EDOC teaching program

EE-627
Advanced III-Nitride Semiconductor Devices

Introduction

Advanced III-Nitride Semiconductor Devices

Profs. Nicolas Grandjean[1], Emmanouil Kioupakis[2] and Elison Matioli[3]
1. IPHYS, EPFL
2. U. Michigan and Visiting professor IMX, EPFL
3. IEM, EPFL

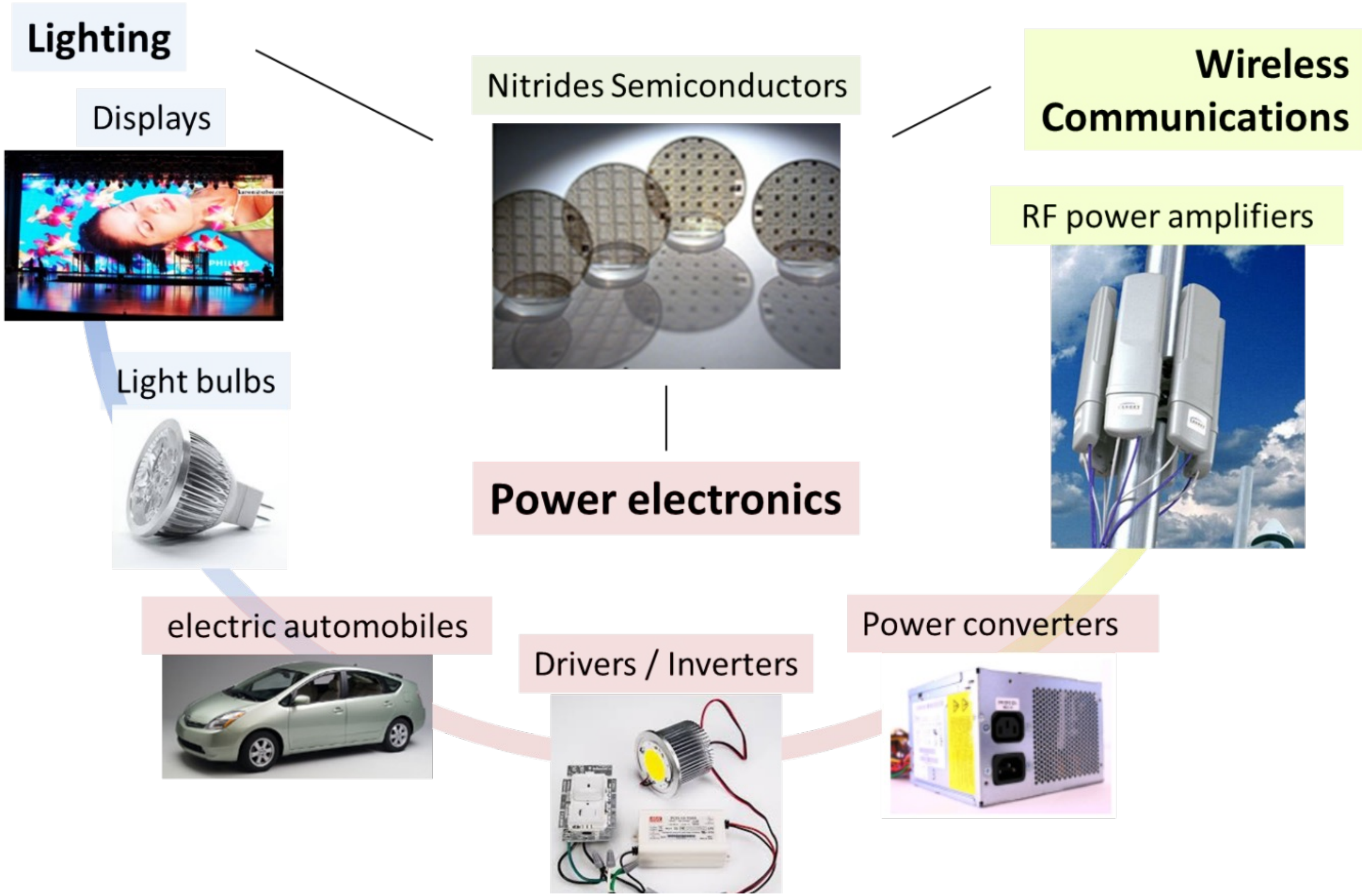
Goals of this course

Why are you taking this class?

