Engineering novel light-emitting devices by controlling light-matter interactions

Konstantinos Daskalakis (Kostas)
Luminous Materials and Devices
Mechanical and Materials Engineering
konstantinos.daskalakis@utu.fi

UNIVERSITY OF TURKU

Outline

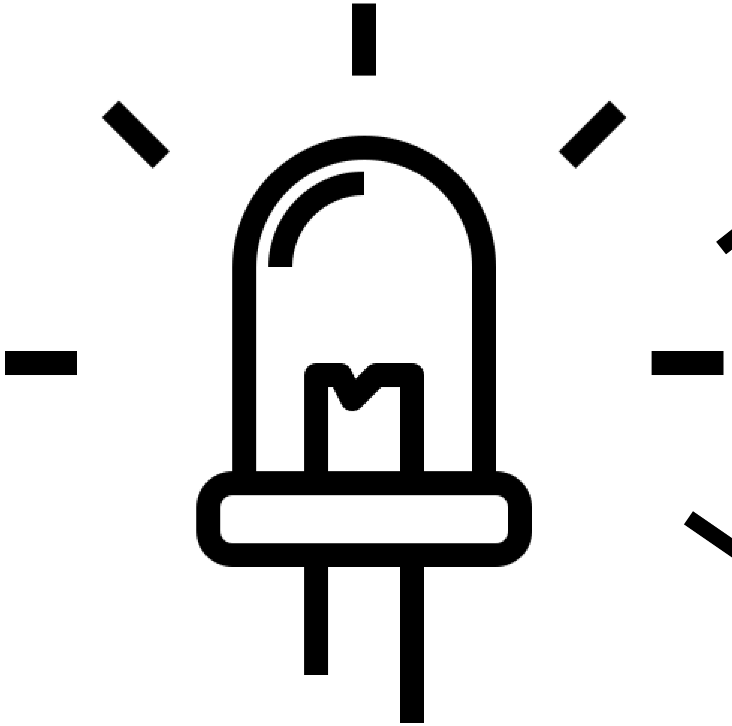
- Light-emitting devices and lighting
- Generating light in semiconductors
- Photonics for controlling light matter interactions

Outline

- Light-emitting devices and lighting
- Generating light in semiconductors
- Photonics for controlling light matter interactions

Light emitting devices

Light-emitting diode (LED)



Laser diode (LD)

LED screens

Applications

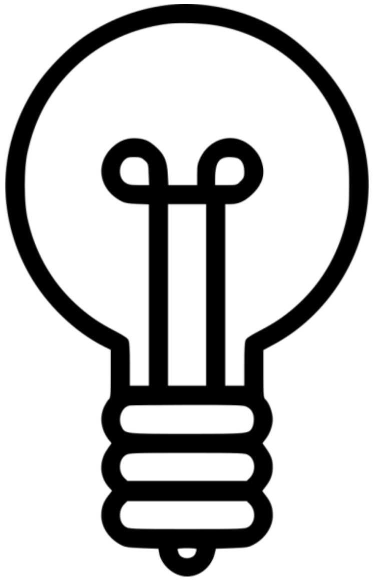
- optical communications
- optical computing and interconnects
- data transmission and signal processing
- optical storage
- optical imaging
- displays
- **lighting**

UNIVERSITY OF TURKU

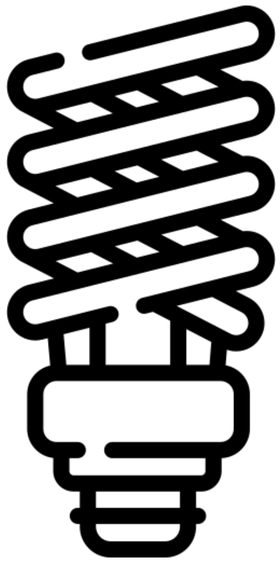
Lighting Technologies ("Light bulbs")

History of light bulb

Age	19th century	20th century	21th century
Lifespan	1000 hours	8500 hours	25000 hours
Cost	$0.5	$4	$6-20
Efficiency	16 lm/W	70 lm/W	300 lm/W
Fabrication	Easy	Very difficult	Difficult



