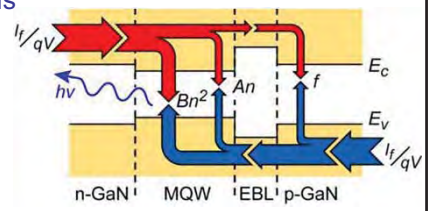


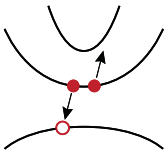
34

Efficiency droop – Proposed explanations

- Indium fluctuations, defects, and delocalization
  - S. Chichibu et al., 1997
  - A. Y. Kim, W. Götz, et al., 2001
  - B. Monnemar and Sernelius, 2007
- Heating (thermal rollover)
  - A. A. Efremov et al., 2006
- Electron leakage due to polarization fields
  - Min Ho Kim et al., 2007
  - M. F. Schubert et al., 2007, 2008, 2009
- Auger recombination
  - Y. C. Shen et al., 2007
  - N. F. Gardner et al., 2007
  - J. Hader et al. 2008
  - C. van de Walle et al. 2009 – 2012
- Defects
  - Density-activated defect recombination
  - J. Hader et al., 2010, 2011







35

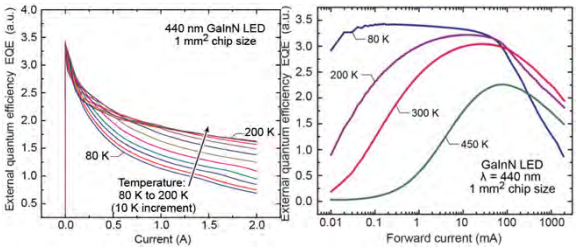
Unique features of III–V nitrides (GaN)

- Polarization fields
  - Capture of electrons into QWs is hindered
  - Electrons drift away from last QW into spacer layer
  - Very thin QWs to reduce QCSE (Quantum-confined Stark Effect)
- Asymmetry between electron and hole transport
  - Electron concentration $n \approx 10^{18}$ cm^{-3}
  - Hole concentration $p \approx 10^{17}$ cm^{-3}
  - Electron mobility $\mu_n \approx 250$ cm^2 / (V s)
  - Hole mobility $\mu_p \approx 2.5$ cm^2 / (V s)
  - $(n \mu_n) / (p \mu_p) > 100$ ➔ High-level injection
- Dislocation density
  - TDD in GaN grown on sapphire is 10^7 – 10^9 cm^{-2}
- InN clusters on GaInN
  - Alloy clustering in GaInN, especially at high In mole fractions

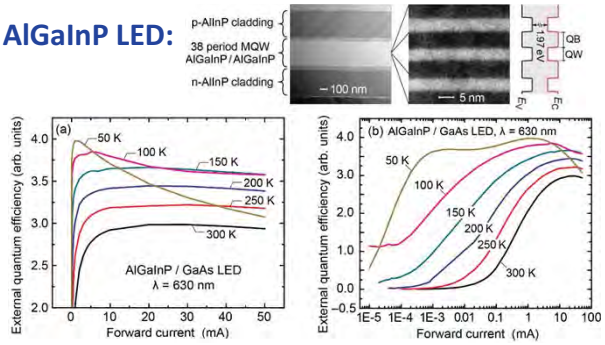
36

Droop in GaN and AlGaInP LEDs

GaInN LED:



AlGaInP LED:



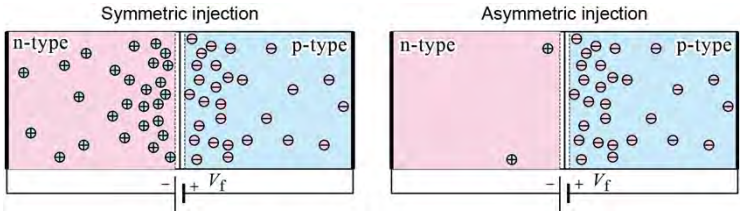
- Different from GaInN, AlGaInP has:
  - No dislocations
  - No narrow active region (MQW with 38 QWs)
  - Lower carrier concentrations in active region
  - No In clustering that was found in GaInN QWs
  - No polarization fields

