# COOLING EFFECT IN LIGHT-EMITTING DIODES JUNCTIONS

P. Pobedinskas, A. Kalkys
*Institute of Materials Science and Applied Research, Lithuania*

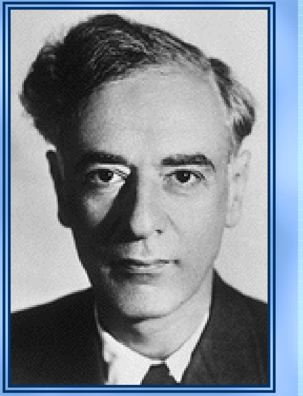
Supervisor prof. A. Žukauskas

# Content

- Historical Overview
- Optical refrigeration
- Cooling in LED junction
- Results
- Summary

# History[1]

Peter Pringsheim
(1881-1963)



Lev Davidovic Landau
(1908-1968)

1929 Pringsheim has shown that cooling of fluorescing gas by means of anti-Stokes fluorescence do not contradict to second thermodynamic law [1].

1946 Landau established the basic thermodynamic consistency of fluorescent cooling and proved that the entropy lost by the sample upon cooling is more than compensated for by an increase in the entropy of the light, resulting from the loss of monochromaticity, phase coherence, and directionality of the beam [2].

[1] P. Pringsheim, "Zwei Bemerkungen über den Unterschied von Lumineszenz und Temperaturstrahlung", *Z. Phys.* 57, 739 (1929).

[2] L. Landau, “On the thermodynamics of photoluminescence”, *J. Phys.* (Moscow) 10, 503 (1946).

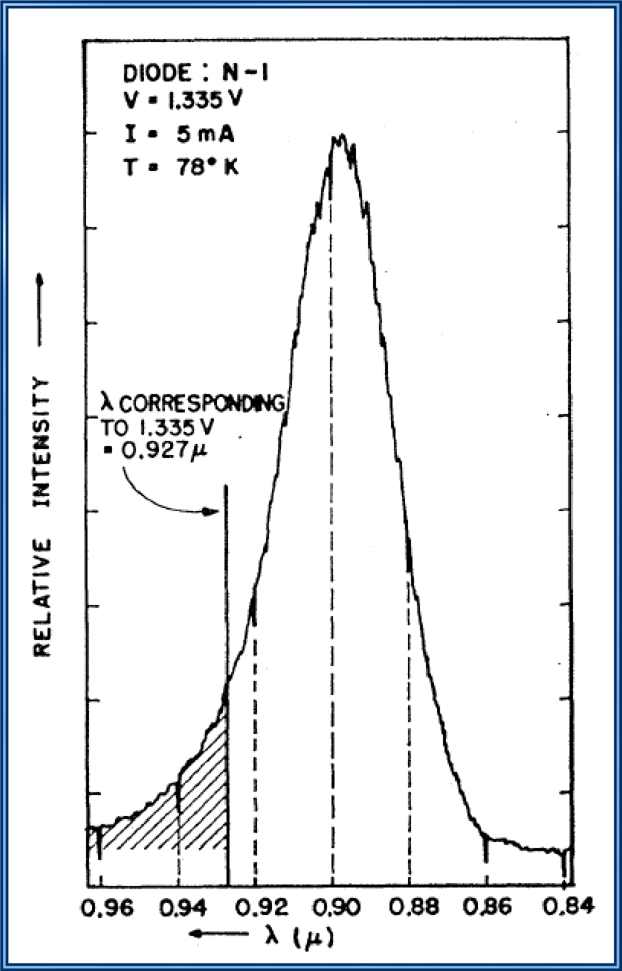
# History$^2$

1957 J. Tauc proposed fluorescent cooling for semiconductors [3].

1964 Dousmanis et al. [4] reported that the energy of the average photon that is emitted from a GaAs diode exceeded the energy supplied by the bias voltage. However, sufficient external quantum efficiencies to produce cooling were never achieved.

Other materials have also been discussed or investigated as possible fluorescent coolers:

- vapor or rare-earth ions in salt crystals (1950);
- organic dye solutions (1972).