Incandescent



Fluorescent

LED

UNIVERSITY OF TURKU

Improving artificial illumination

Nobel Prize in Physics 2014

Isamu Akasaki | Hiroshi Amano | Shuji Nakamura

- **Artificial illumination is an inherently <u>non-sustainable</u> human need!**

[1]Global lighting market currently consumes 20% of total electric power generated; 400 <u>million tons of CO_2</u>

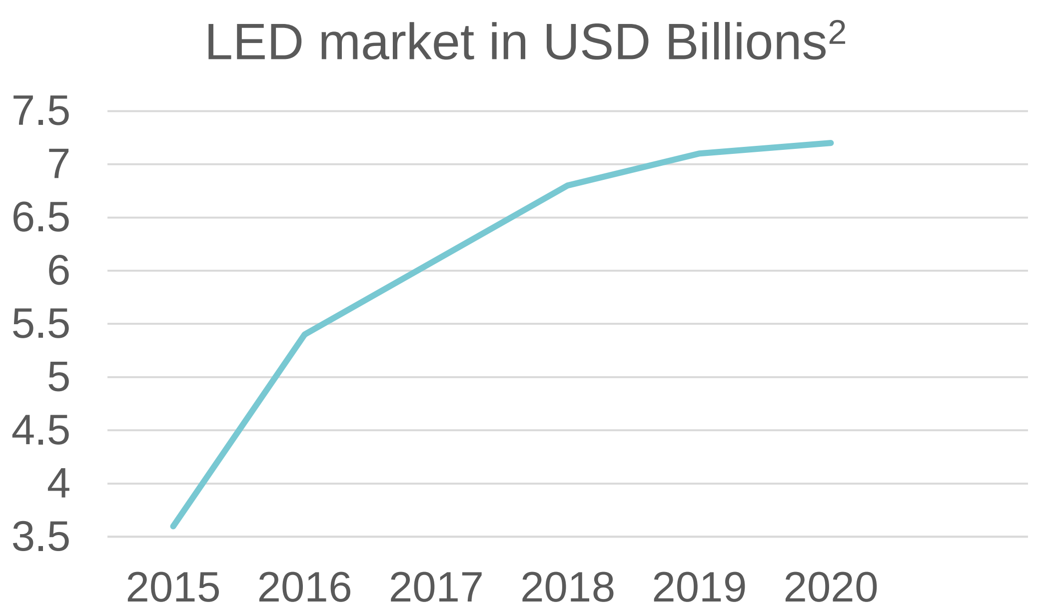
- **The LED breakthrough:**
 Decreased energy consumption.

But, what is the impact to the environment?

[1]T. Baumgartner et. al., “Lighting the Way: Perspectives on the Global Lighting Market.” McKinsey & Company, 2012.

UNIVERSITY OF TURKU

Environmental impact of LEDs



LEDs
-contain rare earth and toxic heavy metal
-mass-produced
-fabrication and waste management has negative environmental impact[4]

2. https://www.ledtopplus.com/blog/analysis-of-the-development-trend-of-led-lamps-market-in-2018-62
3. Franz, M., & Wenzl, F. P. (2017). Critical review on life cycle inventories and environmental assessments of LED-lamps. *Critical Reviews in Environmental Science and Technology*, *47*(21).

OLEDs, a solution with new exciting problems

OLED lamps

New organic LED technology - OLED – almost solves LED problems.

