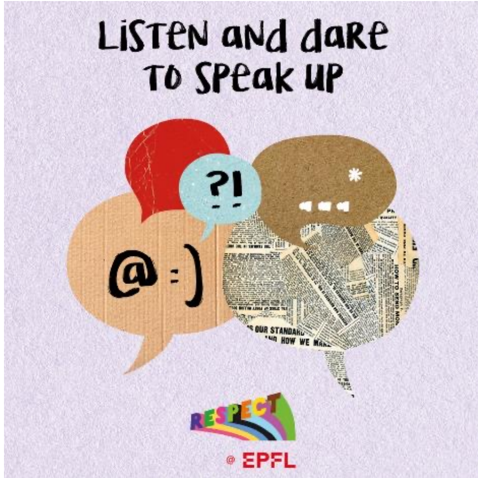
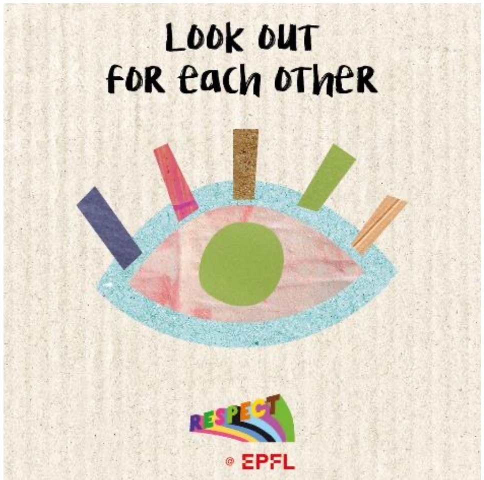
EPFL


Equal opportunity
makes us brighter
RESPECT
@ EPFL


Diversity is
our strength
RESPECT
@ EPFL


Listen and dare
to speak up
?!
@ :)
RESPECT
@ EPFL


Look out
for each other
RESPECT
@ EPFL


Kindness
brings serenity
RESPECT
@ EPFL


Together
we go further
RESPECT
@ EPFL

Génie Electrique et Electronique
Master program
Prof. Elison Matioli

EE-557
Semiconductor devices I

Introduction

EE-557 - Semiconductor devices I

Prof. Elison Matioli
POWERlab - EPFL

Why are you taking this class?

What do will you learn?

Why is that important?

Goals of this class

What do they all have in common?

CPUs

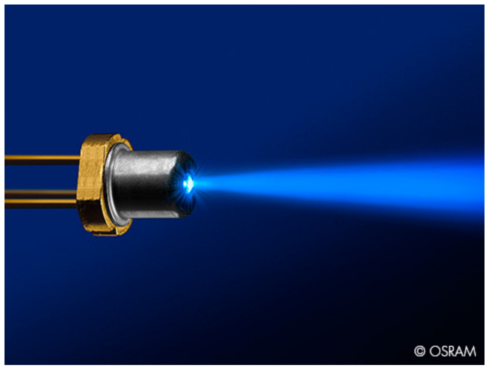
Cell phone

LED

Solar cell

Lasers

Power converter



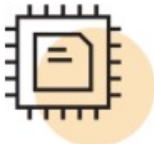
Why is that important?

European Chips Act

the EU will address semiconductor shortages and strengthen Europe's technological leadership. It will mobilise more than € 43 billion of public and private investments and set measures to prepare, anticipate and swiftly respond to any future supply chain disruptions, together with Member States and our international partners.

Strengthen Europe's research and technology leadership towards smaller and faster chips

Put in place a framework to increase production capacity to 20% of the global market by 2030



Build and reinforce capacity to innovate in the design, manufacturing and packaging of advanced chips

Develop an in-depth understanding of the global semiconductor supply chains

Address the skills shortage, attract new talent and support the emergence of a skilled workforce

Goals of this class

- Motivation: why semiconductor devices are key for the 21st century

- Introduce the basics of semiconductors and advance towards compound semiconductors

- Study some of the key electronic materials:
  Silicon, GaAs, GaN, SiC, Diamond

  and devices of today:
  Diodes, MOSFETs, HEMTs, Power transistors
  LEDs, solar cells

- How these components are fabricated in state-of-the-art cleanroom environment?

- How do we measure some of their key properties?

- Final goal of these components:
  Digital applications
  Efficient energy conversion
  LED lighting
  Photovoltaic

What are semiconductor devices?

What is a semiconductor???

Compare Glass, Metal and Semiconductor

metal

Copper:
$\rho = 1.7 \times 10^{-8}\ \Omega m$

glass

Glass:
$\rho = 10^{11} - 10^{15}\ \Omega m$

What is a semiconductor???

Compare Glass, Metal and Semiconductor

Silicon intrinsic:
$\rho = 3.2 \times 10^{3}\ \Omega m$

→

Silicon doped:
$\rho = 4 \times 10^{-4}\ \Omega m$

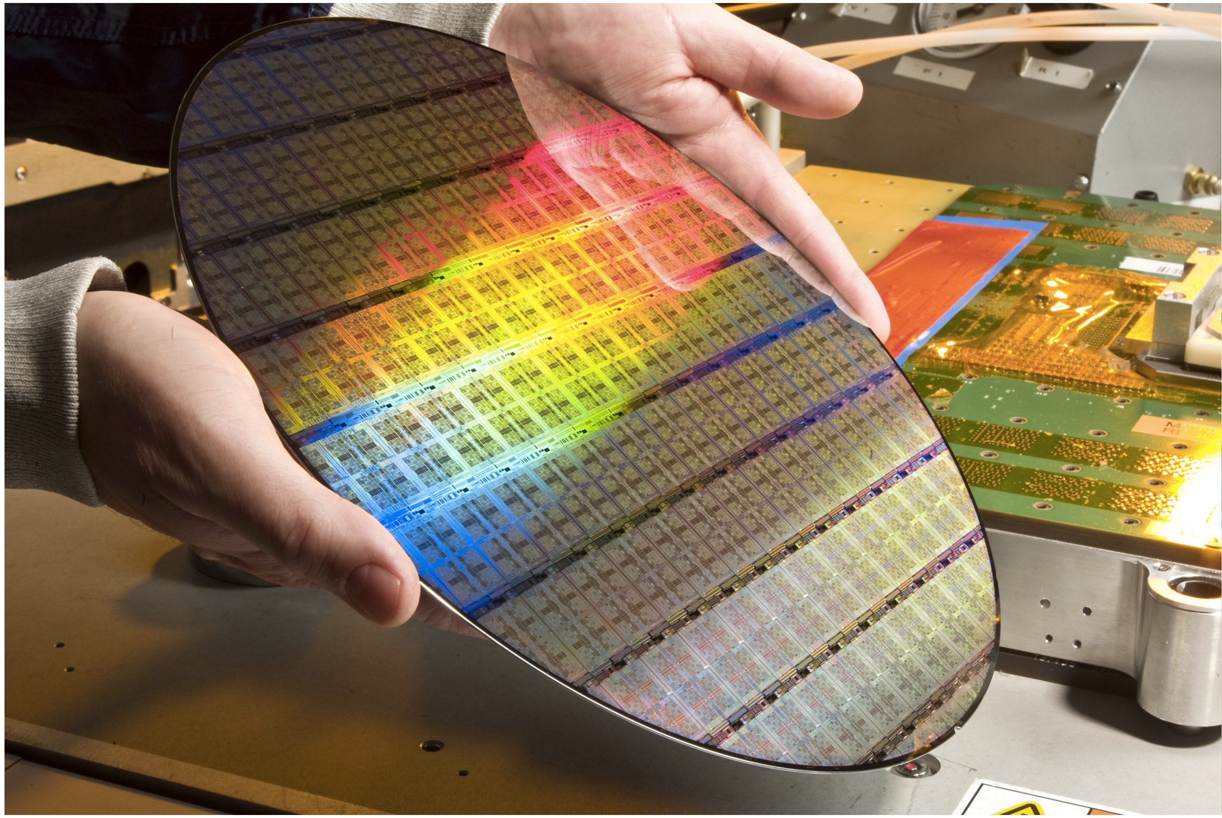
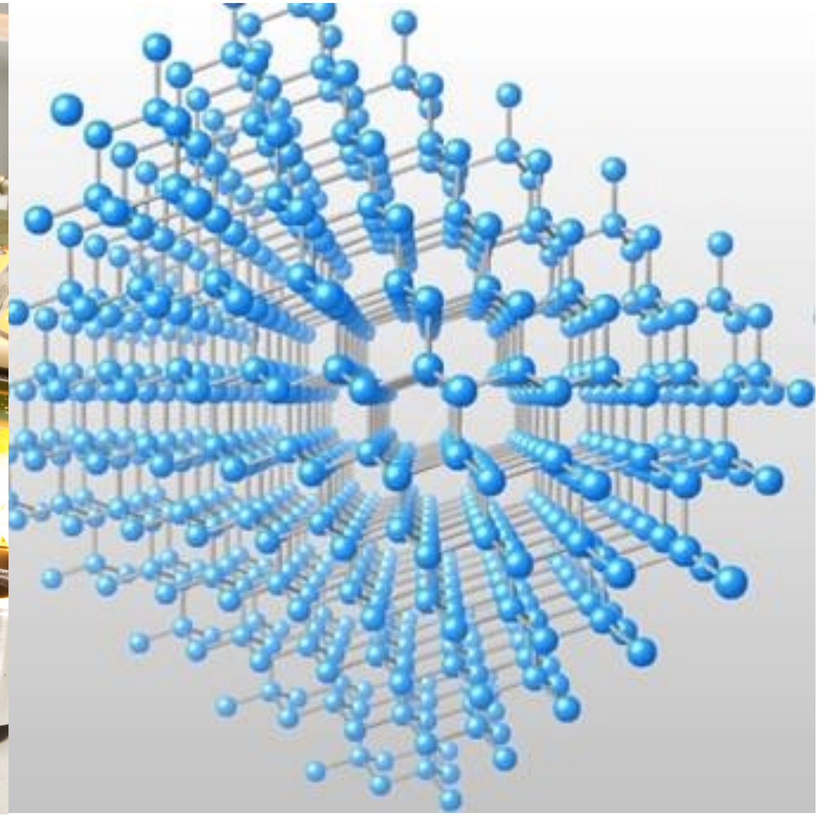


Image from: https://www.techpowerup.com/

Ordered arrangement of the atomic structure: crystalline structure



What is a semiconductor???

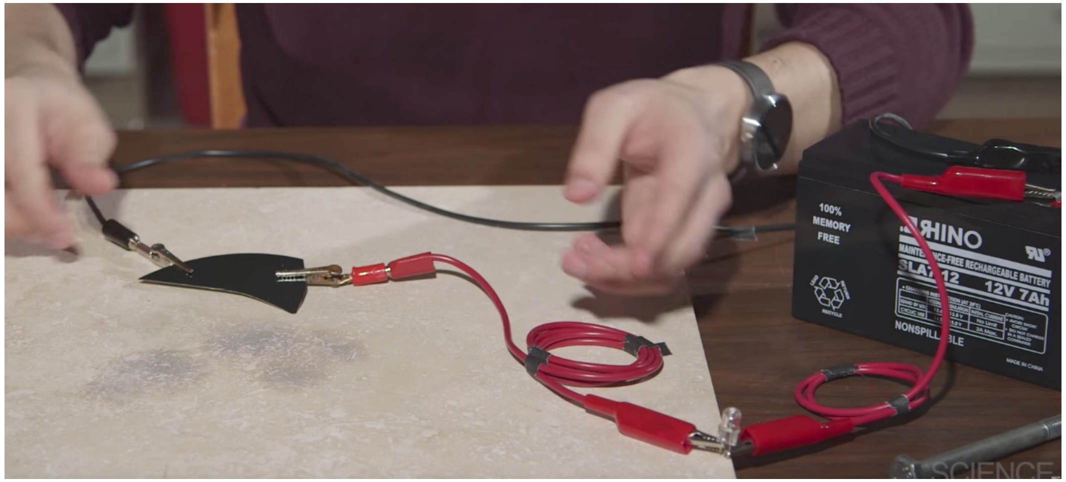
Compare Glass, Metal and Semiconductor

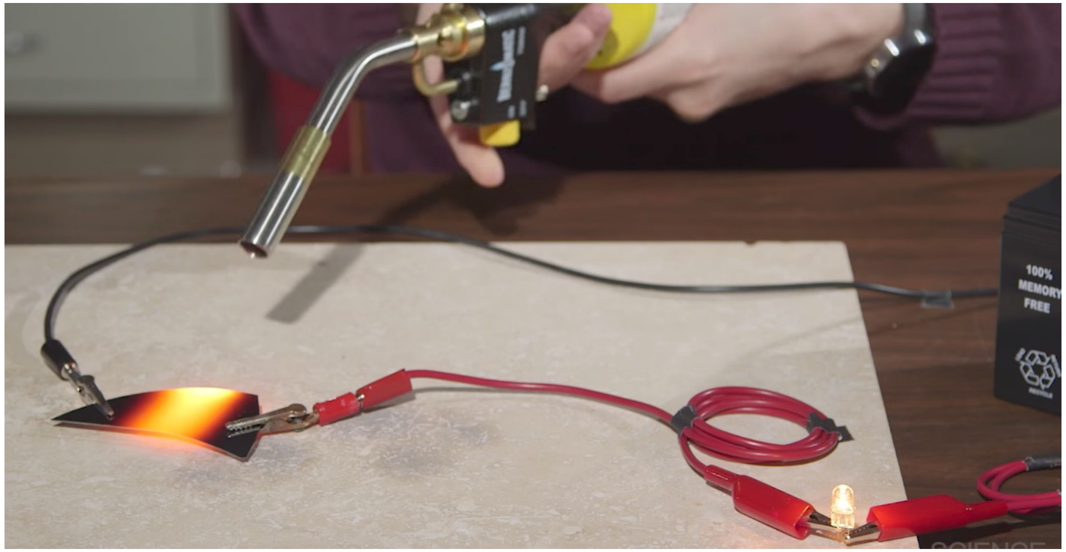
Video from www.youtube.com/watch?v=gUmDVe6C-BU

What is a semiconductor???