What do will you learn?

Why is that important?

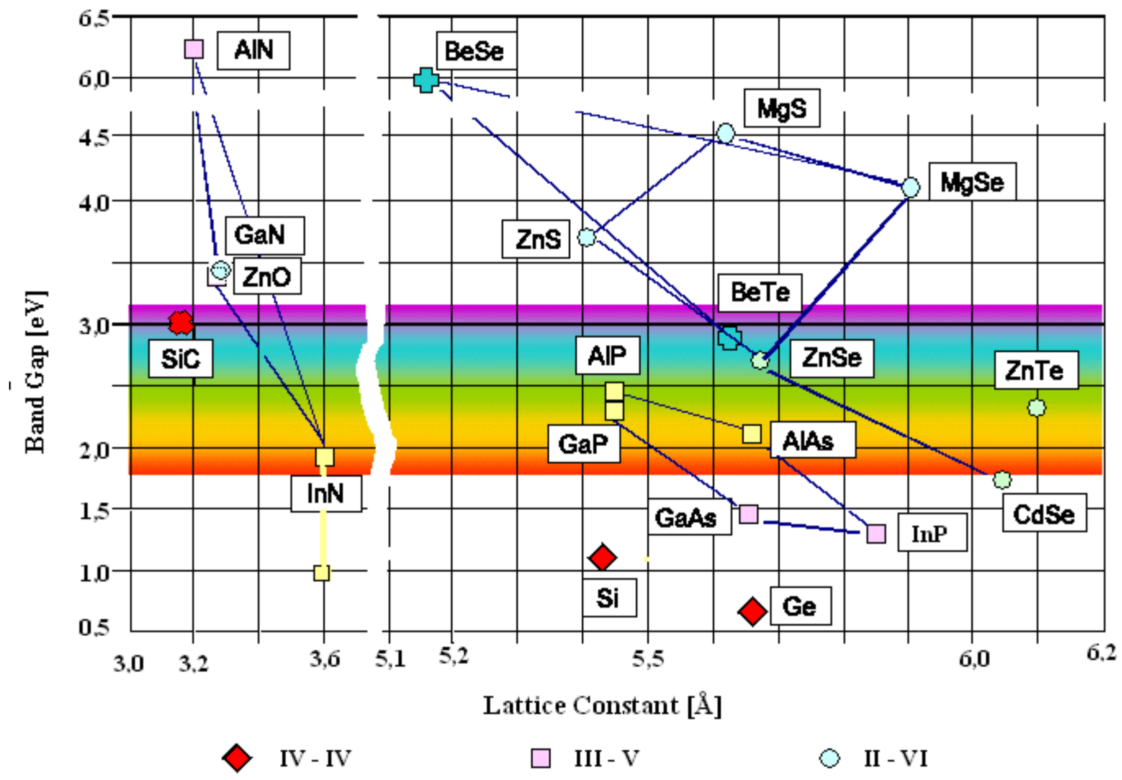
III-Nitrides are an exceptional material



III-Nitrides are exceptional materials

Most III-V compounds radiate at wavelengths above the visible region, i.e. in the **infrared**. However, adding some Al to GaAs **producing AlxGa1-xAs**, will shift the wavelength into the red region of the spectrum - here are our red luminescence diodes and Lasers!

For a long time, there were **no III-V compounds that emit blue light** - this is a severe problem for many potential applications. While SiC could be used to some extent, **it was only with the advent of InGaN that this problem was solved**. SiC and GaN crystals, however, are not of the "zinc-blende" type common to all the III-Vs in the diagram but have a hexagonal unit cell: wurtzite. They therefore do not easily mix with the others!