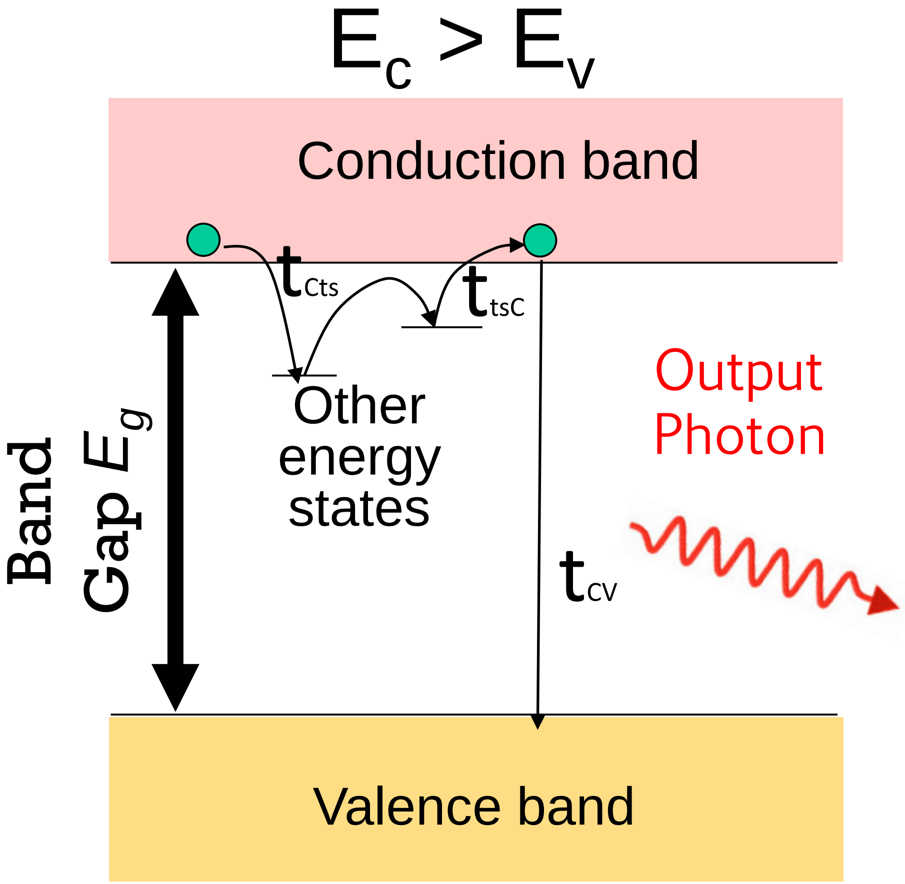
OLEDs are easy to fabricate and organic semiconductors are inherently “green material”.

Today’s COMMERCIAL OLEDs:
1) unstable, 2) small lifetime and 3) use heavy metals.