---

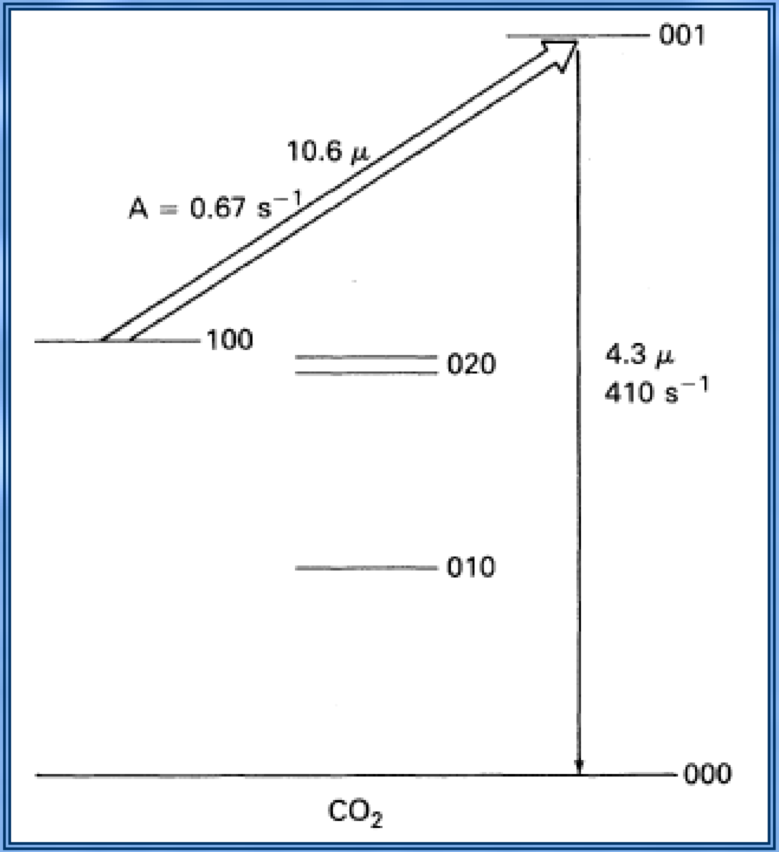
[3] J. Tauc, “The share of thermal energy taken from the surroundings in the electro-luminescent energy radiated from a p-n junction”, *Czech. J. Phys.* **7**, 275 (1957).

[4] G.C. Dousmanis, C.W. Mueller, H. Nelson and K.G. Petzinger, “Evidence of refrigeration action by means of photon emission in semiconductor diodes”, *Physical Review* **133**, A316-318 (1964).

# Optical refrigeration

With the advent of lasers, the first experimental attempt to achieve real fluorescent cooling became possible.

The first system in which actual cooling was observed involved vibrational transitions of carbon dioxide gas pumped by a $CO_2$ laser [5]. The observed pressure changes were consistent with about one degree of cooling.



[5] N. Djeu and W.T. Whitney, "Laser cooling by spontaneous anti-Stokes scattering", *Phys. Rev. Lett.* **46**, 236 (1981).