Compare Glass, Metal and Semiconductor

Silicon wafer





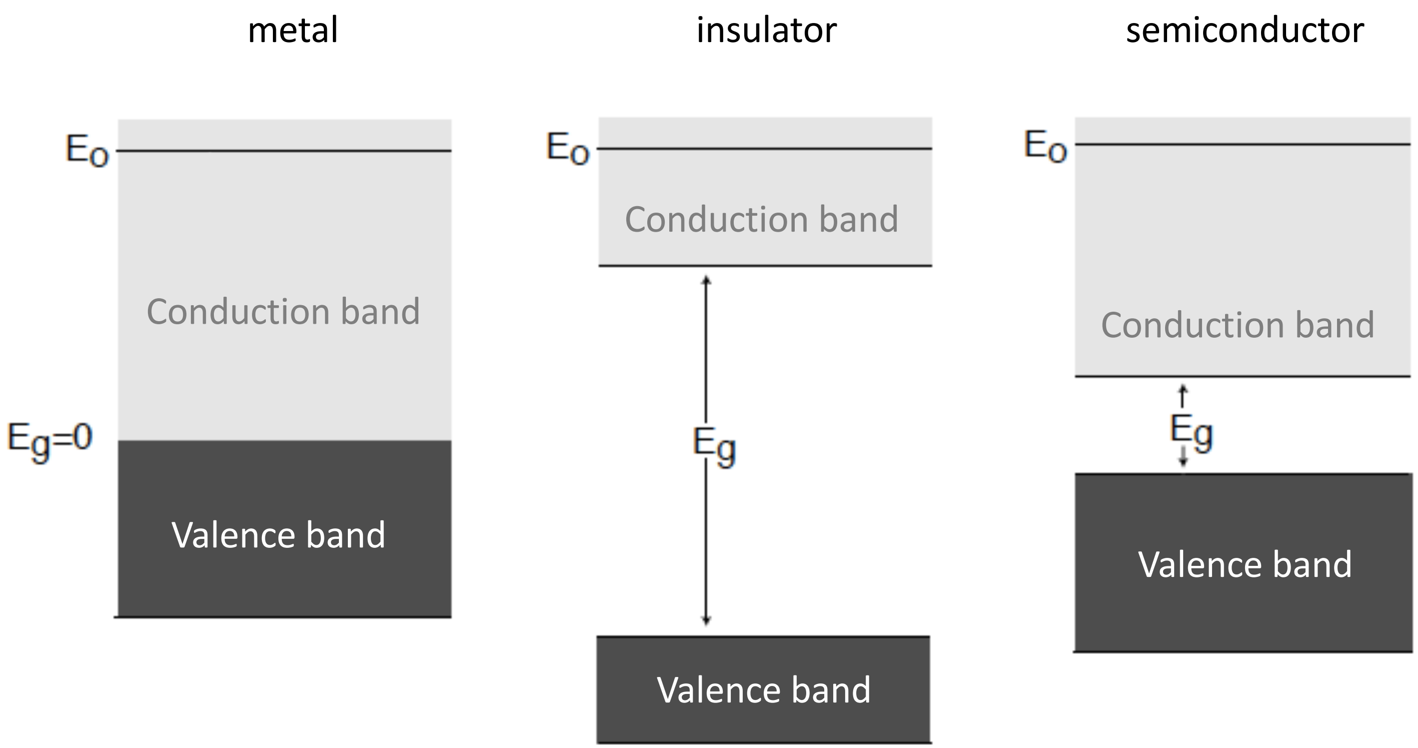
Silicon intrinsic:

$\rho = 3.2\text{x}10^5\ \Omega\text{cm} = 3.2\text{x}10^3\ \Omega\text{m}$

Images from www.youtube.com/watch?v=gUmDVe6C-BU

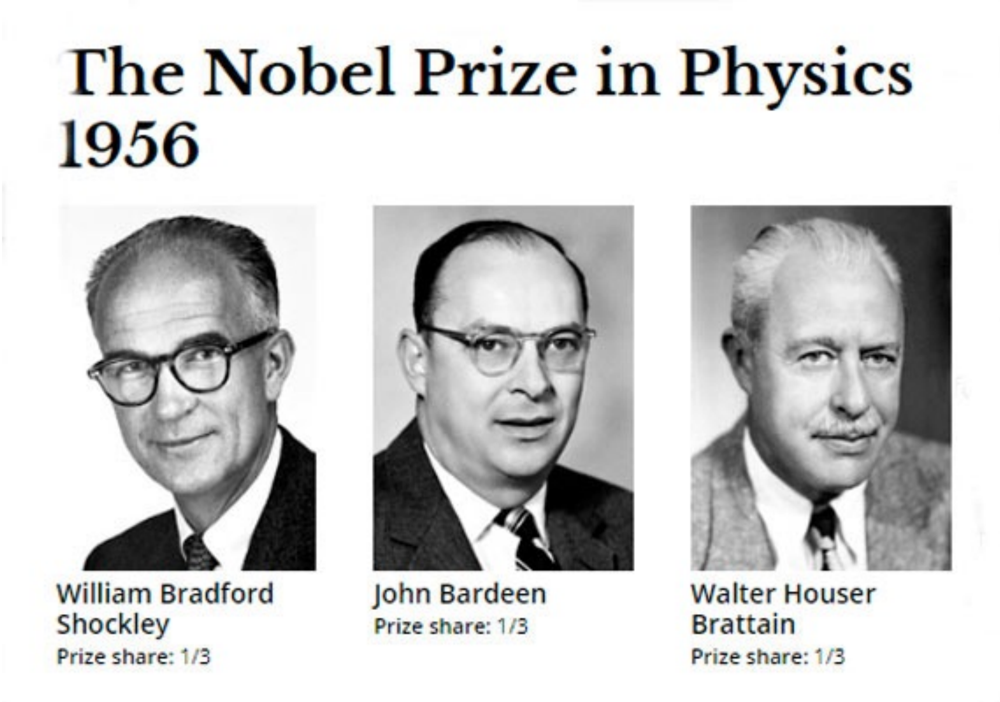
Energy band-gap

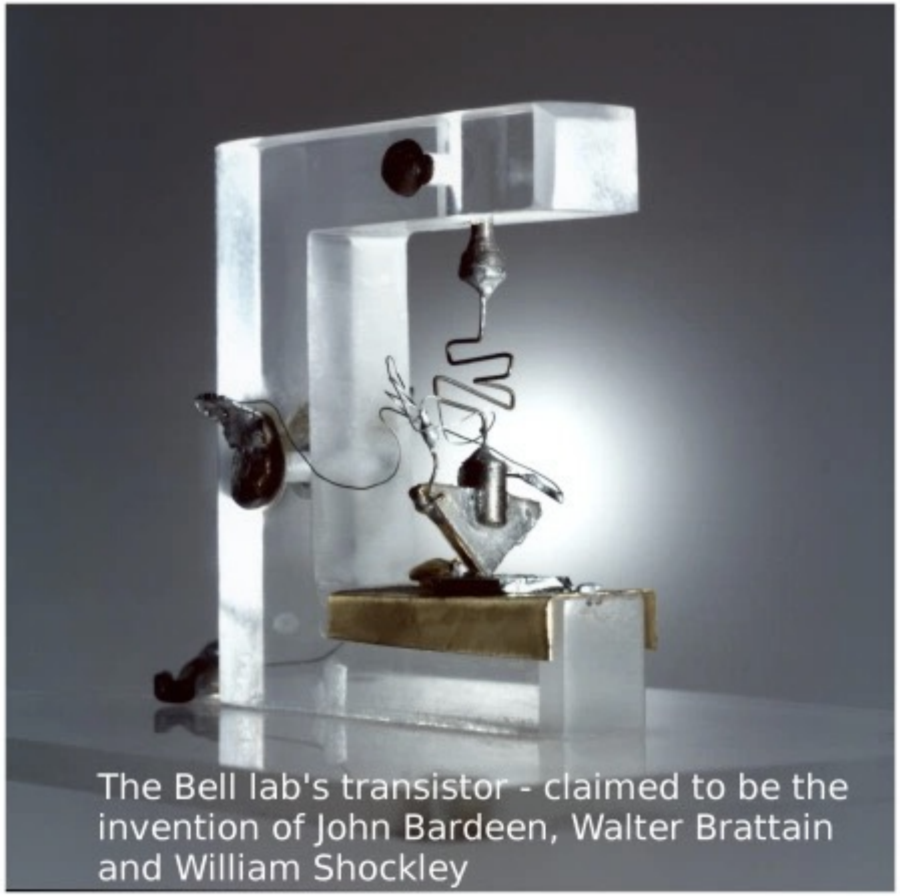
What is an energy bang gap *Eg*?



What are semiconductor devices?

Transistor

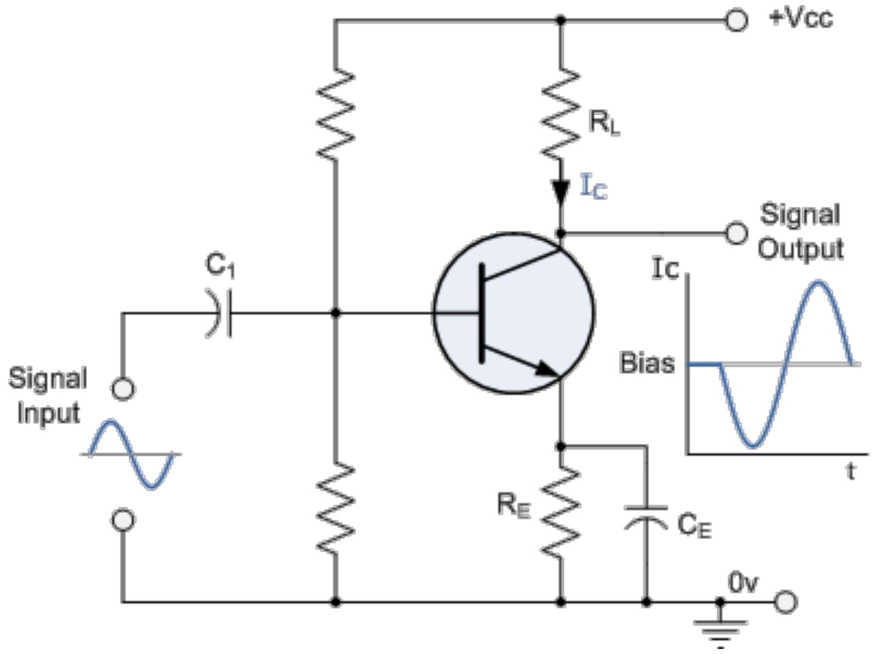




What is so special about it?

What are semiconductor devices?

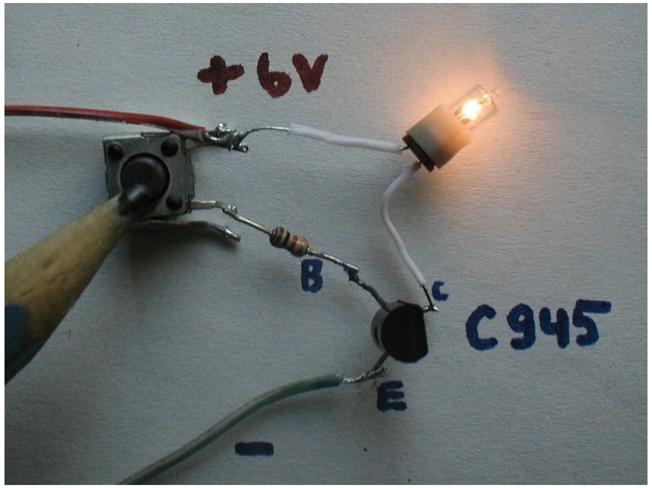
Transistor as amplifiers

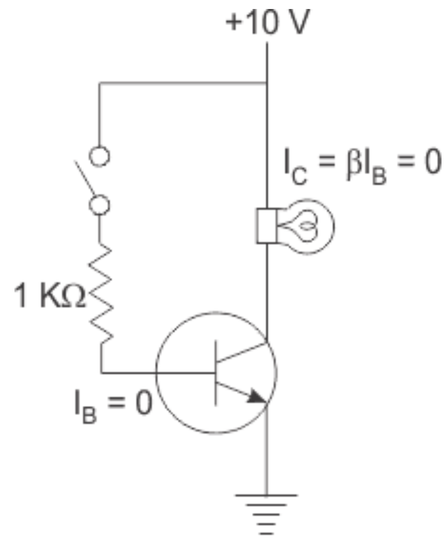


communications

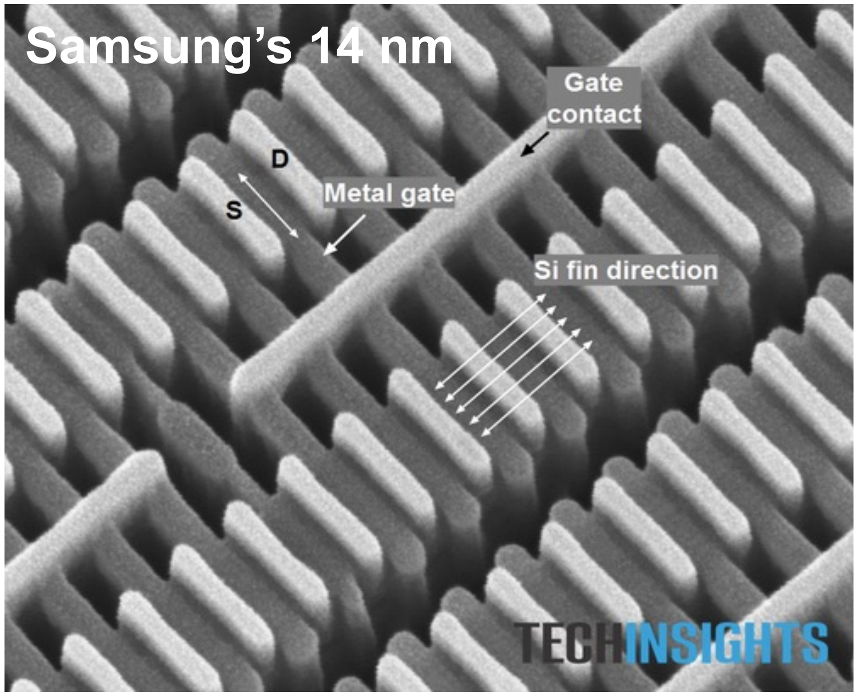
What are semiconductor devices?