➔ Droop in LEDs is a more general problem than initially thought

37

Asymmetry of pn junction

- Symmetry of carrier transport

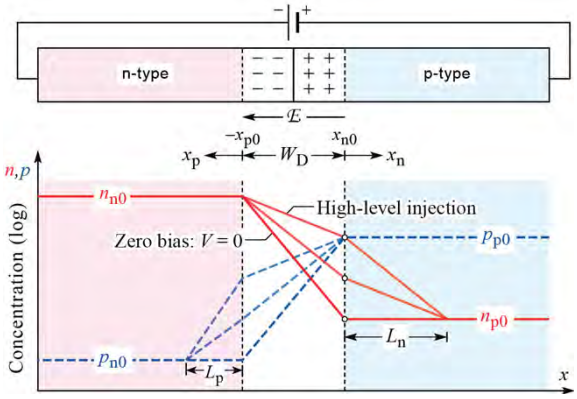


$$J = e\left(\sqrt{\frac{D_p}{\tau_p}}\,p_{n0} + \sqrt{\frac{D_n}{\tau_n}}\,n_{p0}\right)\left(e^{eV/kT} - 1\right)$$

- In GaN:
  - Large difference in free carrier concentration ($n > p$)
  - Large difference in mobilities and diffusion constants ($\mu_n > \mu_p$)

38

Asymmetry of pn junction



- Asymmetry in *n* and *p*
  - ➔ High-level injection
- Asymmetry in μ_n and μ_p
  - ➔ Drift of electrons faster than that of holes
  - ➔ Recombination pushed into p-type layer

39

High injection condition in pn junctions

- Shockley's ***high-injection condition*** (1950):

$$\Delta n_p(0) << p_{p0}$$

- In the presence of a large mobility disparity, the high-injection condition needs to be generalized:

$$\Delta n_p(0)\, \mu_n << p_{p0}\, \mu_p$$

- High-level injection more severe in GaN due to large asymmetry in pn junction

40

Analytic Model for Efficiency Droop

- Electron leakage in low-injection regime

$$J_{\text{Diffiusion}} = \frac{e\, D_n\, \Delta n_p(0)}{L_{\text{p-GaN}}}$$

- Electron leakage driven by electric field in high-injection regime

$$J_{\text{Drift}} = e\,\mu_n\,\Delta n_p(0)\,\mathcal{E} = e\,\mu_n\,\delta\, n_{QW}\,\frac{J_{\text{Total}}}{\sigma_p}$$

- One obtains

$$J_{\text{Drift}} = e\,\mu_n\,\delta\, n_{QW}\,\frac{J_{\text{Total}}}{e\,\mu_p\, p_{p0}} \approx e\, d_{\text{active}}\,\frac{\delta\,\mu_n}{\mu_p\, p_{p0}} B\, n_{QW}^{\,3} = e\, d_{\text{active}}\, C_{DL}\, n_{QW}^{\,3}$$

41

Analytic Model for Efficiency Droop

- Recombination can be described by
  - $R = An + Bn^2 + Cn^3 + \text{f}(n)$
- Analysis shows
  - $\text{f}(n) \propto n_{QW}^{\,3}$ near efficiency peak
  - $\text{f}(n) \propto n_{QW}^{\,4}$ beyond efficiency peak where droop is significant

$$R = A_{SRH}\, n_{QW} + B n_{QW}^{\,2} + \text{f}(n_{QW})$$
$$= A_{SRH}\, n_{QW} + B n_{QW}^{\,2} + C_{\text{Auger}} n_{QW}^{\,3} + C_{DL} n_{QW}^{\,3} + D_{DL} n_{QW}^{\,4}$$