# Optical refrigeration in phosphors

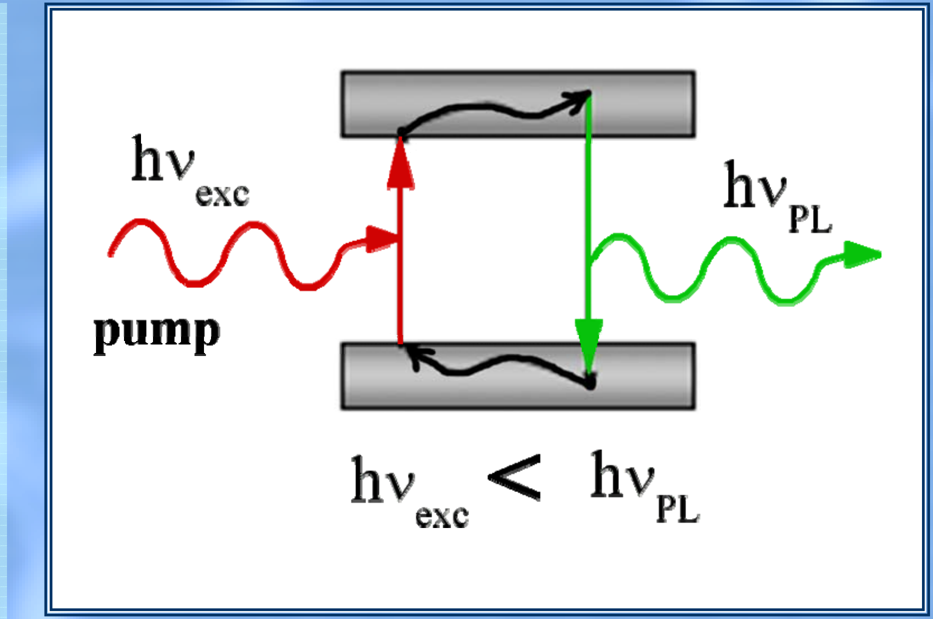
1995 the first optical refrigeration in ytterbium-doped glass [3].

2005 record cooling to 208 K by optical refrigeration with ytterbium-doped glass [4].

Optical cooling also achieved in:

1996 dye solutions [5];

2000 thulium-doped glass [6].



[3] R. I. Epstein, M. I. Buchwald, B. C. Edwards, T. R. Gosnell, and C. E. Mungan, “Observation of laser-induced fluorescent cooling of a solid”, *Nature* (London) **377**, 500 (1995).
[4] J. Thiede, J. Distel, S. R. Greenfield, and R. I. Epstein, “Cooling to 208 K by optical refrigeration”, *Appl. Phys. Lett.* **86**, 154107 (2005).
[5] J. L. Clark and G. Rumbles, “Laser Cooling in the Condensed Phase by Frequency Up-Conversion”, *Phys. Rev. Lett.* **76**, 2037 (1996).
[6] C.W. Hoyt, M. Sheik-Bahae, R. I. Epstein, B. C. Edwards, and J. E. Anderson, “Observation of Anti-Stokes Fluorescence Cooling in Thulium-Doped Glass”, *Phys. Rev. Lett.* **85**, 3600 (2000).