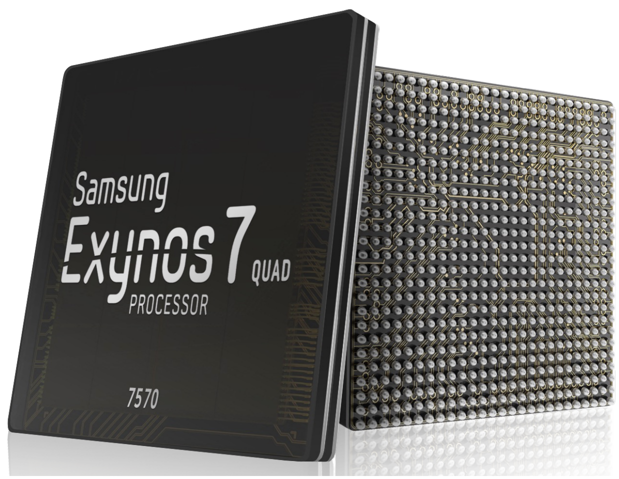
Transistor as one switch



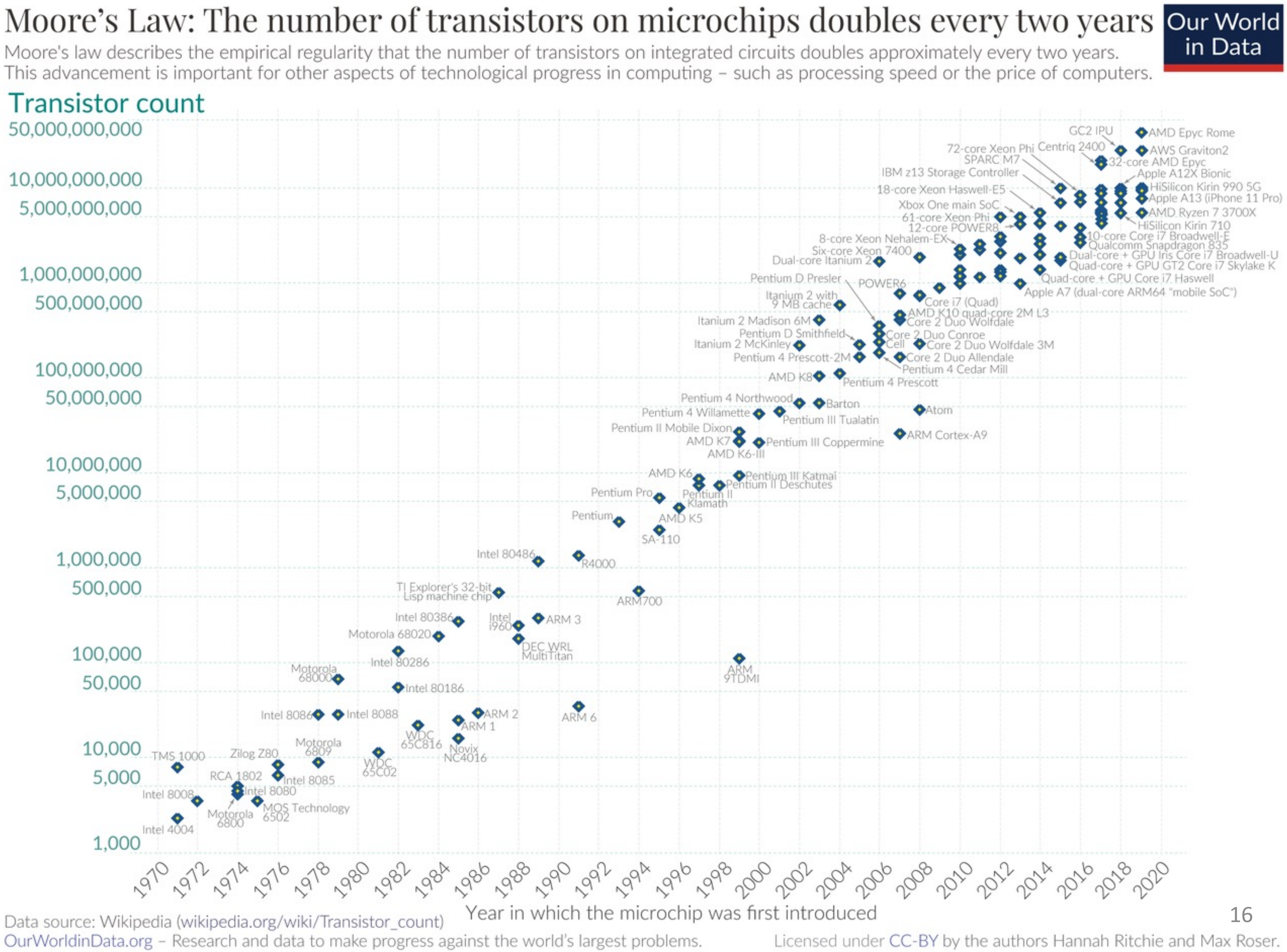


> 100 million transistors: microprocessor

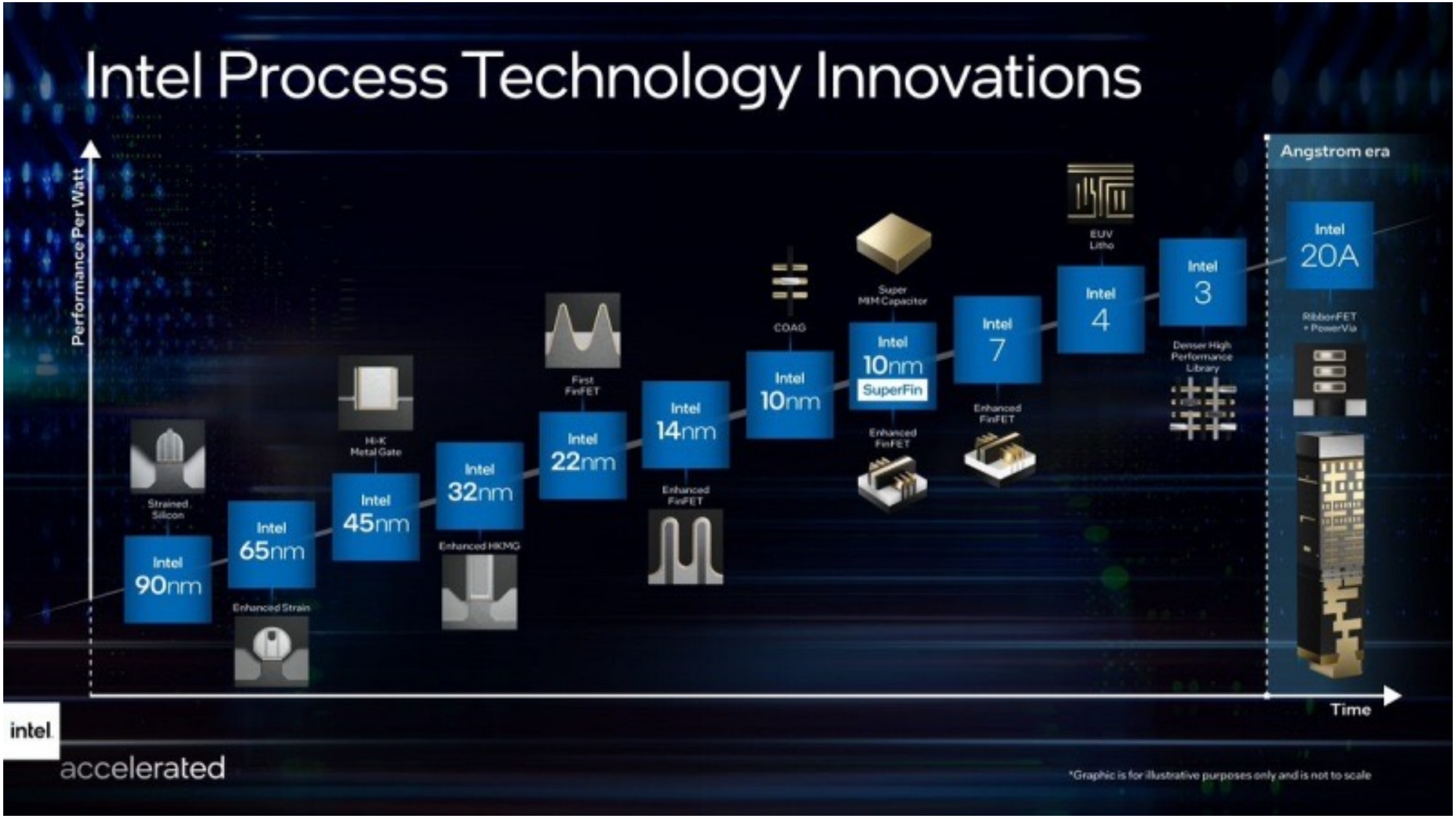




EE-557 - Semiconductor devices I

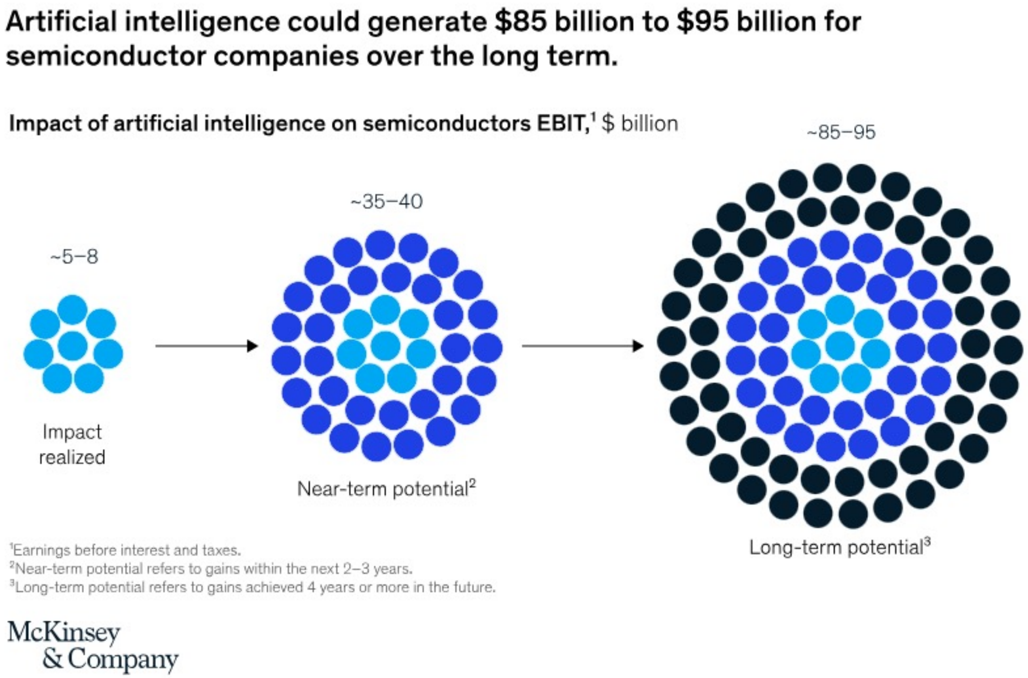


Why do we need new semiconductor physics/devices?



Each time the technology reached the predictive barriers…
imaginative new solutions were developed to further extend Moore's law

Why do we need new semiconductor devices?



- Artificial intelligence
- Internet of things
- Automotive
- Communications
- renewables

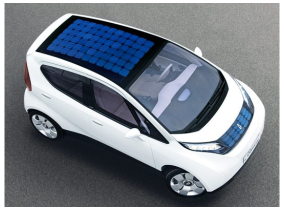
Why do we need new semiconductor physics/devices?