Optoelectronics:

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

Semiconductors efficiently emit light: LED light bulbs

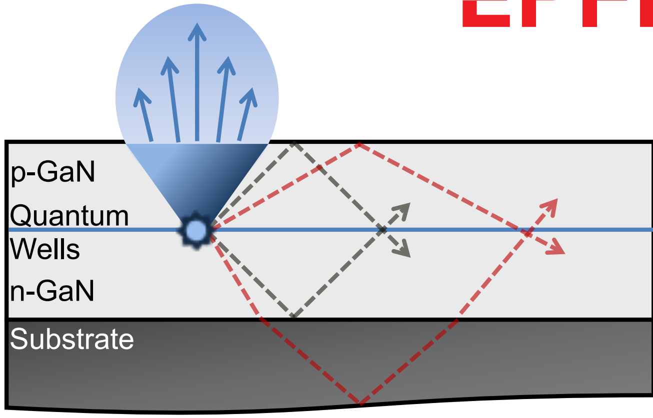
Least Efficient —— Most Efficient

Bulb Type

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

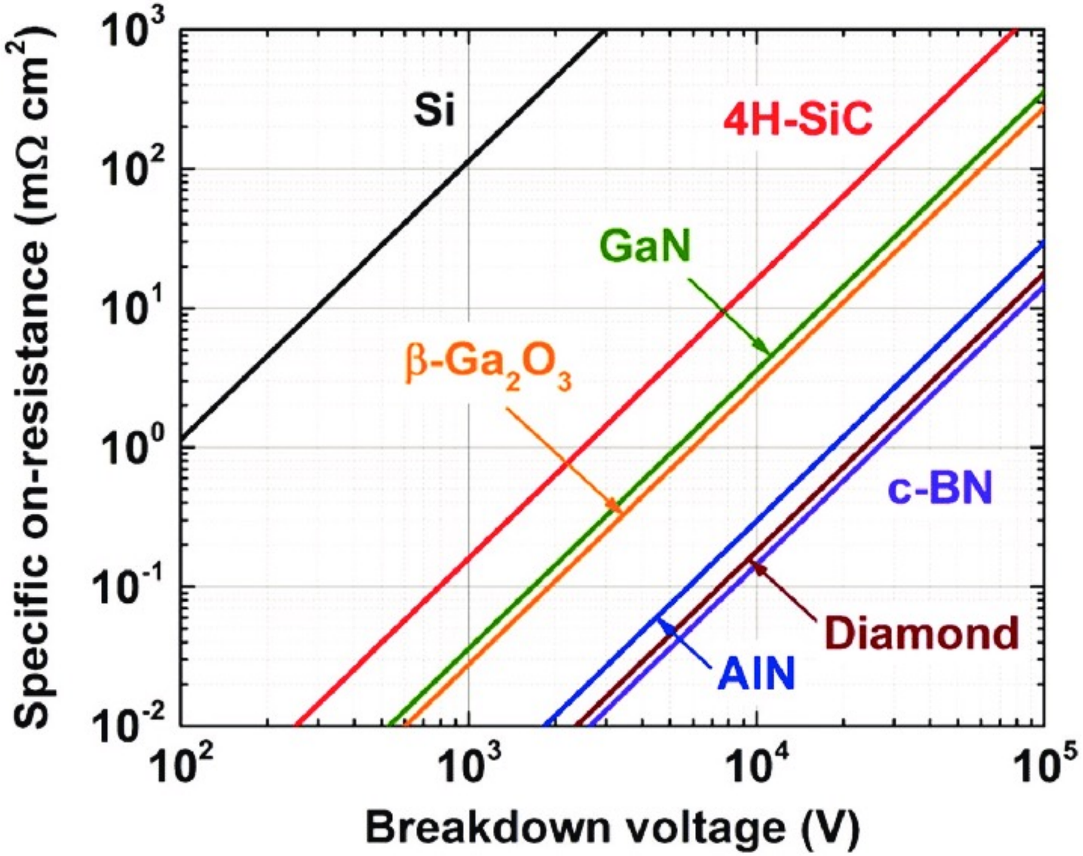


Nobel Prize in 2014

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

Why is light emission in III-Nitrides so efficient?