Outline

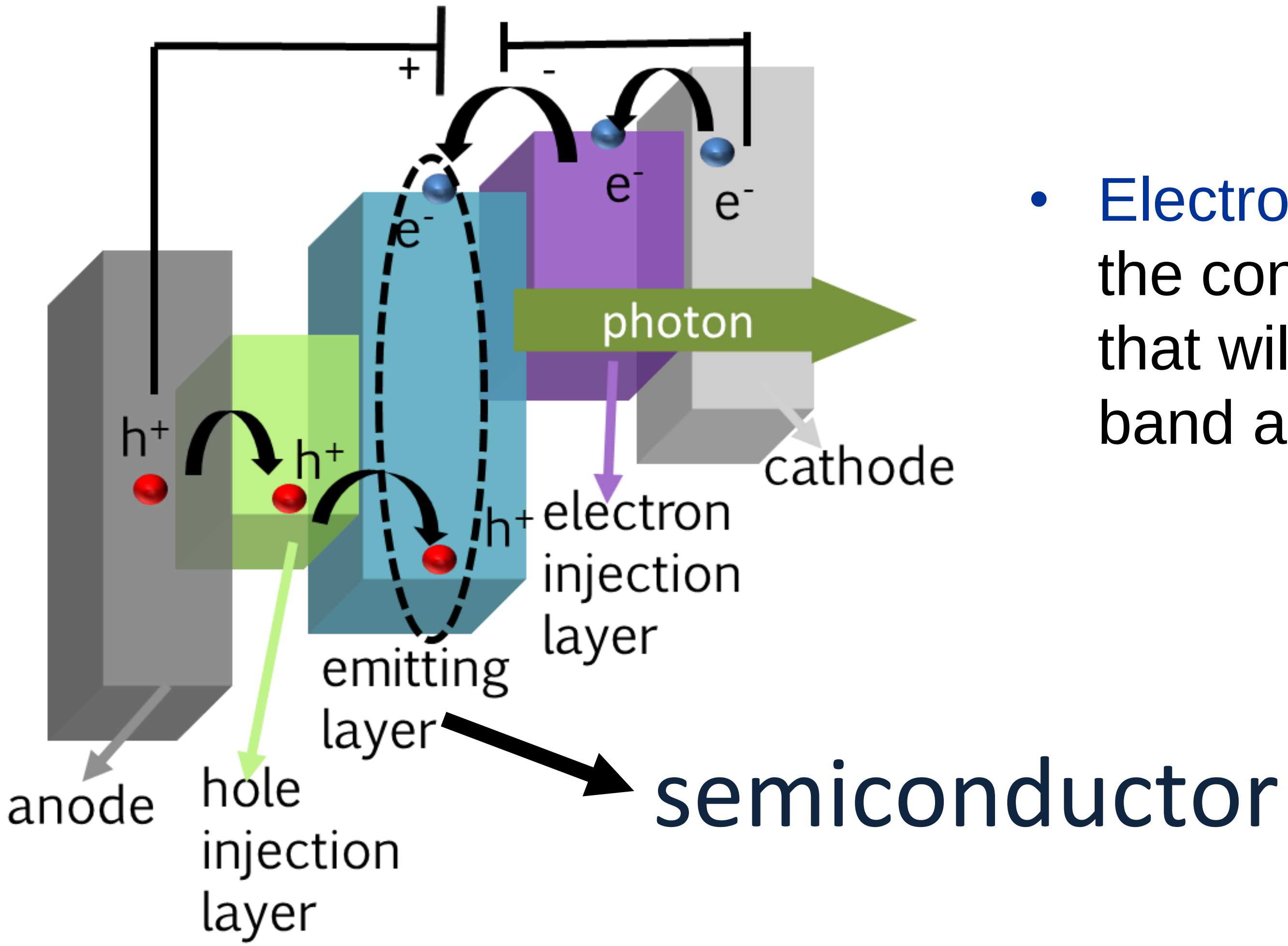
- Light-emitting devices and lighting
- Generating light in semiconductors
- Photonics for controlling light matter interactions

Electroluminescence in semiconductors



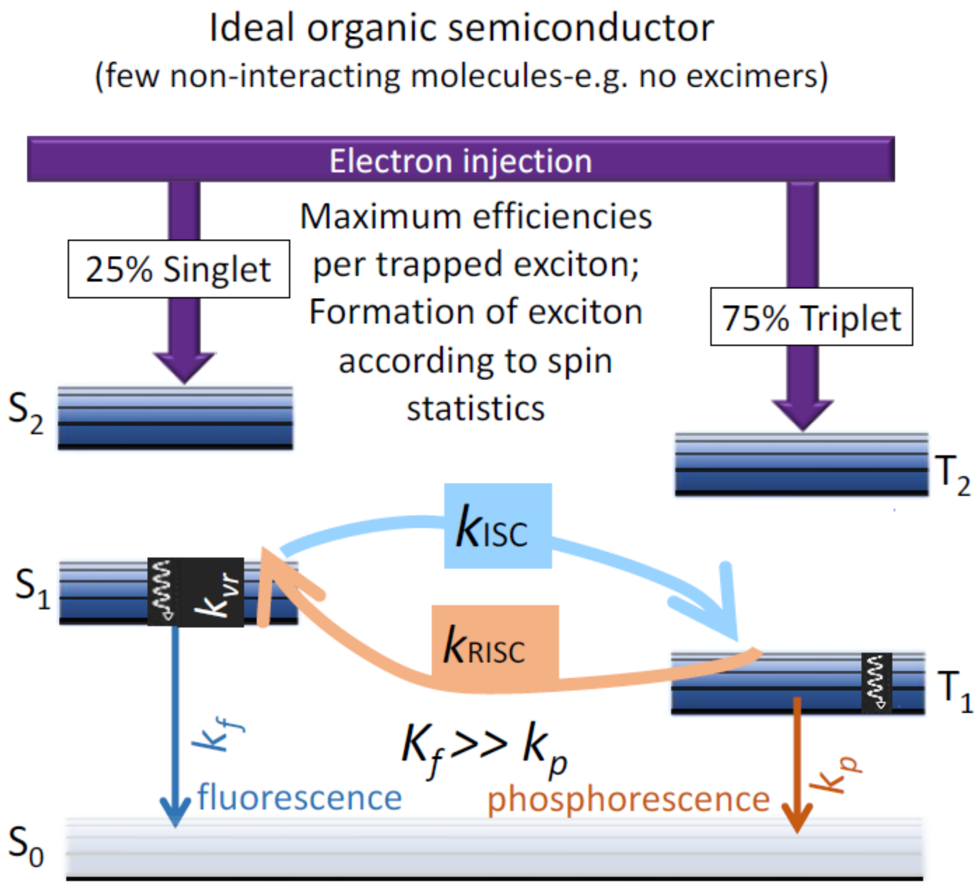
- Electroluminescence –we populate the conduction band with electrons that will (hopefully) relax to valence band and give us photons!