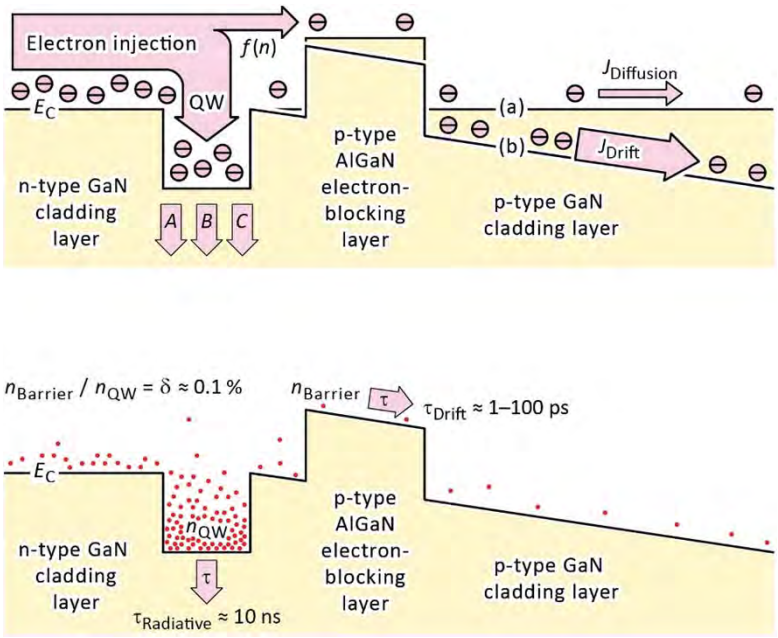
$$C_{DL} = \frac{\delta\,\mu_n}{\mu_p\, p_{p0}} B \qquad D_{DL} = \left(\frac{\delta\,\mu_n}{\mu_p\, p_{p0}}\right)^2 B$$

$$n_{\text{peak-IQE}} = \sqrt{A_{SRH}/C}$$

$$J_{\text{Onset-of-droop}} = e d_{\text{active}} B n_{\text{peak-IQE}}^{\,2} = e d_{\text{active}} \frac{B\, A_{SRH}}{C_{DL}} = e d_{\text{active}} A_{SRH} \frac{p_{p0}\,\mu_p}{\delta\,\mu_n}$$

42

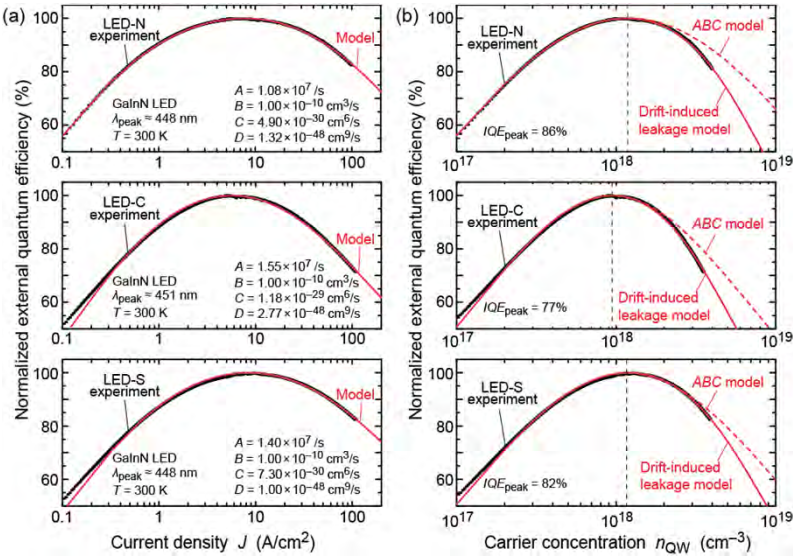
Why does droop occur despite good carrier confinement?



43

Testing of model with devices

- Excellent agreement with experiments



44

Testing models for droop

Properties	Experiments	Drift-induced leakage model
Magnitude of *C* coefficient	$C = 10^{-29}$ cm^6/s ± factor of 10	**~ 10^{-29} cm^6/s**
Onset-of-droop current density	1 – 10 A/cm^2	✓
Temperature dependence of the droop	$T\downarrow$ ➔ $C\uparrow$	✓
Symmetry of the *EQE*-vs.-*n* curve	Asymmetric	**Asymmetric**
Droop in different materials	GaInN and AlGaInP	✓

45

Future

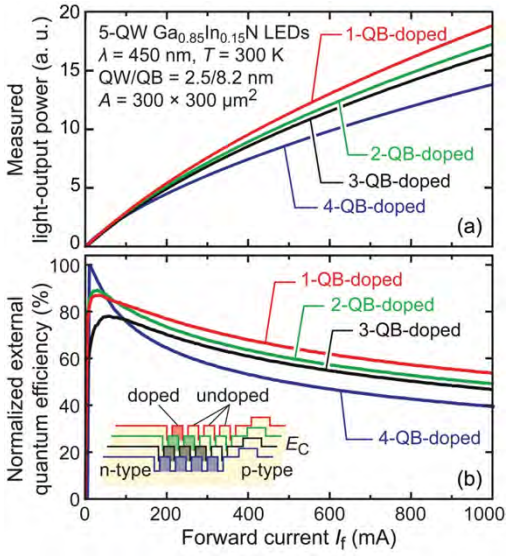
$$C_{DL}\, n^3 = \frac{\delta\, \mu_n}{\mu_p\, p_{p0}} B\, n^3$$