III-Nitrides are exceptional materials



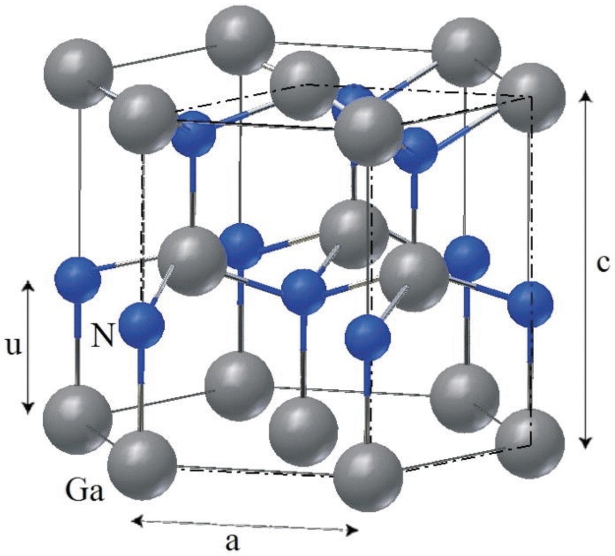
III-Nitrides for electronics:

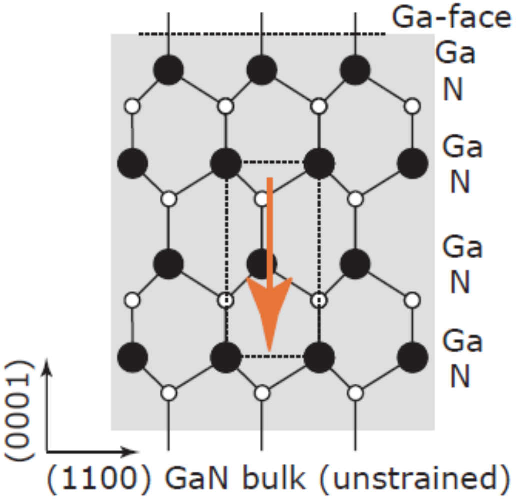
- High electron velocity (×3 than Si)
- High carrier density (×3 than Si)
- High breakdown voltage (>×10 than Si)

Case for GaN: Basics of III-Nitrides

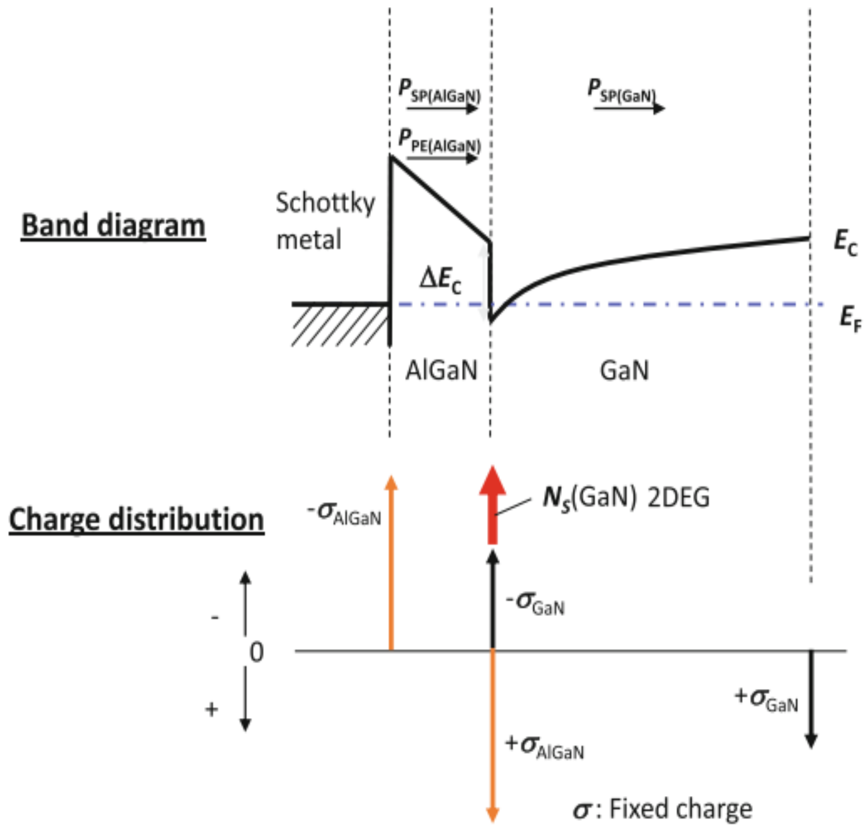
What is truly unique of III-Nitrides?