Electroluminescence in semiconductors



- Electroluminescence –we populate the conduction band with electrons that will (hopefully) relax to valence band and give us photons!

OLEDs have many non-radiative paths: low lifespan and efficiency



- In OLEDs, generating EL is a complex process!

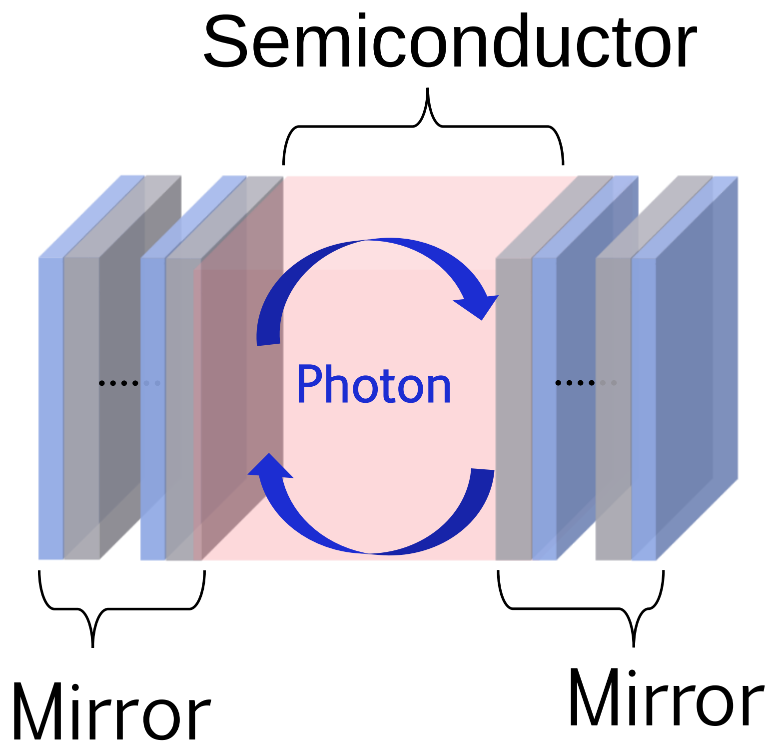
Xiao et. al., *Appl. Sci.*, vol. 8, no. 9, p. 1449, Aug. 2018.
Murawski et. al., *Adv. Mater.*, vol. 25, no. 47, pp. 6801–6827, 2013.
Li et. al., *Nat. Commun.*, vol. 10, no. 1, p. 731, Dec. 2019

Outline

- Light-emitting devices and lighting
- Generating light in semiconductors
- Photonics for controlling light matter interactions