Energy conversion

Wind turbines

Solar panels

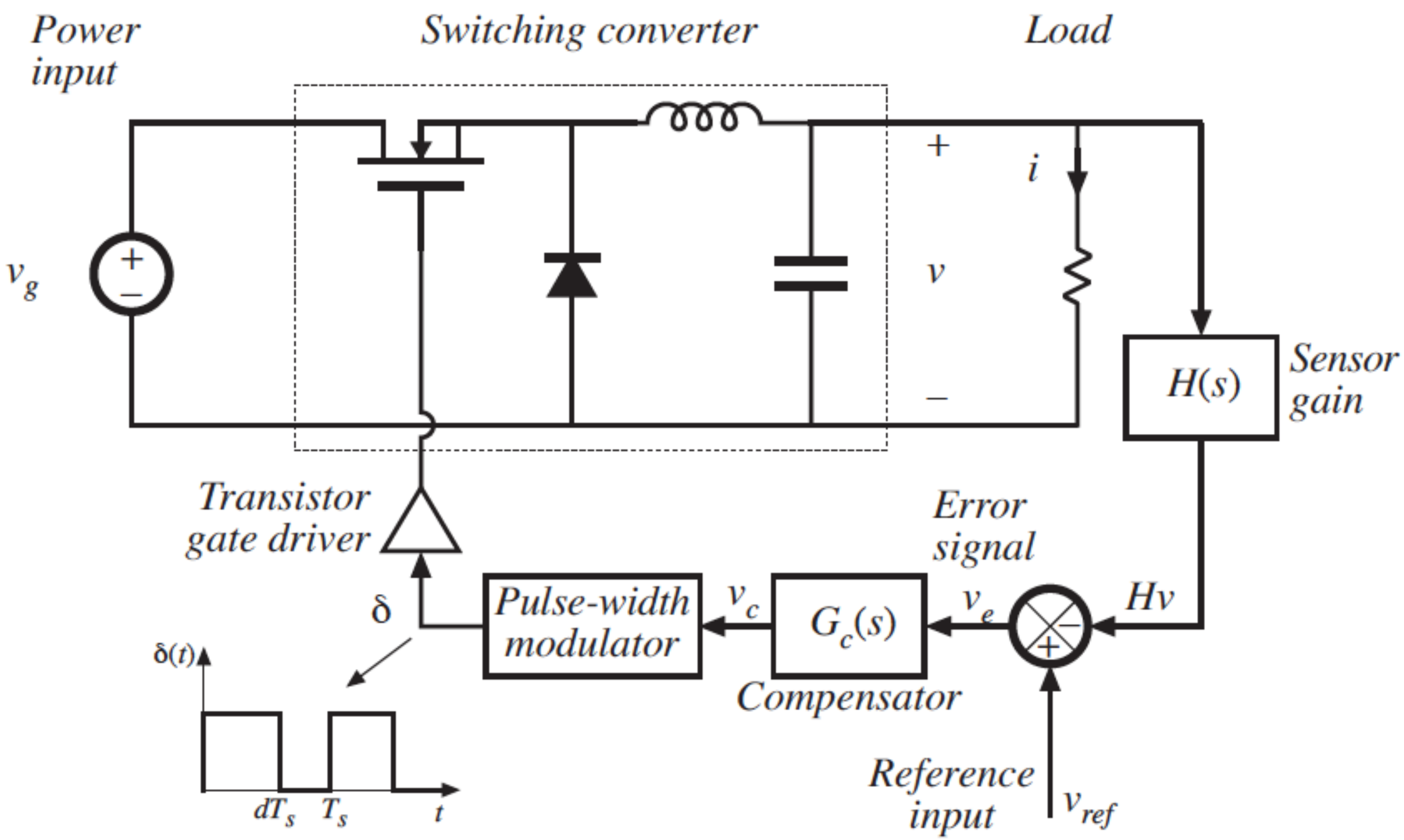
Electric vehicles



Data centers

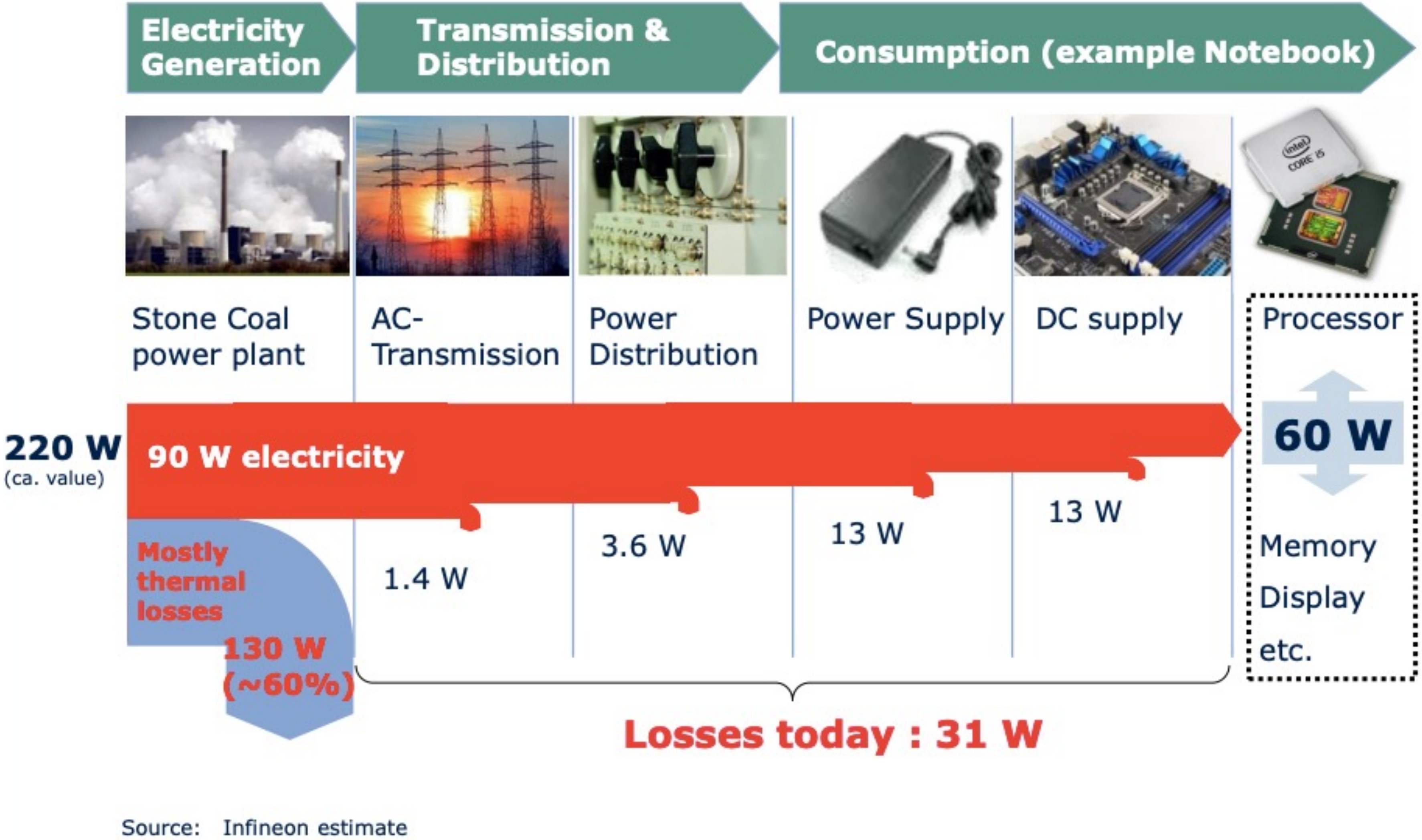
LED light bulbs

Power converter: Transistors + diodes + filters + control



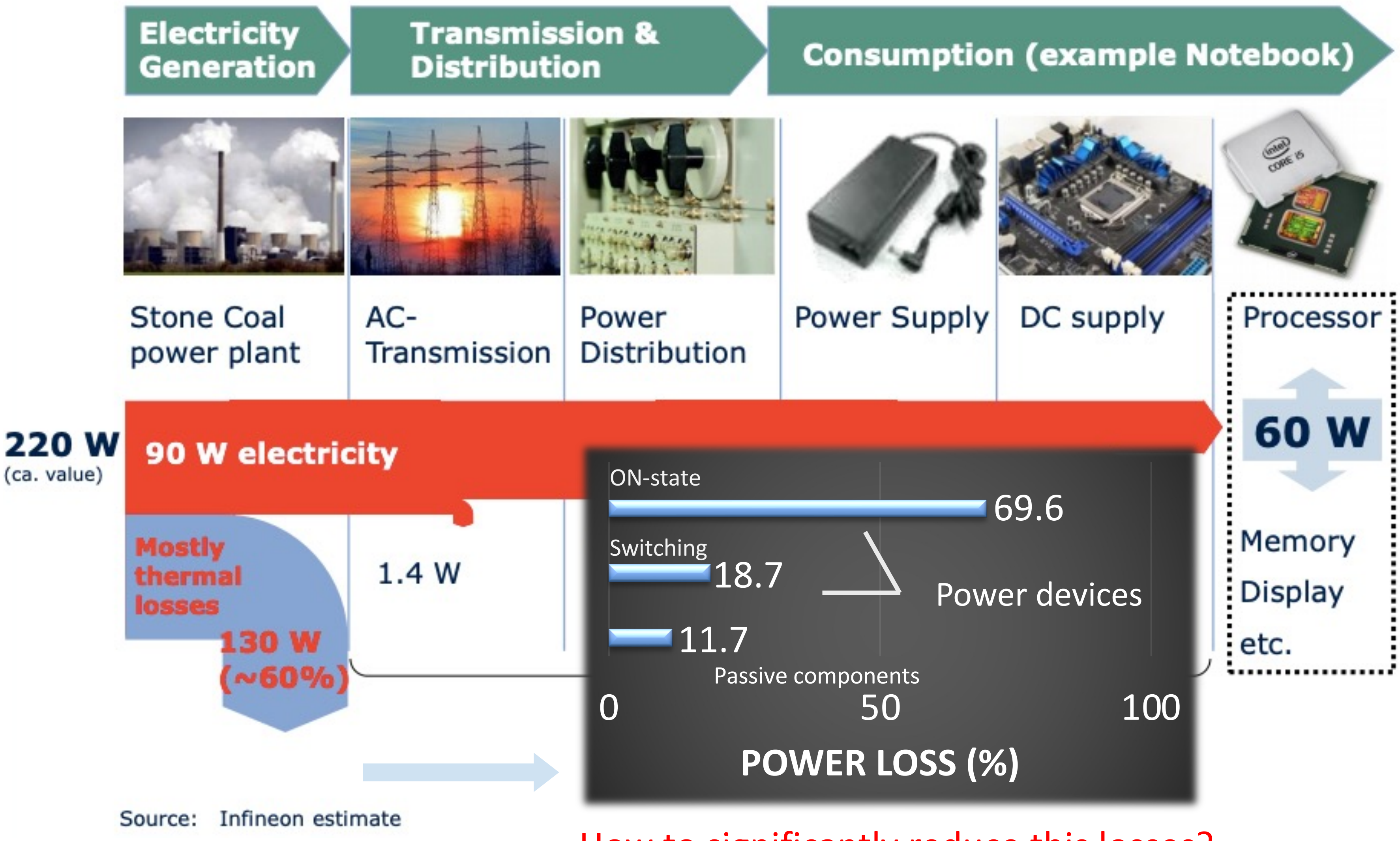
In the case of high voltage converters, we need **power transistors and diodes**

Power Electronics: large potential for energy efficiency



[1] Infineon Technologies Austria AG, “GaN Power Devices: Development, Manufacturing, and Application,” ICNS 2017, Strasbourg, France.
[2] O. Deblecker, Z. De Grève and C. Versèle, Comparative Study of Optimally Designed DC-DC Converters with SiC and Si Power Devices, Advanced Silicon Carbide Devices and Processing, 2015.

Power Electronics: large potential for energy efficiency

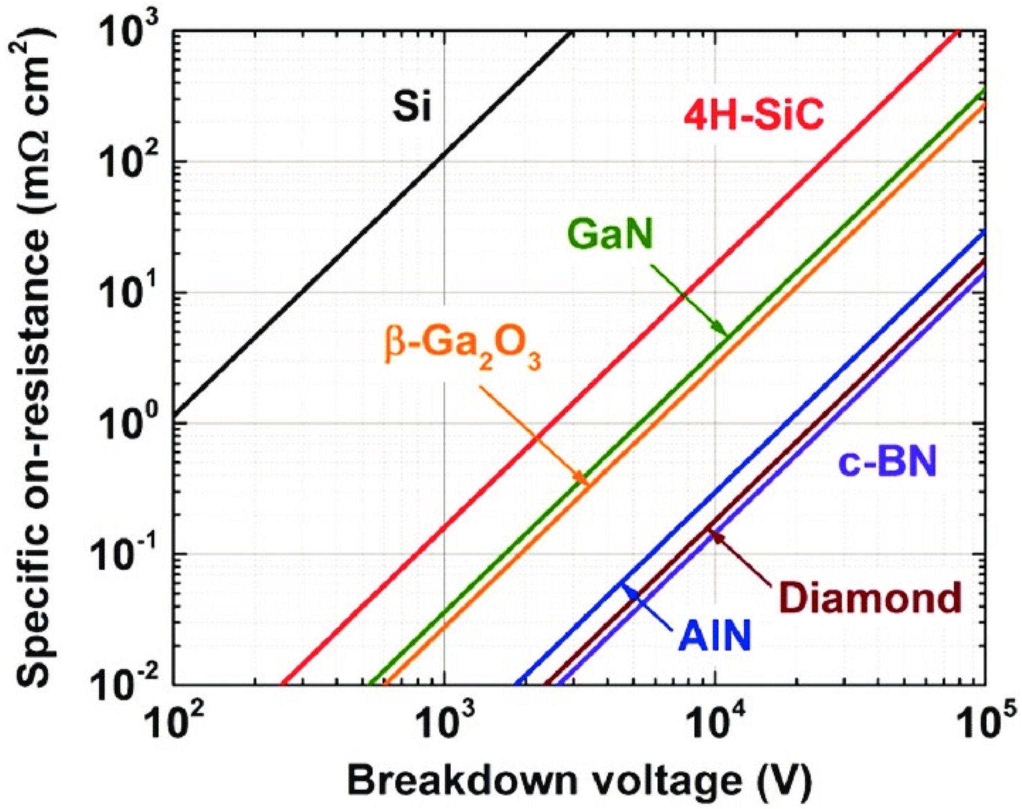


How to significantly reduce this losses?

[1] Infineon Technologies Austria AG, "GaN Power Devices: Development, Manufacturing, and Application," ICNS 2017, Strasbourg, France.
[2] O. Deblecker, Z. De Grève and C. Versèle, Comparative Study of Optimally Designed DC-DC Converters with SiC and Si Power Devices, Advanced Silicon Carbide Devices and Processing, 2015.

Semiconductors for POWER applications

What makes one material better than another?



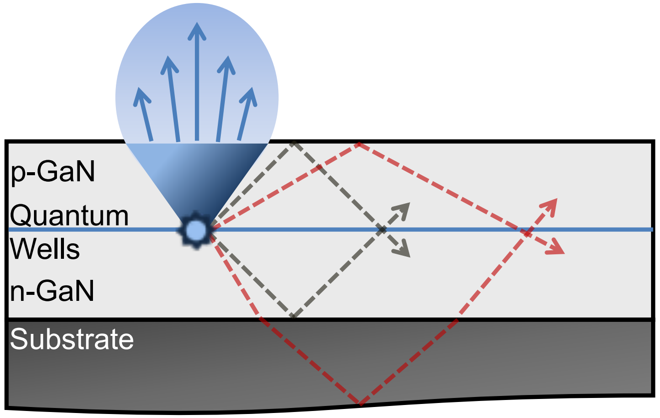
Semiconductors also emit light: LED light bulbs

Least Efficient → Most Efficient

Bulb Type	Incandescent	Halogen	CFL	LED
	Energy used	Energy used	Energy used	Energy used
450 Lumens (Bright)	40w $4.82/yr	29w $3.49/yr	11w $1.32/yr	9w $1.08/yr
800 Lumens	60w $7.23/yr	43w $5.18/yr	13w $1.57/yr	12w $1.44/yr
1100 Lumens	75w $9.03/yr	53w $6.38/yr	20w $2.41/yr	17w $2.05/yr
1600 Lumens (Brightest)	100w $12.05/yr	72w $8.67/yr	23w $2.77/yr	20w $2.41/yr
Rated Life	1 Year	1-3 Years	6-10 Years	15-20 Years

Lighting accounts for 20-30% of electric bill

Estimated energy cost per year is based on 3 hours of use per day at 11 cents per kWh in an average single family home according to the Dept. of Energy



Nobel Prize in 2014

Prof. Shuji Nakamura
Prof. Hiroshi Amano
Prof. Isamu Akasaki

Why is that important?

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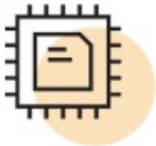

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Develop an in-depth understanding of the global semiconductor supply chains

Address the skills shortage, attract new talent and support the emergence of a skilled workforce

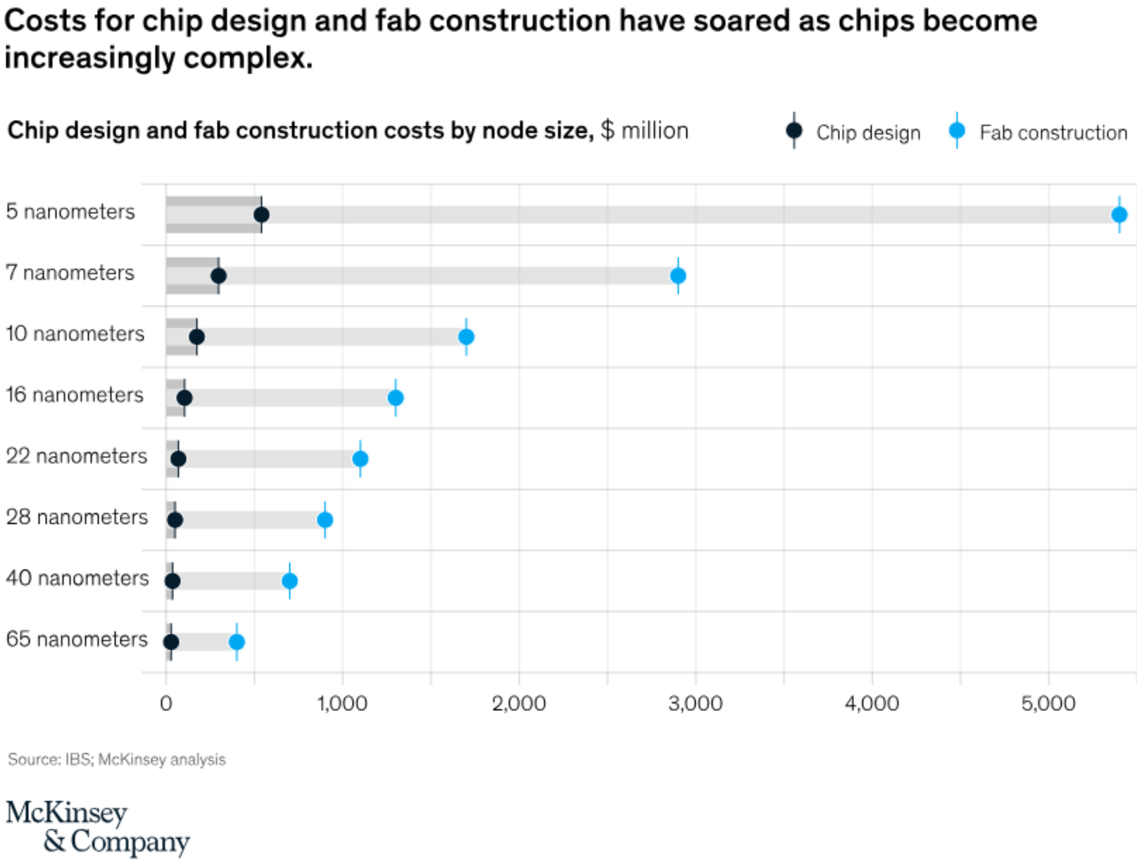
Fabrication technologies:

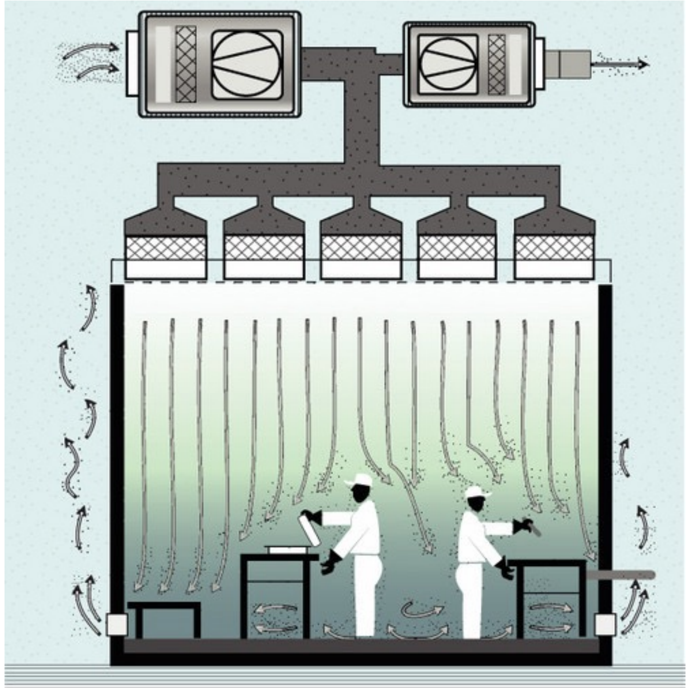
How do we convert a semiconductor into a transistor?