Wurtzite structure





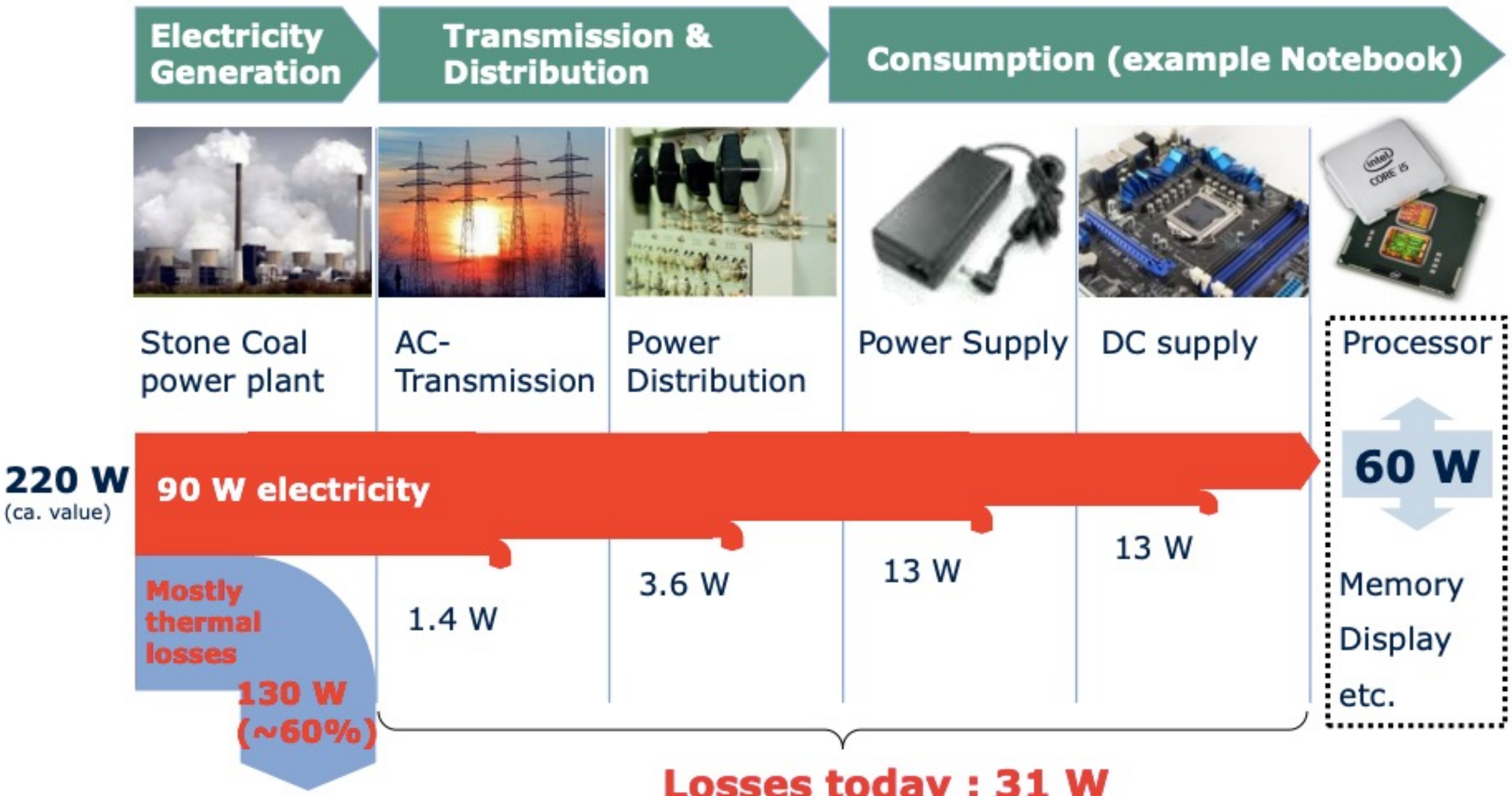
AlGaN/GaN



Can be used for efficient power and RF devices

Motivation for power electronics

Power Electronics: large potential for energy efficiency



Source: Infineon estimate

[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.