UNIVERSITY OF TURKU

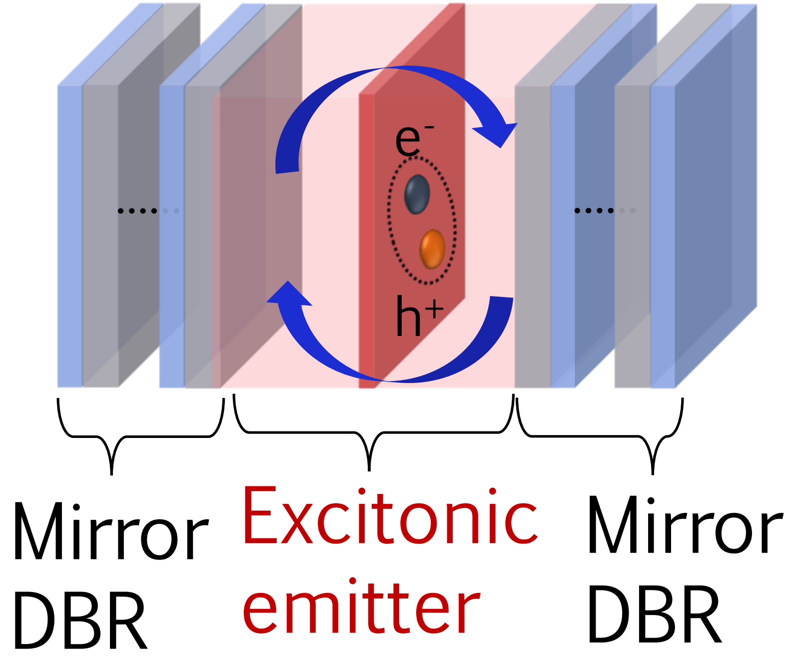
Controlling emission rates with microcavities



We can use photonics to:

- Accelerate processes that result in emission of light with specific colour.
- Suppress non-radiative processes.

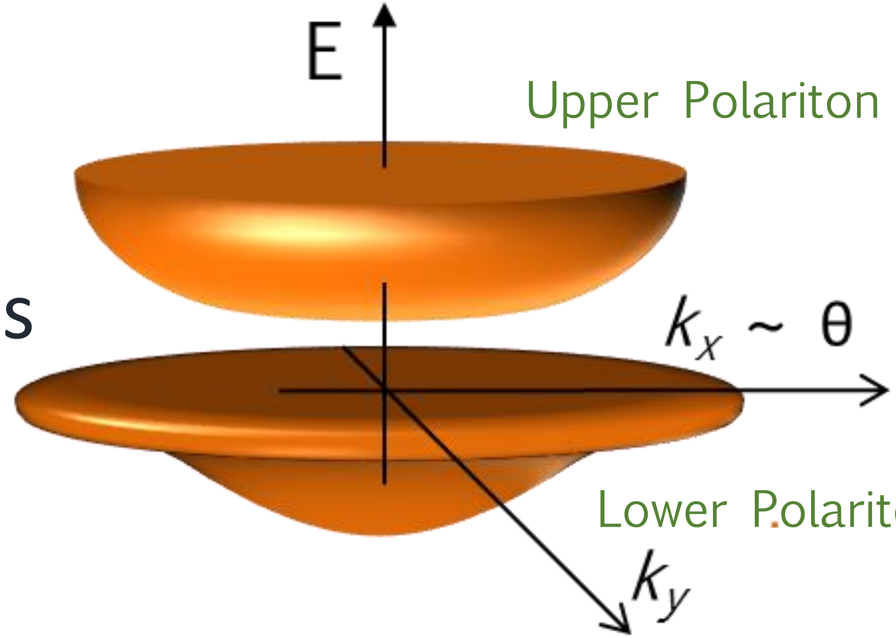
Creating new states “Polaritons in microcavities”



We can use photonics to:

- Induce strong interactions between light and matter to create new energy states (eigenstates).