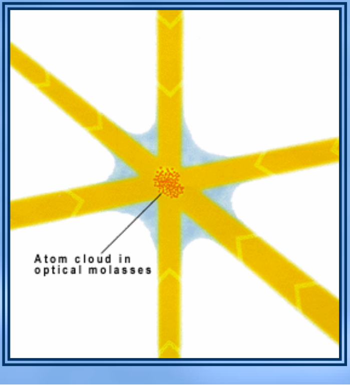
# The Nobel Prize in Physics 1997

Steven Chu,
Stanford
University

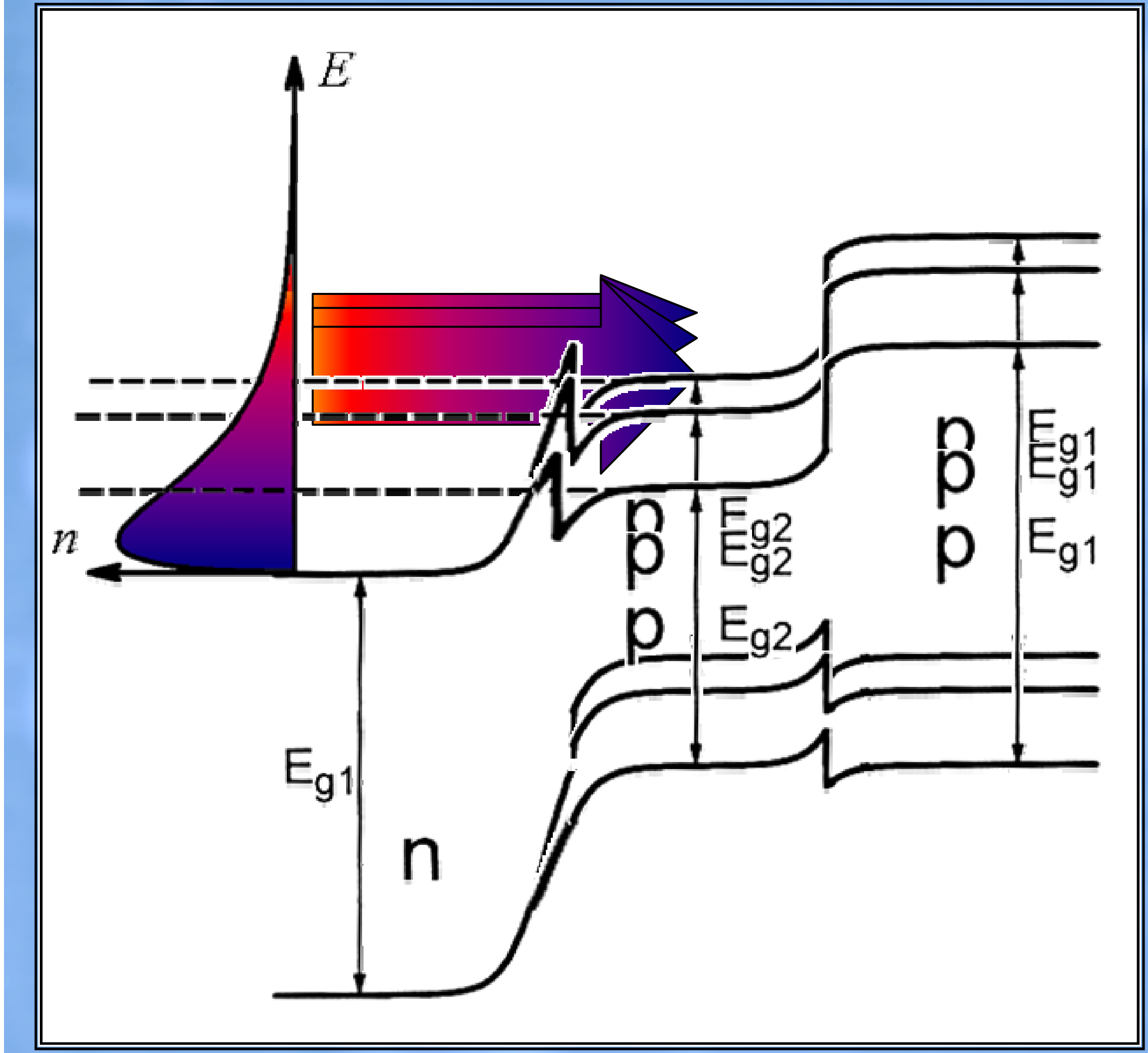
Claude Cohen-Tannoudji,
The Collège de
France

William D.
Phillips,
NIST

**"for development of methods to cool and trap atoms with laser light"**



# Cooling in LED junction



Electrons in the conduction band of n-type region are distributed by Fermi-Dirac law.

Even at low supplied bias voltage high energy tail of electrons can move to p-type region where they recombine with holes.