EE-557 - Semiconductor devices I

Fabrication technologies:

How do we convert a semiconductor into a transistor?

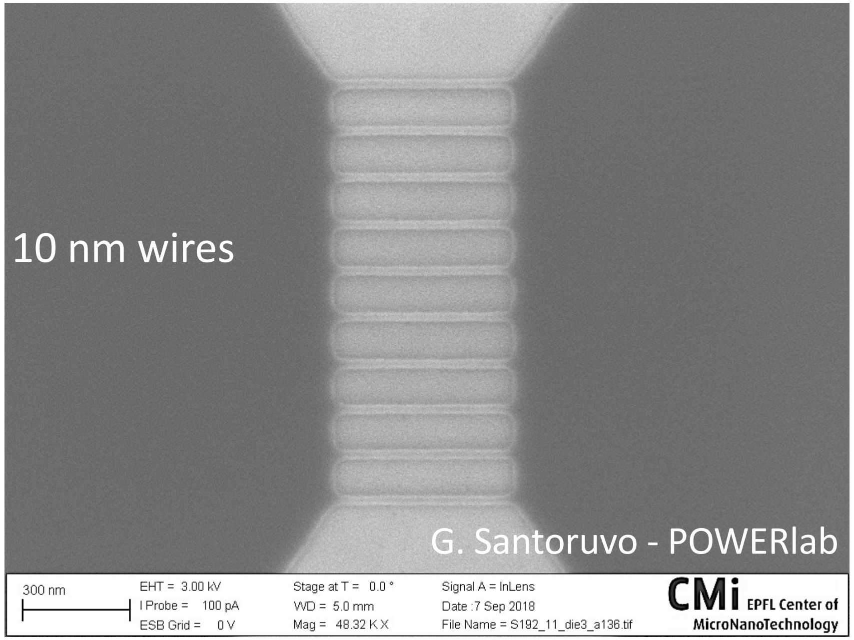


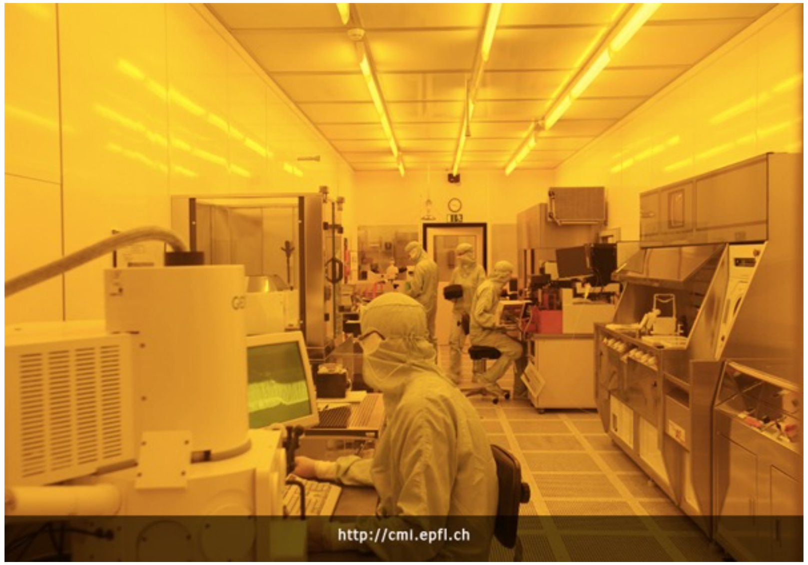


- Cleanrooms have controlled level of contamination:

  Specified by the number of particles per cubic meter at a specified particle size.
- The ambient air outside 35,000,000 particles per cubic meter, 0.5 mm and larger in diameter
- Class 10 cleanroom has at most 352 particles of 0.5 um size in a cubic meter

Cleanroom at EPFL – class 100





Content of the course:

- Introduction to Semiconductors
- Carrier Generation and Recombination
- Optical properties
- Charge Transport
- Non-uniformly doped semiconductors
- p-n junctions
- Metal-semiconductor junctions
- Metal Oxide Semiconductor
- Power MOSFETs and devices

Documentation du module

- Course notes – Prof. E. Matioli (http://moodle.epfl.ch)
- J. A. del Alamo, Integrated Microelectronic Devices: Physics and Modeling, Pearson
- S. M. Sze and K. K. Ng, Physics of Semiconductor Devices, Wiley
- D. Schroder, Semiconductor Material and Device characterization, Wiley
- Extra required documents will be announced during classes

How to take advantage of this course:

- **The material for the course will be made available on moodle before each class;**
- **I will try to register each lecture in video and upload them (not guaranteed). You will benefit a lot more by coming to class.**
- **There will be more resources to read posted on moodle than what is covered in class:**

  Read from the text book at least the topics covered in class
- **The physical text book is available in the library:**

  J. A. del Alamo, Integrated Microelectronic Devices: Physics and Modeling, Pearson

Class structure:

14 weeks – 4 lectures of 45 minutes per week: 56 lectures

38 theoretical lectures
14 exercice lectures – grouped in 7 lectures of 1h30 (in red in the syllabus)
2 exam sessions fo 1h30 : 1 mid-term and 1 final

Class are on:

mondays	15h-17h	MEB 331
wednesdays	10h-12h	BS160

Starts at 15 min after the hour and finishes at the hour

Evaluation :

- **Mid-term exam: Nov. 6th 2024 (40%)**
- **Final Exam: Dec. 18th 2024 (60%)**

Syllabus (on moodle)

EE 557 - Semiconductor Devices I

Date	lecture number	title	content
09.09.2024	1	Introduction	Introduction to the class: final goal
			what is a semiconductor?
			Examples: data processing, energy conversion, LEDs
			Introduction to lab, master and semester projects
11.09.2024	2	Band structure	Crystal lattice, energy bands
			Band Diagram
16.09.2024	3	Density of States and carrier density	Density of States
			Carrier Statistics
			Effective mass
18.10.2024	4	Doping	Doping
	EX1		intrinsic and extrinsic
			equilibrium concentration
			np product, Fermi level
			Ionization
23.09.2024	5	Exercise 1	
25.09.2024	6	Carrier Generation and Recombination	Introduce phonons, electrons and photons
			Recombination, Generation, Lifetime
			Generation and recombination - light pulse
30.09.2024	7	Optical properties	
			Silicon solar cells
			LEDs
02.10.2024	8	Charge Transport	thermal velocity
			Carrier transport: drift and diffusion
			Set of equations
			Diffusion
07.10.2024	9	Non-uniformly doped semiconductors and quasi Fermi levels	Non-uniformly doped semiconductors
	EX2		Quasi-Fermi levels
09.10.2024	10	Exercise 2	
14.10.2024	11	Carrier flow - Schokley equations	
16.10.2024	12	p-n junctions (half of the content)	introduction (solar cells, LEDs, diodes)
			p-n junctions in TE
28.10.2024	13	pn junctions (finish)	p-n junctions under bias
	EX3		
30.10.2024	14	non-idealities and switching behavior	
			Solve Exercices 3 in the black board (Quasi fermi levels)
04.11.2024	15	Exercise 3 - before exam (solve midterm)	switching characteristics
06.11.2024	16	mid term	
11.11.2024	17	Mid-term correction	
13.11.2024	18	Metal semiconductor junctions	Schottky
			Schottky barrier: measurement
			band line up
18.11.2024	19	Schottky and Ohmic contacts	Schottky diodes - devices
	EX4		Ohmic: TLM
			exercices Schottky
20.11.2024	20	Metal Oxide Semiconductor	MOS capacitors
			interface traps
25.11.2024	21	Metal Oxide Semiconductor and its dynamics	MOSFETs
			Three terminal MOSFET - 1st class
27.11.2024	22	Exercise 4	
02.12.2024	23	MOSFETs	mosfets
	EX5		dynamic performance
			Dynamic and CV
			mobility and inversion layer
04.12.2024	24	Power devices	basics of power devices
			Baliga's figure of merit
			Power diodes
			Power MOSFETs
09.12.2024	25	Exercise 5	
11.12.2024	26	Advanced concepts	
16.12.2024	27	Revision / Exercises / Questions	
18.12.2024	28	Finals	

Class structure:

- 38 theoretical lectures in class (in black)
- 14 exercice lectures – grouped in 7 lectures of 1h30 (in red)
- 2 exam sessions of 1h30 : 1 mid-term and 1 final (in blue)
- I will have conferences abroad during 2 dates (in yellow), a replacement video will be uploaded (and/or a replacement TA will be annonced)

A little about me:

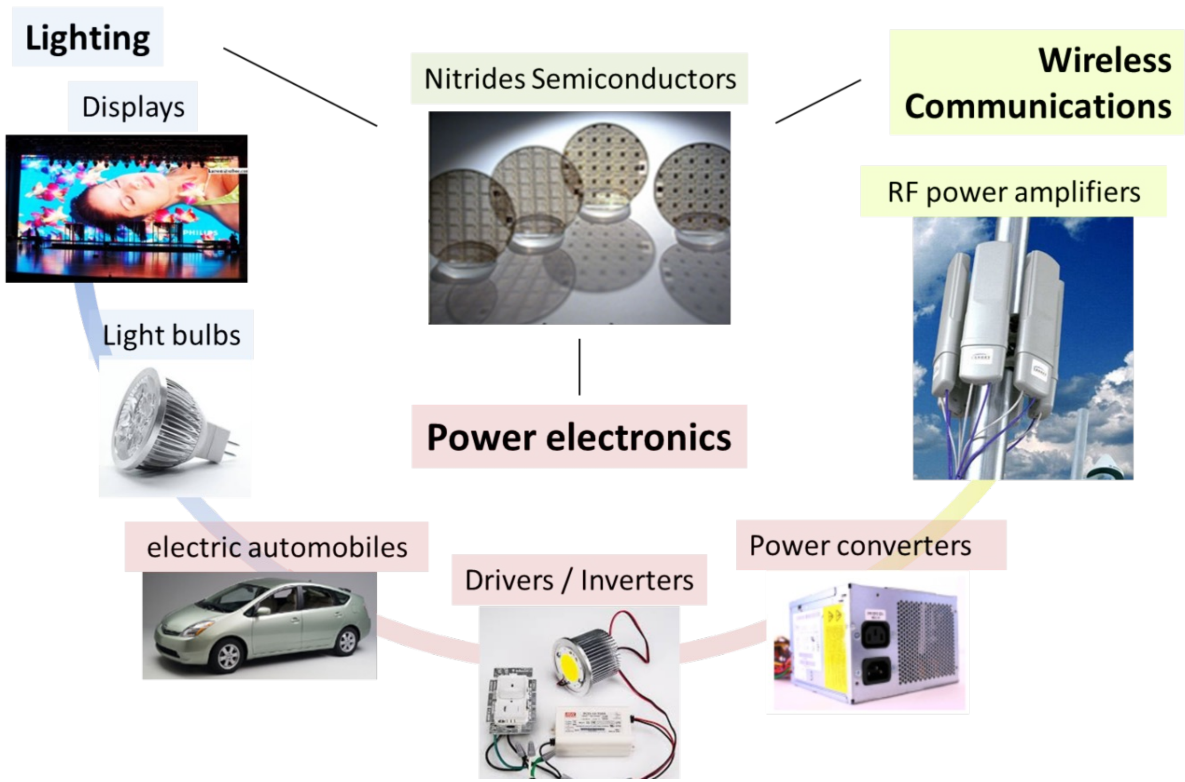
Ecole Polytechnique Fédérale de Lausanne (EPFL)
Professor - Institute of Electrical Engineering (STI)

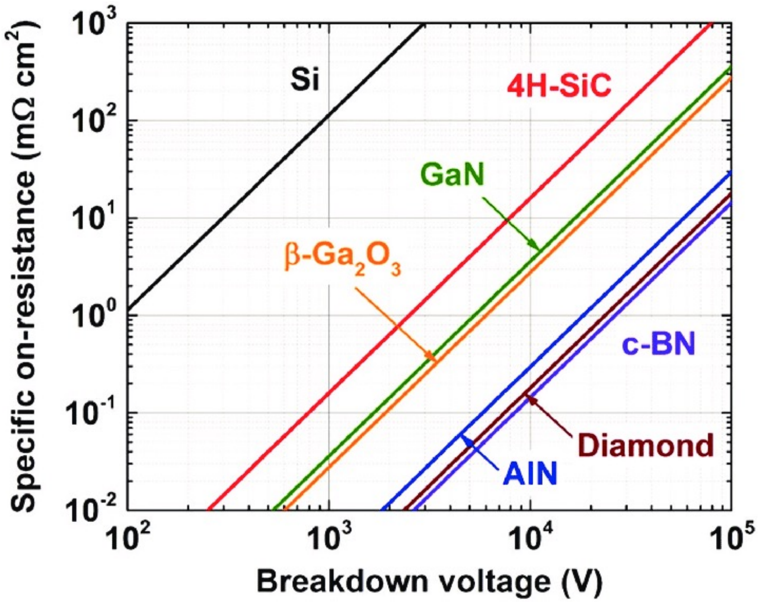
Massachusetts Institute of Technology, USA
Electrical Engineering and Computer Science (EECS)