- Reduce n
  - Thinner QBs; Reduction of n-type doping in active region
- Increase p_{p0}
  - New dopants; p-type GaInN; p-type superlattices
- Increase μ_p
  - New material compositions; strain; modulation doping
- Decrease δ
  - Polarization-matched EBL; polarization-matched MQW; Reduction of polarization charge at spacer-EBL interface
- Reduce $\mathcal{E}$ (Polarization field)
  - Non-polar growth; Polarization matching concept

46

The Efficiency Droop has been reduced !

- Hindering electron transport through ***tailored doping*** of quantum barriers reduces the escape of electrons from the active region



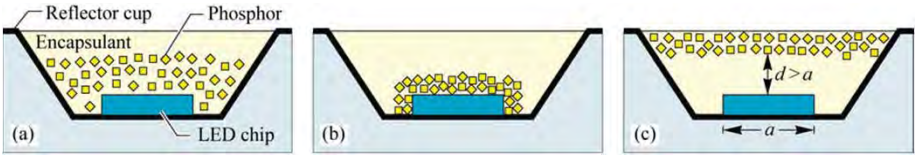
47

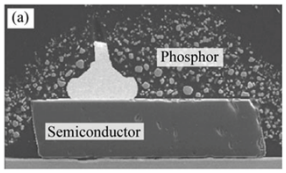
Phosphor Distributions

48

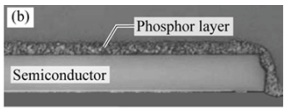
Innovation in white LEDs – Phosphor distribution

- Novel phosphor distributions promise higher efficiency

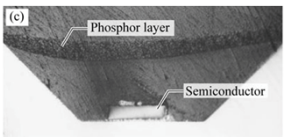




Proximate distribution
(after Goetz *et al.*, 2003)



Proximate distribution
(after Goetz *et al.*, 2003)



Remote distribution
(after Kim *et al.*, 2005)

Kim et al., Jpn. J. Appl. Phys. Exp. Lett. 44, L649 (2005)

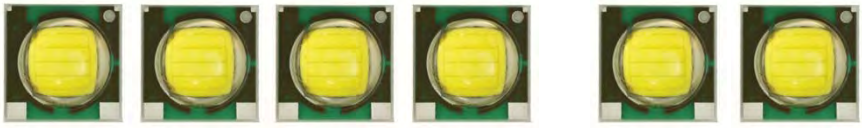
Luo et al., Appl. Phys. Lett. 86, 243505 (2005)

49

The Future of Lighting

50

The bright future of LED lighting



Cree Company LEDs

Pictures downloaded from Internet

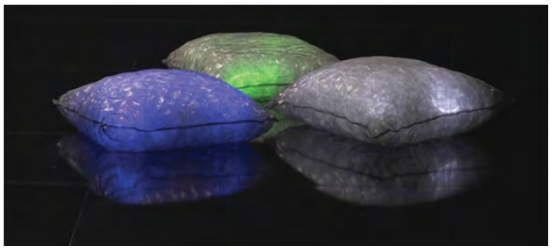
51

The bright future of LED lighting

Pictures downloaded from Internet

52

The bright future of LED lighting



Pictures downloaded from Internet

53

Conclusion

- The Future of Lighting has begun
  - We are beginning to appreciate what can be accomplished by going "beyond the replacement paradigm"
- Challenges
  - Light extraction
    - New materials with tunable refractive index
    - New LED structures
  - The Efficiency Droop
    - The technical community is divided on the question of the Efficiency Droop
    - However, a consensus may form around the Asymmetry of carrier transport being the origin of the droop
- The Promises are greater than the Challenges
  - We are entering a new era in lighting
  - Huge energy savings are made possible
  - Very positive environmental effects are enabled
  - Smart Lighting – The Future of Lighting

54

Acknowledgements

- Support:
  - Samsung LED Company
  - Sandia National Laboratories (SNL) under EFRC program in SSL Sciences
  - Department of Energy
  - National Science Foundation
  - Korean Ministry for Knowledge and Economy (MKE)
  - Magnolia Solar Company

55