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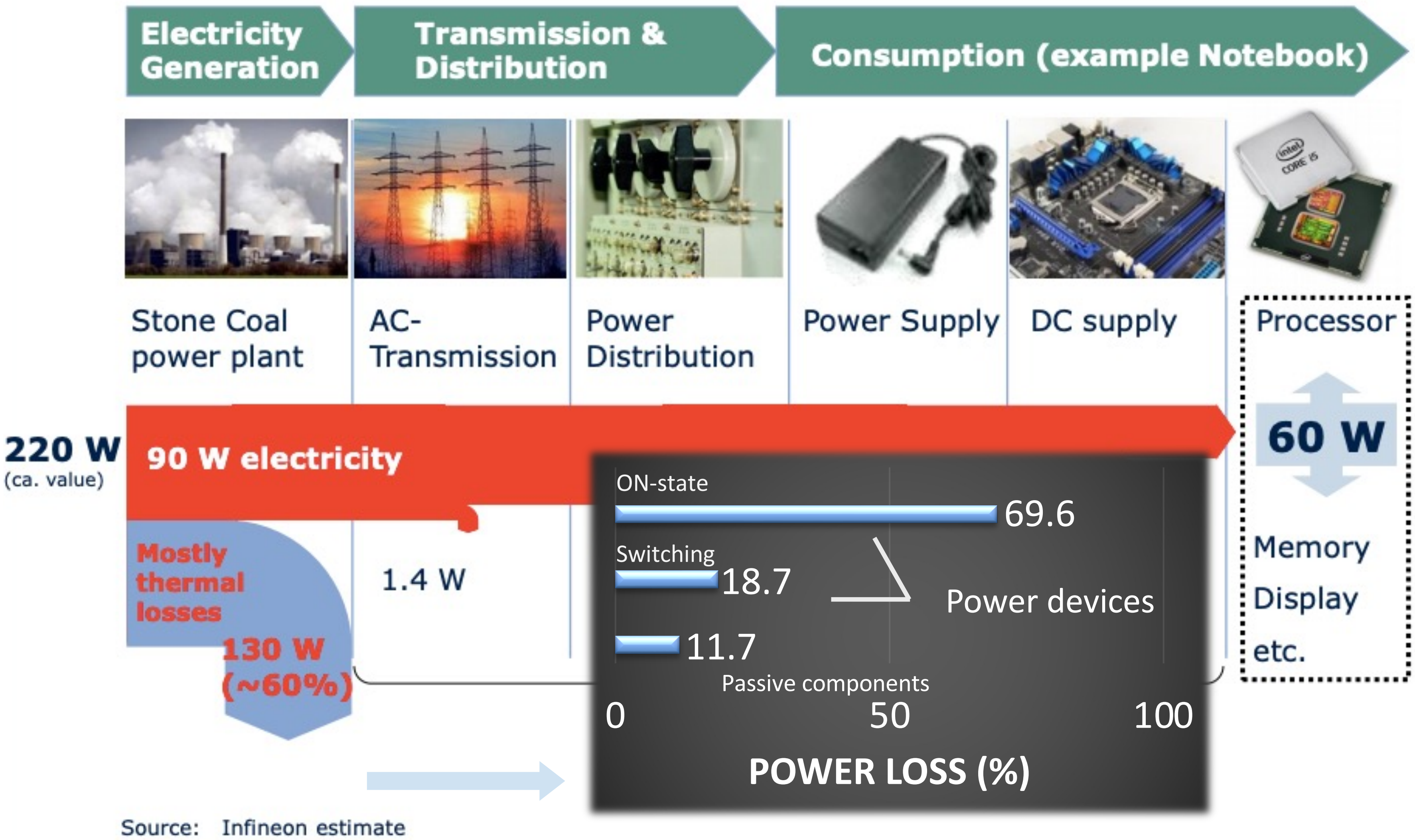


How to significantly reduce this losses?

[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.

Why is that important?