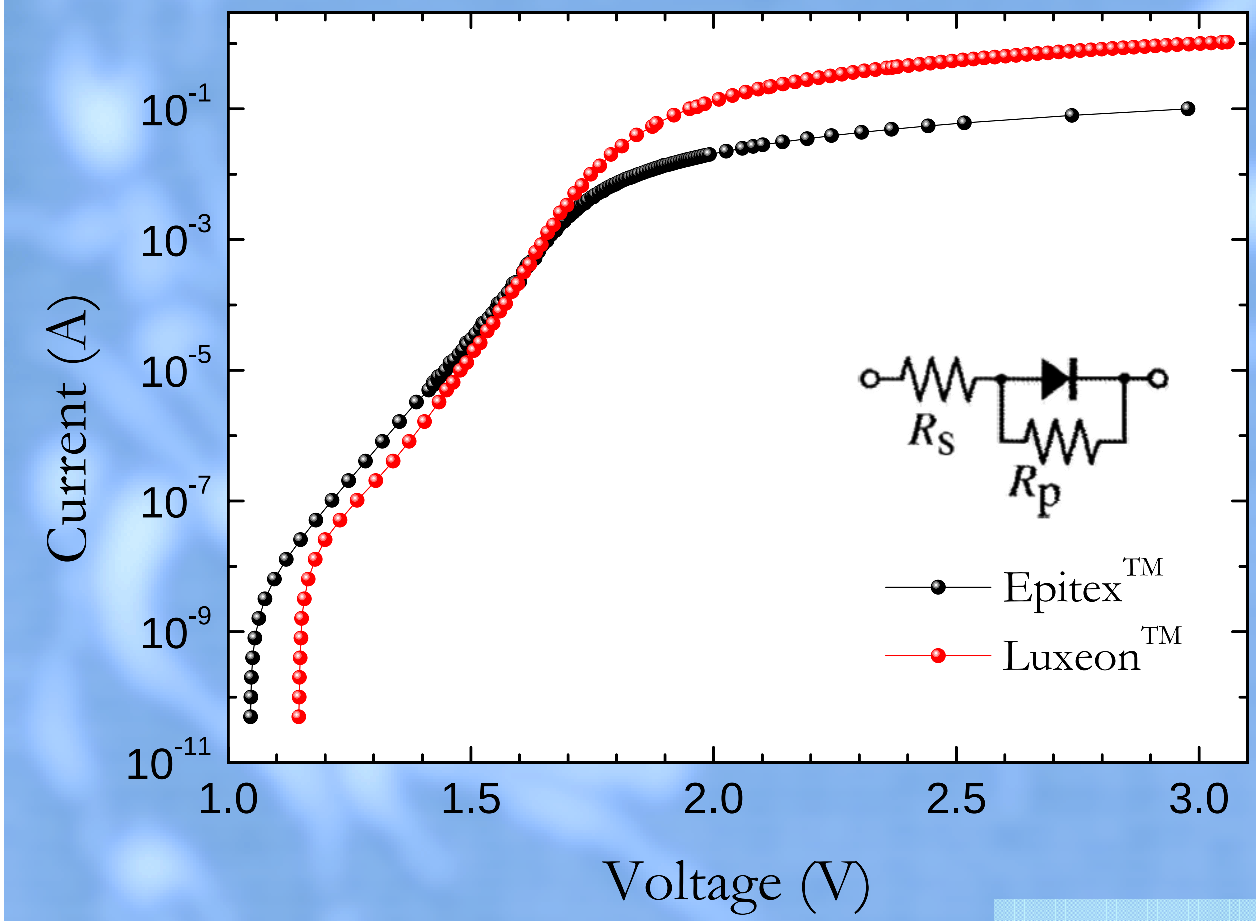
Extraction of high energy electrons results in system cooling.

# The subject of research

In this work, we have investigated two commercial red LEDs:

- Epitex™ low-power AlGaAs LED (40 mW);
- Luxeon™ high-power AlGaInP LED (3 W).

# *I – V* characteristics



$R_S$ - LED series resistance due to contact and cladding layers. It was extracted from the differential *I-V* characteristics [7].