University of California, Santa Barbara USA
Ph.D., Materials Science

Ecole Polytechnique, France Promotion X2002
B.Sc. - Applied Physics / Applied Mathematics

III-Nitrides are an exceptional material





Optoelectronics:

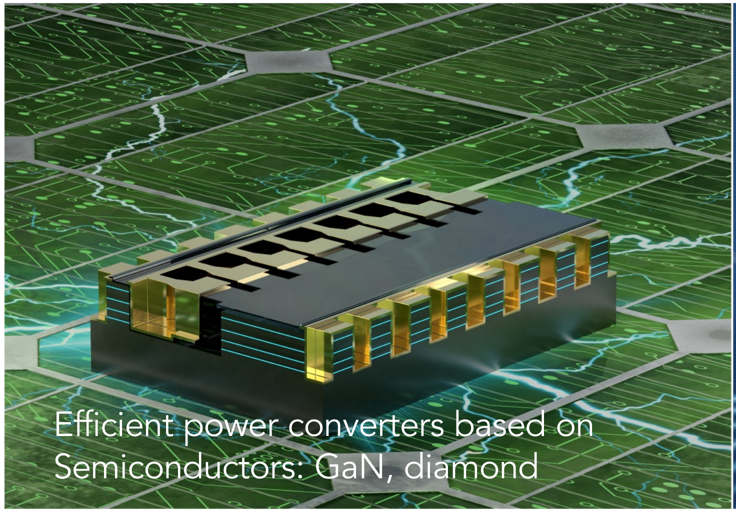
- High internal quantum efficiency: LEDs
- Polarized light emission: displays
- Tunable direct band gap: solar cells

Electronics:

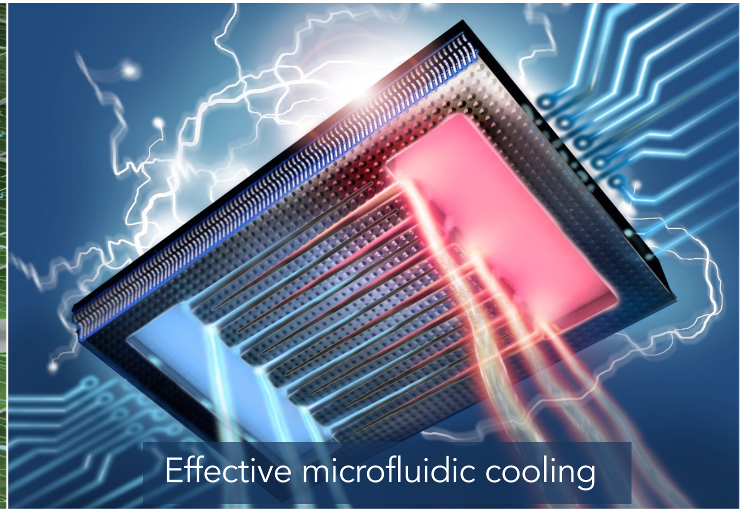
- High electron velocity (×3 than Si)
- High carrier density (×3 than Si)
- High breakdown voltage (>×10 than Si)

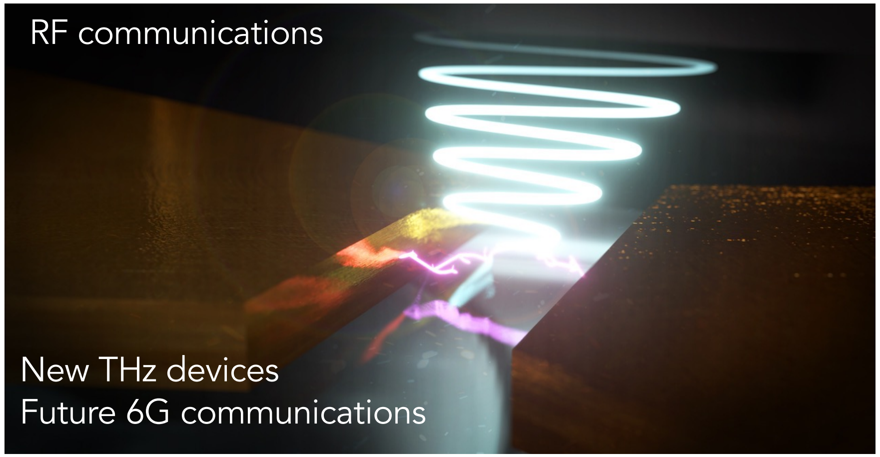
POWERlab@EPFL - Our activities

Power semiconductors



Cooling of electronics

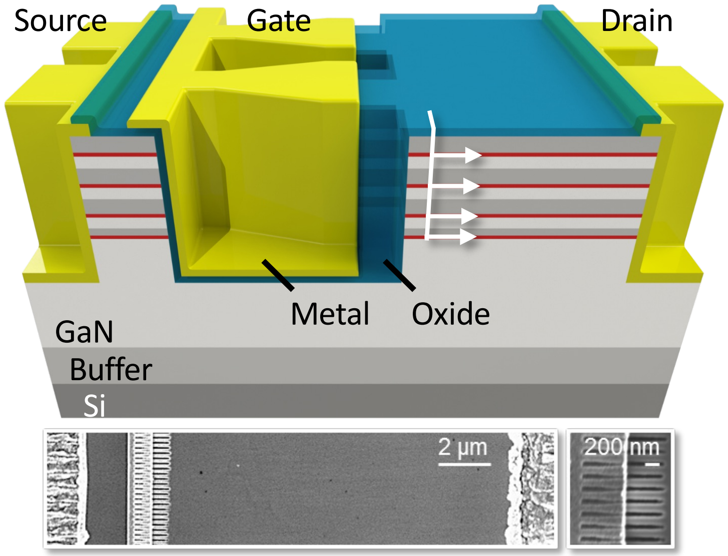




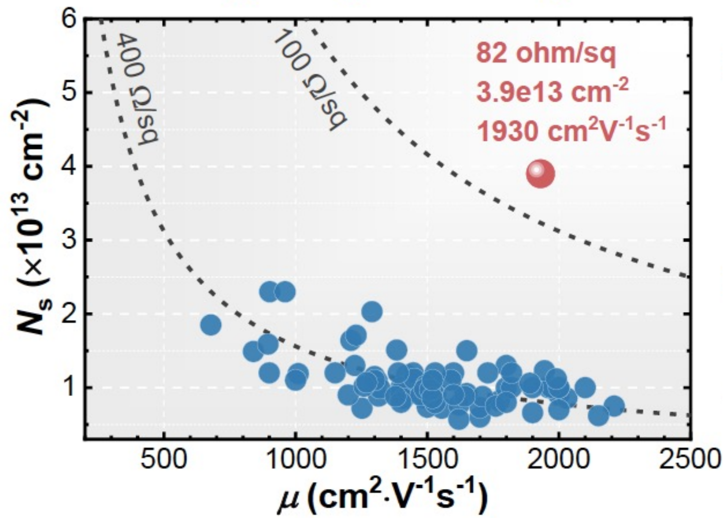
Snapshot of our laboratory:
I. Nanostructure for power electronic devices

Multi-channel power devices for ultra-low resistance and high breakdown voltage

1. Multiple 2DEG channels



Much higher conductivity



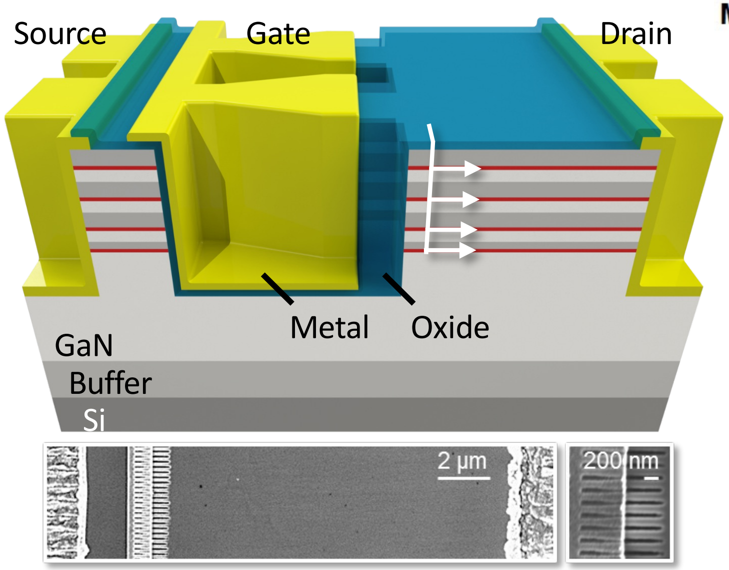
More than 5x-higher conductivity: significantly lower resistive losses!

Snapshot of our laboratory:
I. Nanostructure for power electronic devices

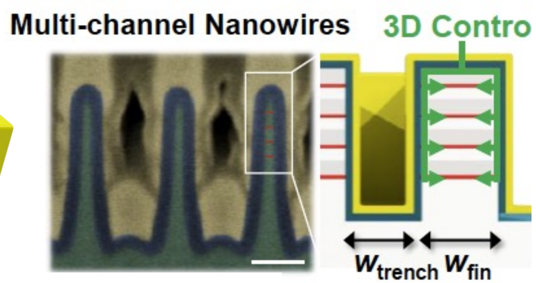
POWER lab

Multi-channel power devices for ultra-low resistance and high breakdown voltage

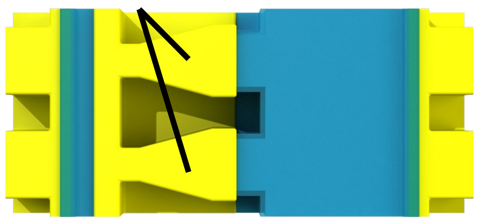
1. Multiple 2DEG channels



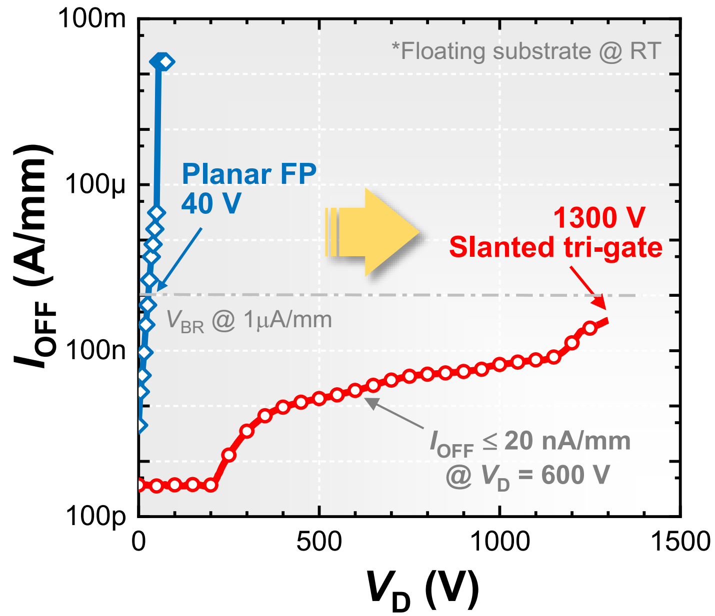
2. Tri-gate control



3. Slanted tri-gate termination



High breakdown voltage of 1300 V



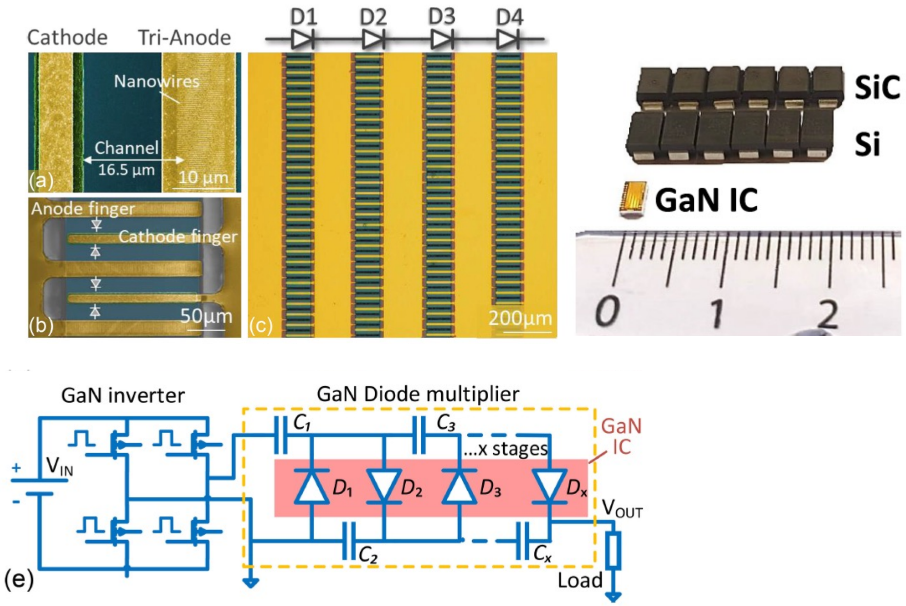
3D geometry increased the breakdown voltage from 40V to 1300V

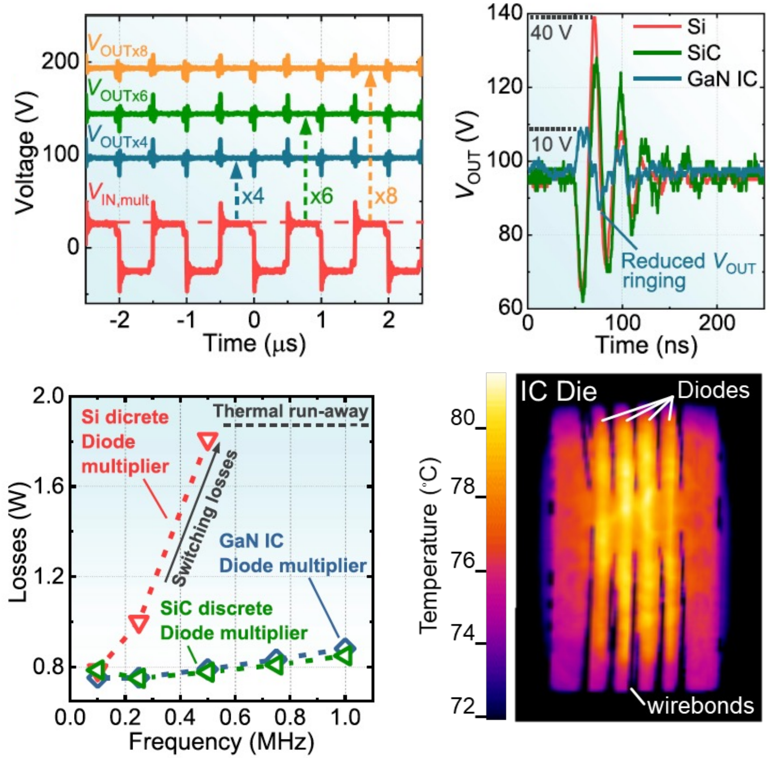
- J. Ma, C. Erine, M. Zhu, L. Nela, K. Cheng, E. Matioli, 2019 **IEEE International Electron Devices Meeting (IEDM)**, San Francisco, 2019
- L. Nela, J. Ma, C. Erine, P. Xiang, T.-H. Shen, V. Tileli, K. Cheng, E. Matioli, **Nature Electronics**, 2021
- J. Ma, G. Kampitsis, P. Xiang, K. Cheng and E. Matioli, IEEE Electron Device Letters, 2018.
- J. Ma, C. Erine, P. Xiang, K. Cheng and E. Matioli, Applied Physics Letters, 2018.