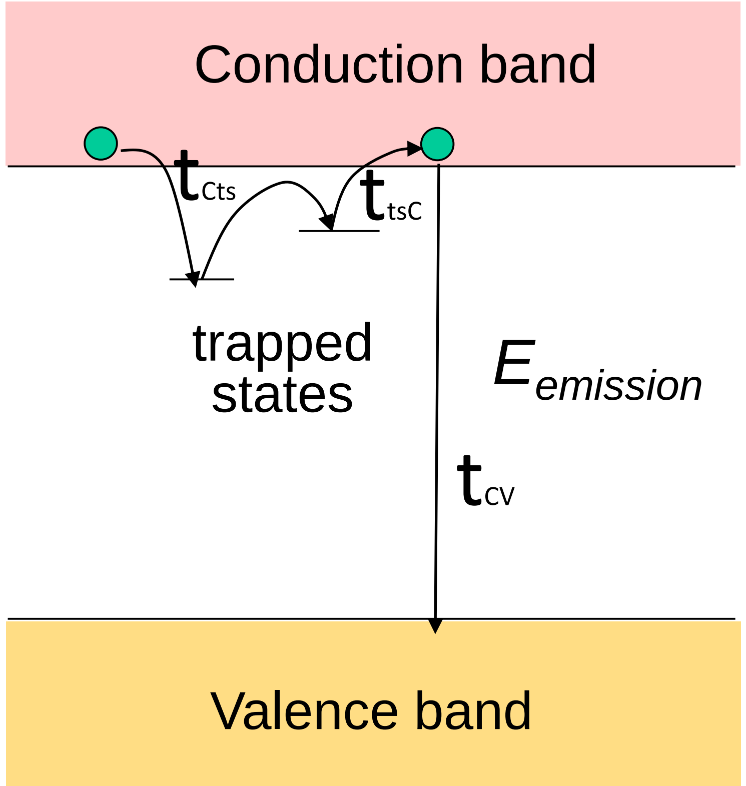
Polaritons



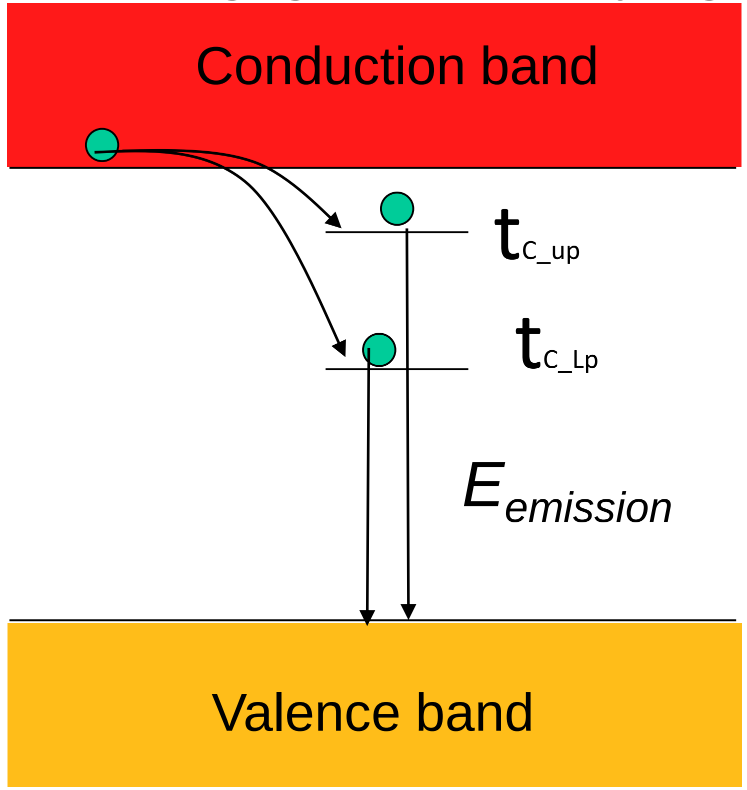
Engineering optical properties of materials

Polaritons have properties of both light and matter and allow us to tune emission rates.