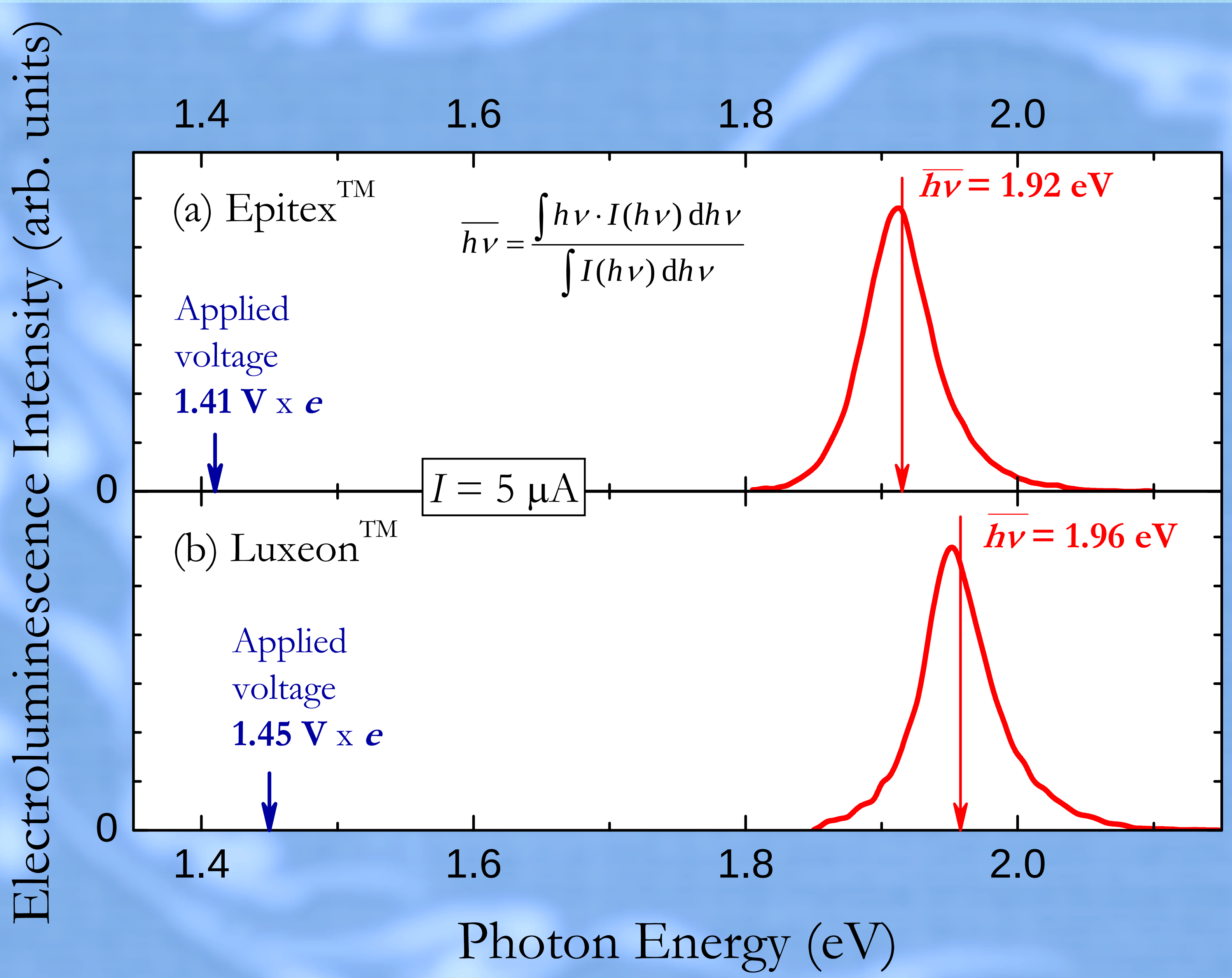
$$I\frac{dV}{dI} = R_s I + \frac{k_B T}{e}$$

$R_S$ = (12,17 ± 0,06) Ω [Epitex™ ]

$R_S$ = (1,006 ± 0,005) Ω [Luxeon™]

[7] E.F. Schubert, *Light-Emitting Diodes*, Cambridge University Press 59-61 (2003).

# Electroluminescence spectra



$$\overline{h\nu} = \frac{\int h\nu \cdot I(h\nu)\, \mathrm{d}h\nu}{\int I(h\nu)\, \mathrm{d}h\nu}$$