EPFL

Snapshot of our laboratory: Integrated GaN-on-Si Schottky diodes

Diode voltage multiplier GaN IC

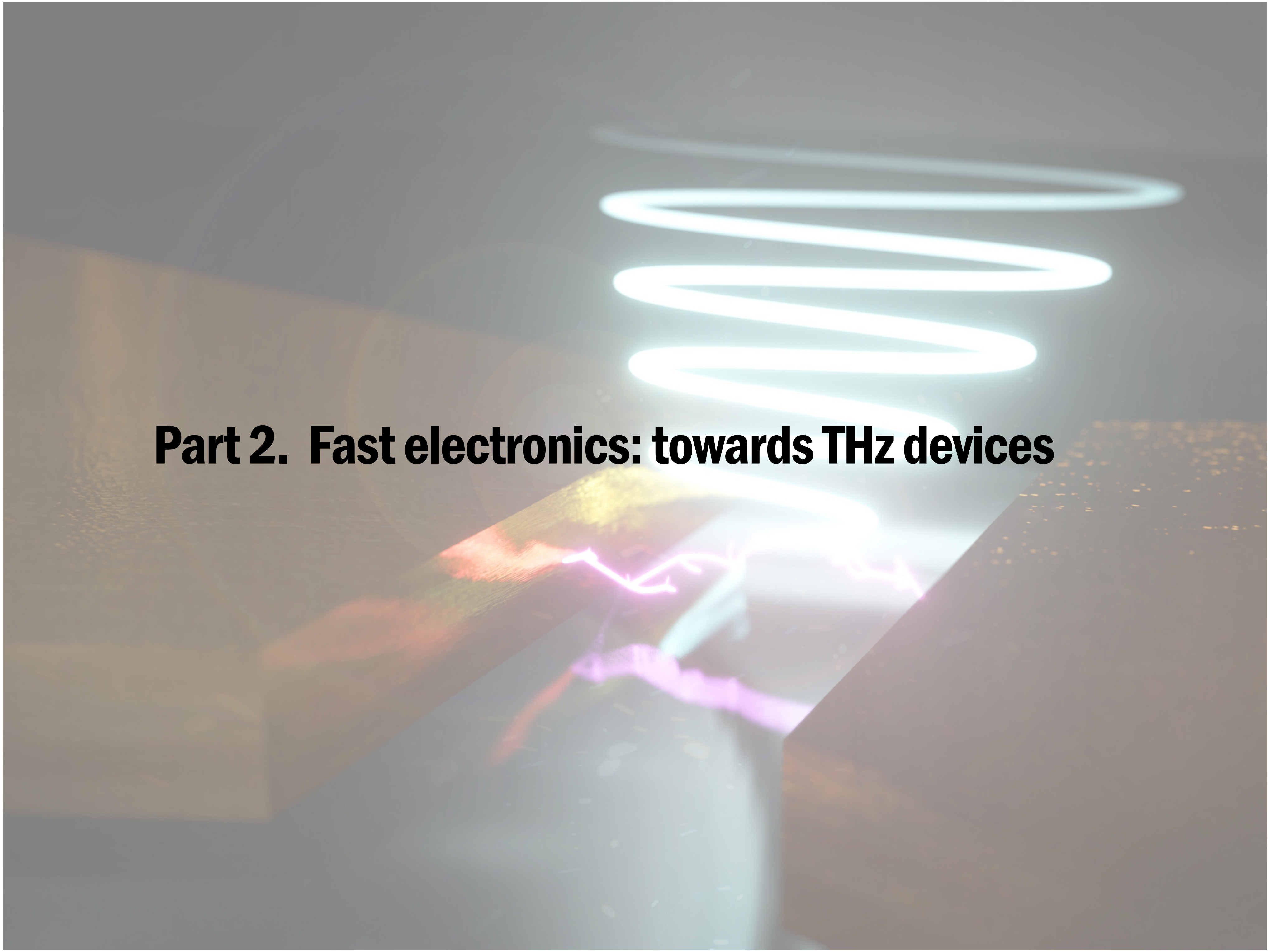




High frequency switching in GaN integrated devices: small devices and energy storage elements

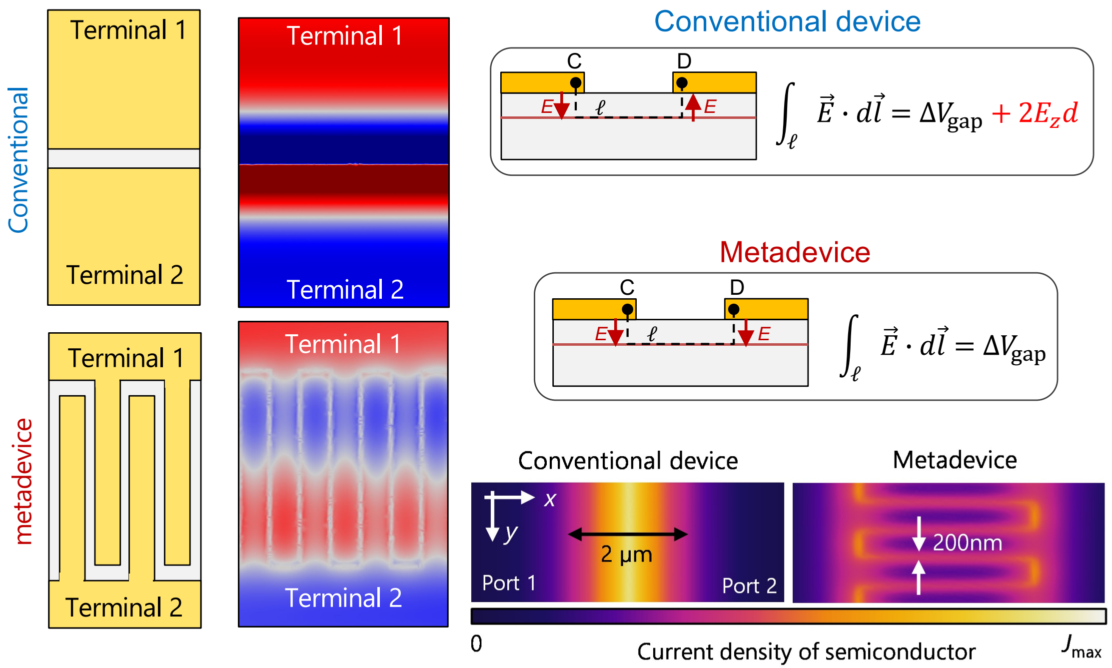
L. Nela, R. Van Erp, G. Kampitsis, H. K. Yildirim, J. Ma and E. Matioli, "*Ultra-compact, High-Frequency Power Integrated Circuits Based on GaN-on-Si Schottky Barrier Diodes*" ***IEEE Transactions on Power Electronics,*** *vol. 36, no. 2, 2021*

Part 2. Fast electronics: towards THz devices

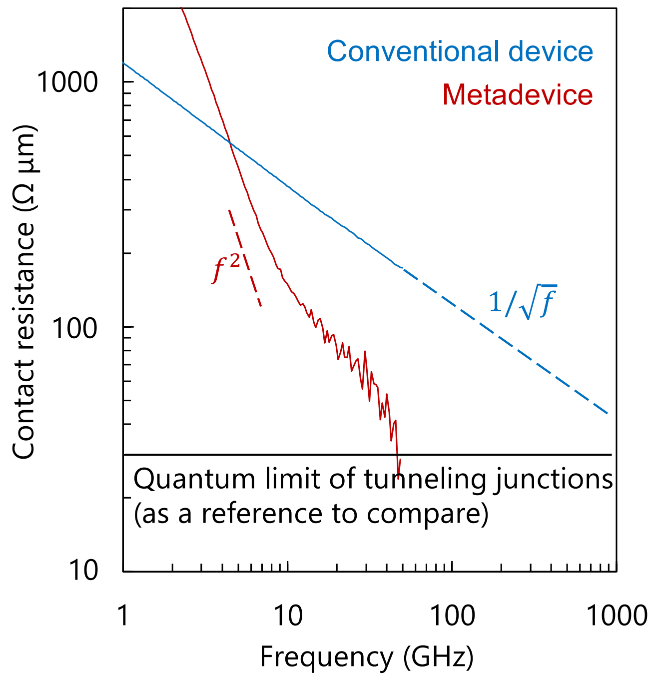


Snapshot of our laboratory: Microscopic manipulation of RF fields

POWER lab



Microscopic manipulation of RF fields



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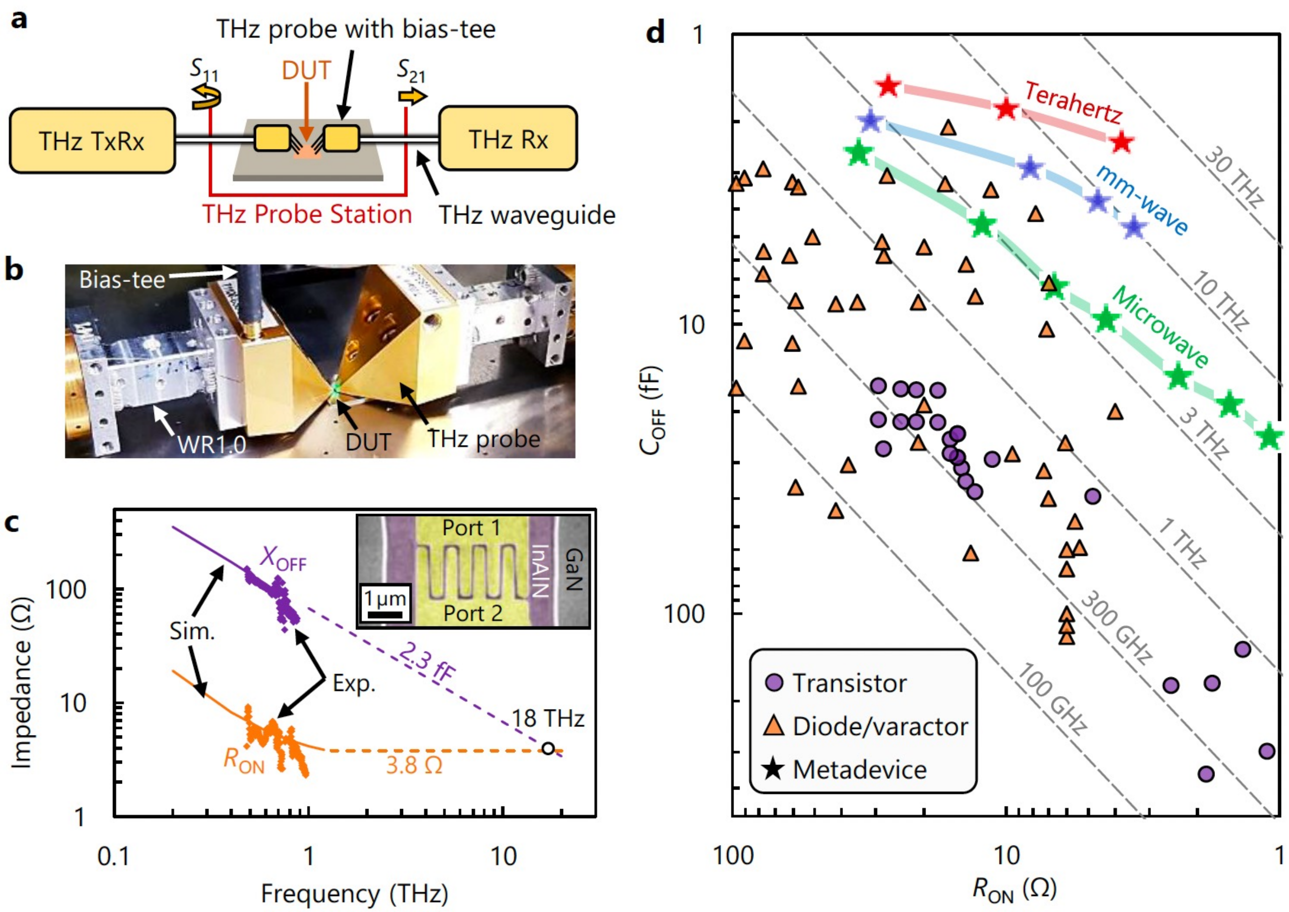
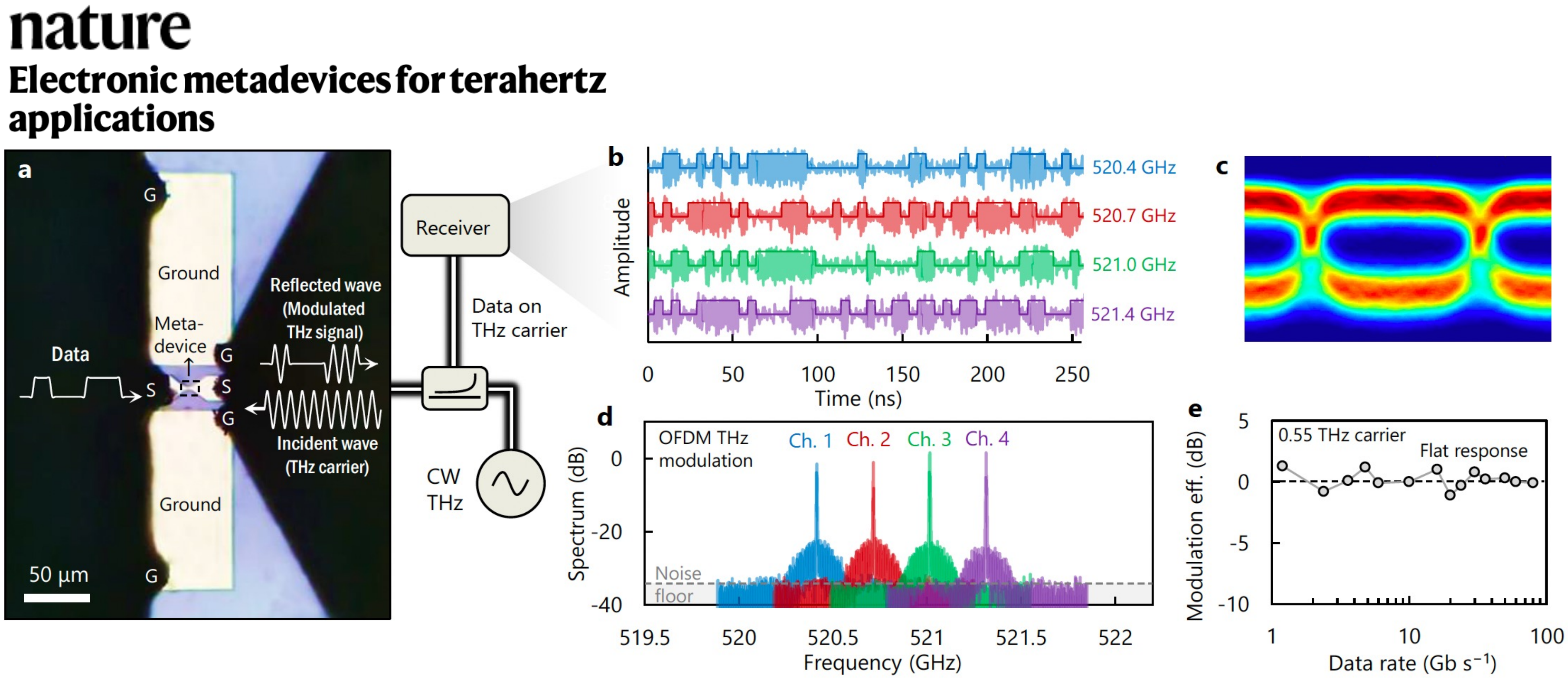
Replacing the straight-gap by a stripe array, enhances the conductance of the device