Before strong light-matter coupling



After strong light-matter coupling



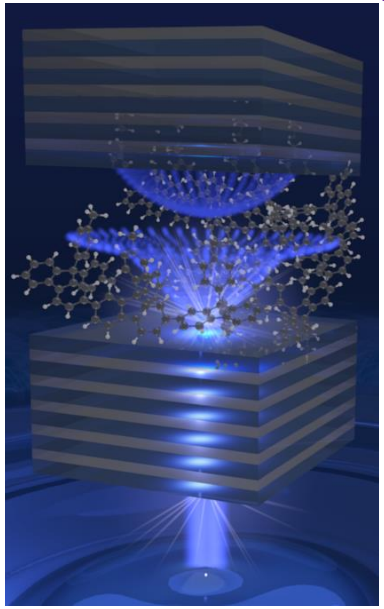
Stranius et. al., *Nat. Commun.*, vol. 9, no. 1, p. 2273, Dec. 2018.
Hertzog et. al., *Chem. Soc. Rev.*, vol. 48, no. 3, pp. 937–961, Feb. 2019.
Berghuis et. al., *Adv. Funct. Mater.*, p. 1901317, Jul. 2019.
Wang et. al., *Nat. Commun.*, vol. 12 p. 1874, 2021.
Wang et. al., *Nat. Commun.*, vol. 10 p. 1614, 2021.

UNIVERSITY OF TURKU

LMD research in a nutshell

LMD

Molecular solid-state lasers



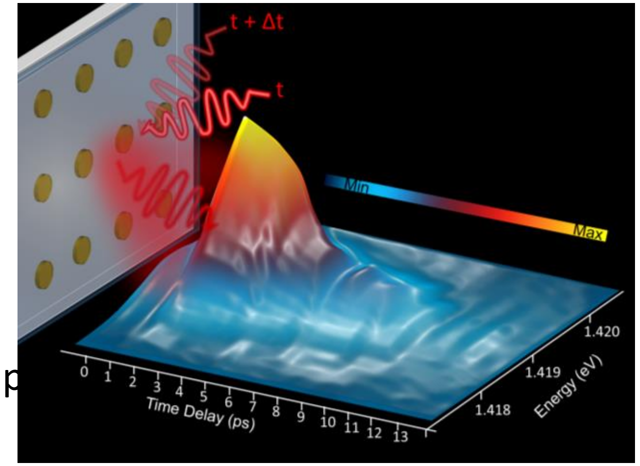
Daskalakis et. al. *Nature Materials*, 13(3), p. 271 (2014). *Physical Review Letters* 115 (3) 035301 (2015). Lerario et al. *Nature Physics* 13 (9) p. 837 (2017).

Improving OLEDs

IEEE SPECTRUM

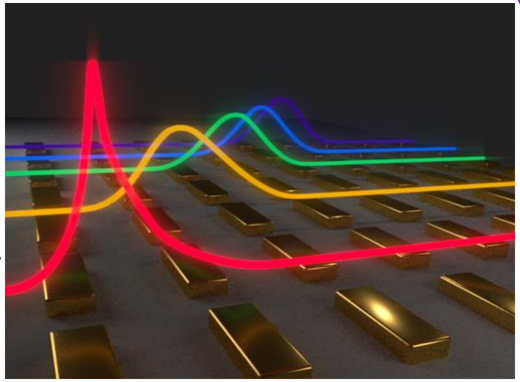
Daskalakis et. al. *ACS Photonics*, *6*(11), p. 2655 (2019).

Tiny and ultrafast lasers



Daskalakis et. al. *NanoLetters*, 18 (4), p. 2658 (2018).

Manipulating dynamics in molecules



Hakala et. al. *Nature Physics* 14 (7) p. 739 (2018). Väkeväinen et. al. *Nature Communications* 11 (1) p. 3139 (2020).

UNIVERSITY OF TURKU

Acknowledgements

Aalto University

Päivi Törmä
A. Väkeväinen
T. Hakala
A. Moilanen
R. Guo
J. Martikainen

Imperial College London

École Polytechnique Montréal

S. Kéna-Cohen
R. Murray

S. Maier
A. Fieramosca

Institute of Physics Polish Academy of Sciences

N. Bobrovska
M. Matuszewski

CNR NANOTEC Institute of Nanotechnology

G. Lerario
F. Barachati,
D. Ballarini
L. Dominici
M. De Giorgi
G. Gigli
D. Sanvitto

erc Starting Grant

European Union's Horizon 2020 research and innovation programme (grant agreement No. [948260])

University of Turku

UNIVERSITY
OF TURKU