Applied
voltage
**1.41 V** x ***e***

Applied
voltage
**1.45 V** x ***e***

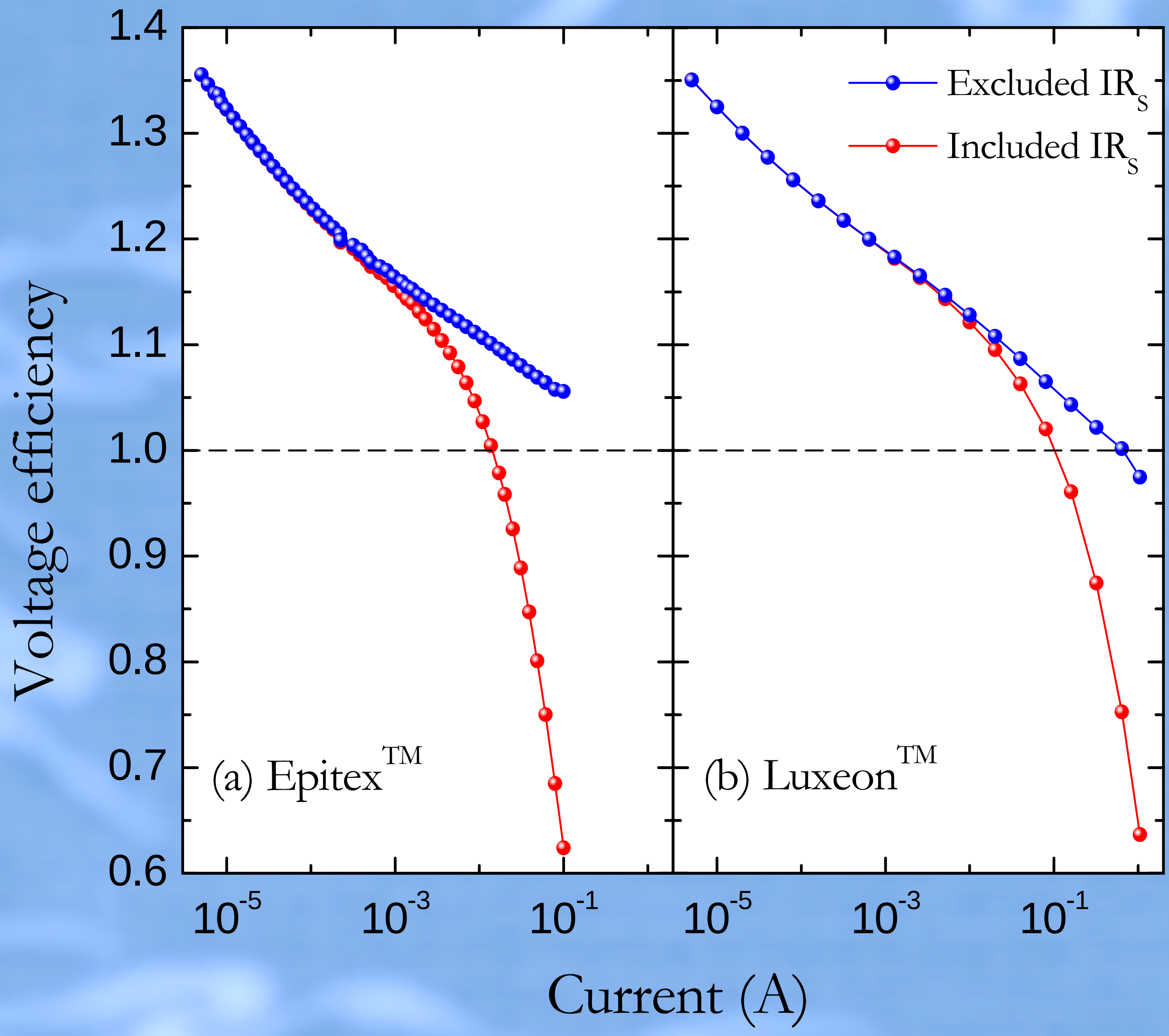
# Voltage efficiency

$$\eta_V = \frac{qV}{h\nu}$$

$q = 1.6 \times 10^{-19}$ C

*V* – the forward voltage drop :

- ● in p-n junction
- ● across the LED



# Hypothetical p-n junction cooling power

Cooling power:

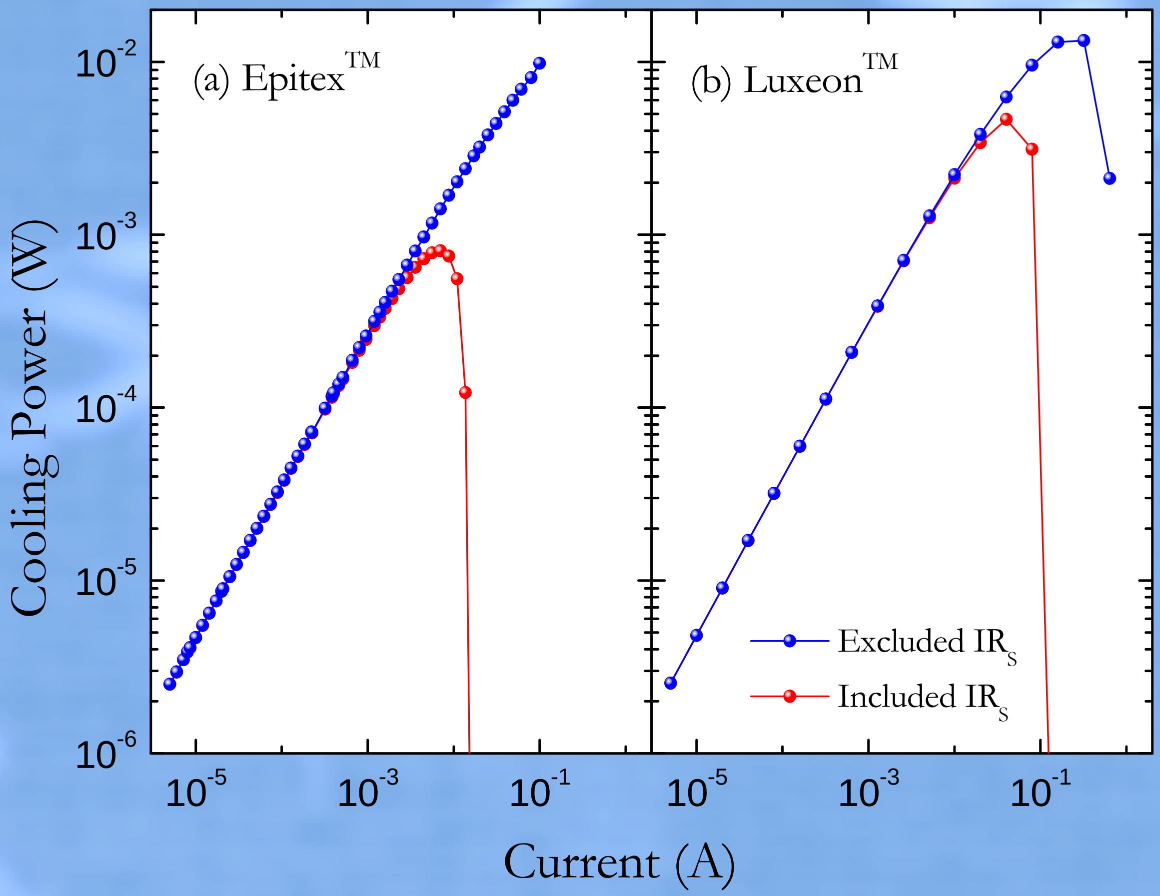
$$P = \eta\left(\overline{h\nu} - qV\right)I$$

Efficiency:

$$\eta = \eta_{ext} \times \eta_V$$

$$\eta_{ext} = \eta_{inj} \times \eta_{rad} \times \eta_{opt}$$

*ext* – external quantum efficiency
*inj* – injection efficiency
*rad* – internal quantum efficiency
*opt* – light-extraction efficiency



Experimental dependencies of hypothetical p-n junction cooling power on current for the red LEDs, assuming the external quantum efficiency is unity.

# Summary

- For internal cooling $\eta$>1 is required. In our experiment $\eta_v$ is 1.35 at 5 μA, so if $\eta_{ext}$ would be more than 0.74 we could observe net cooling.
- $P_{\max}^{\eta=1} = 10\ \mathrm{mW}$.
- Series resistance is one of the limiting factors that prevent electroluminescence cooling at high currents.