Snapshot of our laboratory: Electronic metadevices for THz



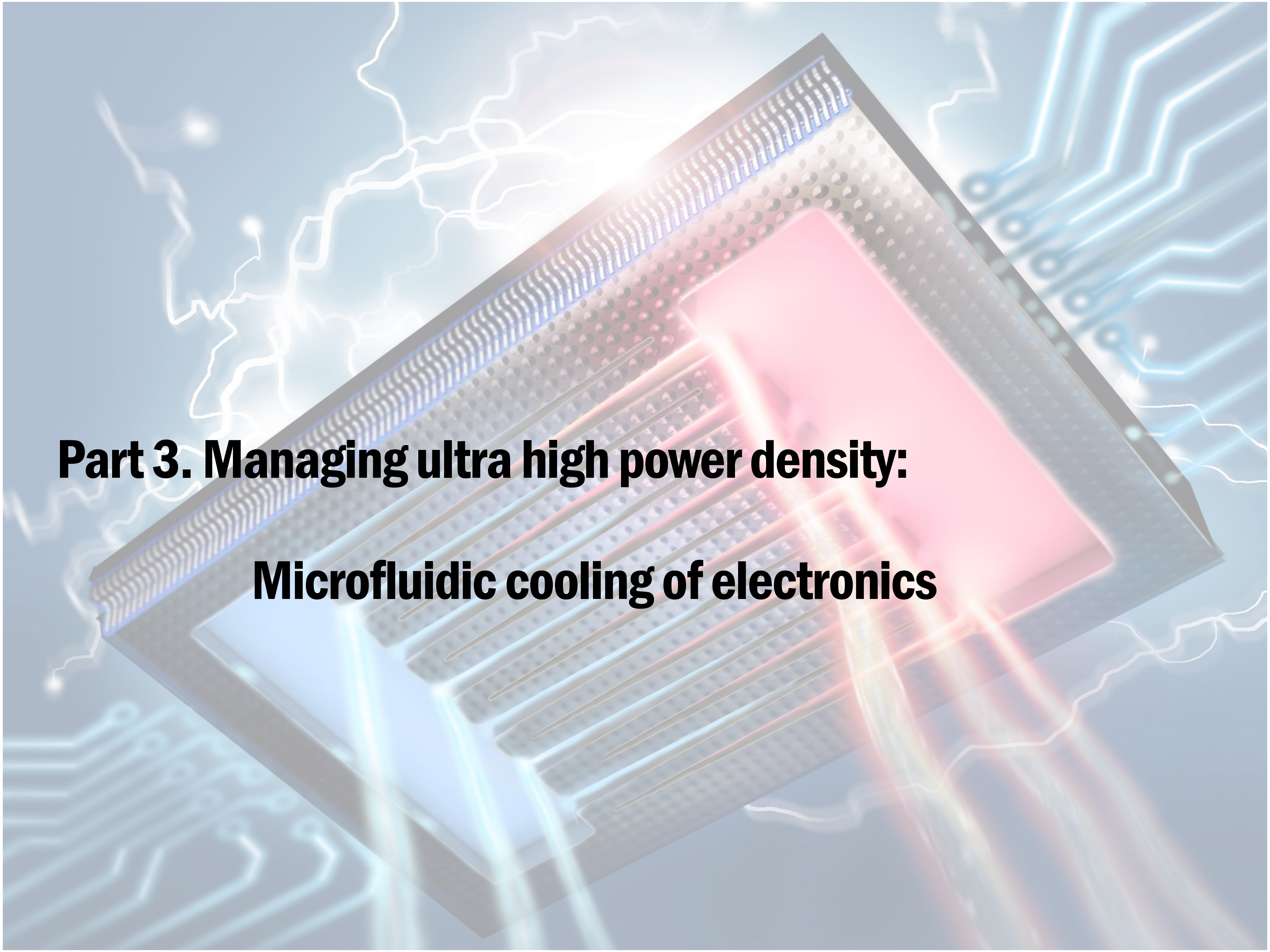
M. Samizadeh and E. Matioli, *Electronic Metadevices for terahertz applications*, **Nature** (2023)

Snapshot of our laboratory: Electronic metadevices for THz



High-performance THz data transmitters using electronic metadevices

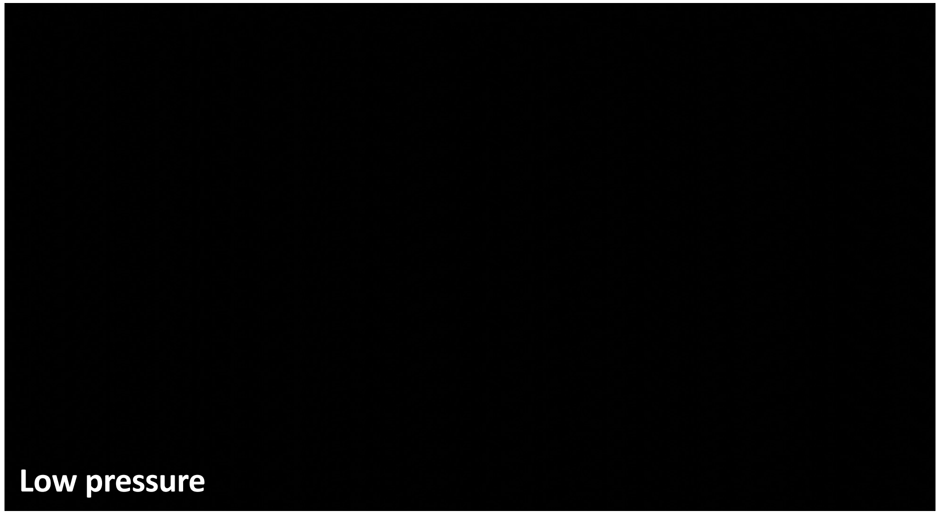
M. Samizadeh and E. Matioli, *Electronic Metadevices for terahertz applications*, **Nature** (2023)



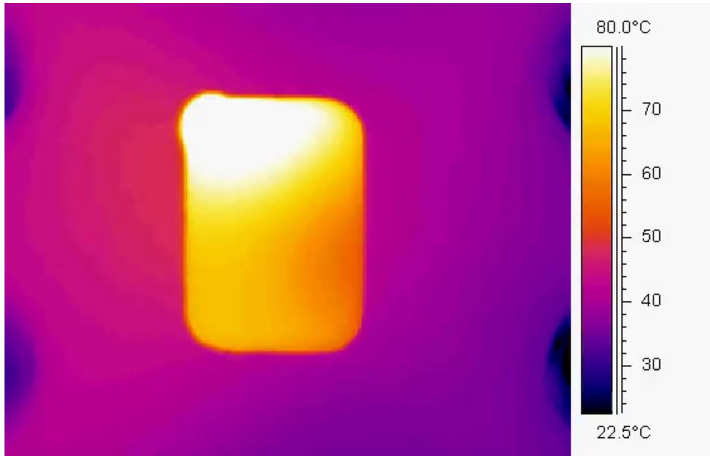
Part 3. Managing ultra high power density:

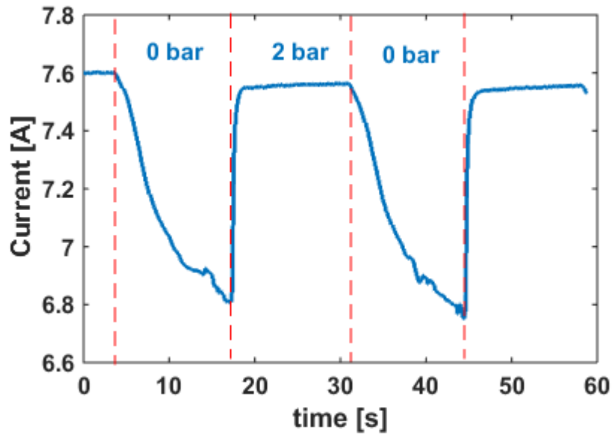
Microfluidic cooling of electronics

Snapshot of our laboratory: Near-junction microfluidic cooling



R. van Erp, G. Kampitsis, L. Nela, R. Soleimanzadeh and E. Matioli, ***Nature*, 2020**.





All devices were fabricated at the EPFL cleanroom facilities (CMI)

CMi EPFL Center of MicroNanoTechnology

Elison Matioli

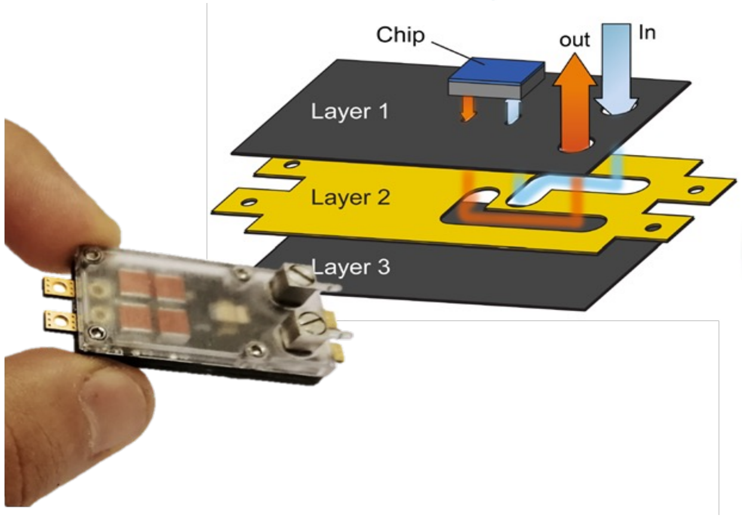
Snapshot of our laboratory:
Fully-integrated power IC with microfluidic cooling

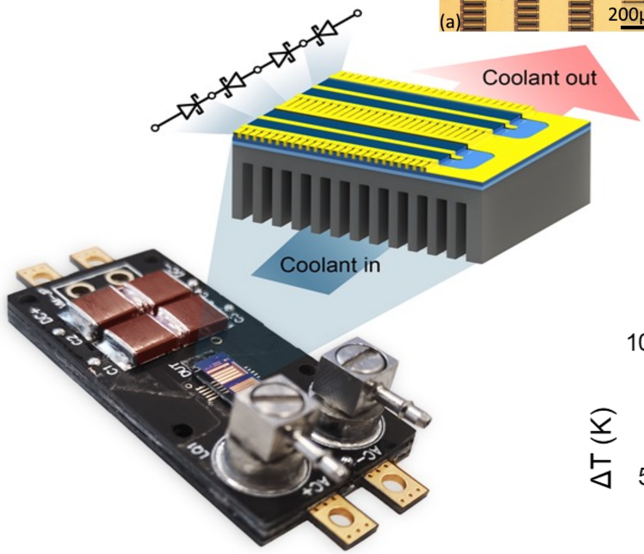
nature

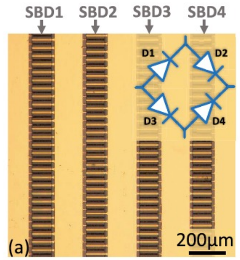
Article | Published: 09 September 2020

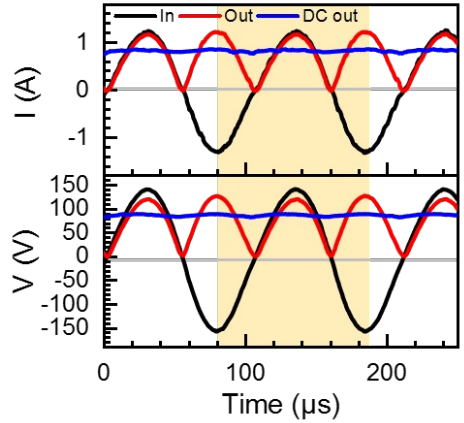
Co-designing electronics with microfluidics for more sustainable cooling

Remco van Erp, Reza Soleimanzadeh, Luca Nela, Georgios Kampitsis & Elison Matioli









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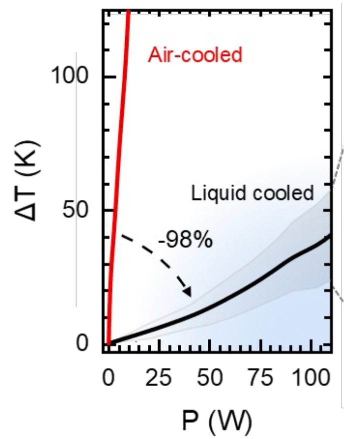

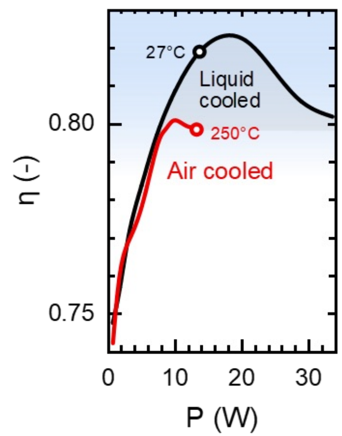

Efficient thermal management enables integration of power devices for high power density applications

R. van Erp, R. Soleimanzadeh, L. Nela, G. Kampitsis and E. Matioli, ***Nature*** 585 (7824), 211-216 (2020).
L. Nela, R. Van Erp, G. Kampitsis, H. K. Yildirim, J. Ma and E. Matioli, ***IEEE Transactions on Power Electronics***, vol. 36, no. 2, pp. 1269-1273, Feb. 2021

Bachelor and Masters Projects

The POWERlab offers several projects for EPFL students, at the bachelor and master levels, to work closely with our Ph.D. students and postdocs. Below is the list of available projects:

Bachelor and Master Semester Projects:

Master Thesis (30 ECTS credits)
There are several projects available for Master thesis for EPFL students. Please contact Prof. Matioli to discuss in more details.

If you are interested and would like to have more information please contact **elison.matioli@epfl.ch**