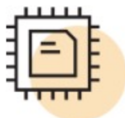
Electrification and digitalization of our society requires efficient semiconductor devices

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

This course is divided in 4 parts

PART I – Epitaxial Growth (Prof. N. Grandjean)

- Growth considerations and device performance
- Main growth techniques for Nitrides (MOVPE, MBE)
- Advance topics relevant to epitaxy

PART II - Theoretical part (Prof. E. Kioupakis)

- Background physics: From atoms to crystal to band structure
- Band structures and alignments for nitrides and other semiconductors
- Atomic vibrations and phonons
- From bands to optical spectra and transport properties.
- Heterojunctions/heterostructures: Brief introduction to band alignment

PART III - **Optoelectronic devices (Prof. N. Grandjean)**

- Optical properties and basics
- Optical transitions, excitons, spectroscopy, etc..
- Basics of III-Nitride LEDs and lasers, EQE, IQE, laser etc...
- Current trends in optoelectronic devices - state of the art

Part IV – Electronic Devices (Prof. E. Matioli)

- Electronic and transport properties
- Basics for electronics: HEMTs, Lateral devices: comparison between MOSFETs and HEMTs
- Radio frequency devices: equivalent circuit, how to measure, FOM: important aspects
- Power devices: Vertical and lateral device principles, FOM, PIN and Schottky diodes, MOSFETs
- Efficient converters: Analysis of losses
- Current trends in electronics - state of the art

This course is divided in 4 parts

There will be 3 lab visits:

- EPiX: EPFL epitaxy platform
- LASPE: Optoelectronic physics and devices
- POWERlab: POWER and RF electronic devices

Evaluation:

Students will be grouped to give presentations on given topics: 5 groups of 4 people

Each presentation will be 12 min + 8 min Q&A. Every group member has to present (3 min each)

Each group presents 3 times on different topics; **Choose the topics in your group and let me know by email**

The presentations and the Q&A are evaluated;

The class participation is also evaluated (the rest of the class has to ask good questions)

Grade: average of the presentations (90%)+ participation (10%)

Syllabus (on moodle)

Proposed Doctoral Course - EE 627 - Advanced III-Nitride Semiconductor Devices

Offered to EDPY, EDPO, EDMI, EDEE, EDMX

Professors: Elison Matioli, Emmanouil Kioupakis and Nicolas Grandjean

Lecturer	date	title
Elison	18.02.2025 (first half - introduction) Introduce parts from all professors	**Introduction** Introduction to the class: final goal Motivation: Why heterojunctions LEDs, LDs, HEMTs, etc… Introduction to the three parts of the class Split the students in groups, explain the exercises, 12 min + 8 min QA
Part I - Epitaxy part		
Nicolas	18.02.2025 (second half)	**Epitaxial Growth: how these structures are grown in practice** Growth considerations and device performance Main growth techniques for Nitrides (MOVPE, MBE)
Nicolas	20.02.2025	**Epitaxial Growth: how these structures are grown in practice (cont.)** Growth of III-Nitride structures Advance topics relevant to epitaxy
Alok	25.02.2025	Lab's visit (EPiX) - Alok present all machines
Elison and TAs	27.03.2025	Student presentations on Epitaxy, students can choose the topic or pick an example below: Exercice 1: literature review: presentation on growth - literature review and key breakthrough in III-nitride growth Exercise 2: Research presentation: presentation of experimental results of particular aspects of III-Nitrides
Part II - Theoretical part		
Manos	04.03.2025	**Background physics: From atoms to crystal to band structure** Introductory quantum: Schrodinger, particle in a box, harmonic oscillator, atoms. Connecting atoms (quantum) to crystal to bands, LCAO. Band stru Atomic vibrations and phonons: phonon dispersions, acoustic and optical modes. Phonon band structures of nitrides. Electron-phonon coupling in ni From bands to optical spectra and transport. Basic optical and electrical properties: nitrides and other III-Vs Basic electronic properties : mobility, LO phonon scattering, saturation velocity, BV introduce experiments: how to measure mobility, lattice constants, band gap, phonons, etc…
Manos	06.03.2025	**Background physics: From crystal to band structure** Thermodynamics of enthalpy vs. entropy, phase stability. introduction and connection to DFT - examples of your own research, connect to state of the art
Manos	11.03.2024	**Imperfect crystals: defects, alloys, phonons** Thermodynamic ideas of imperfections, how to characterize, what they do on the functional properties. Alloys, tunability of properties. Scattering Doping and their qualitative difference with detrimental defects. Formation and ionization energy. Scattering of electrons and phonons by defects. Example: Doping of AlN: DX centers, polaronic acceptors. Electron-hole recombination: Shockley-Reed-Hall, radiative, Auger.ABC model. Connection to Opto devices. Impact ionization and breakdown volta
TAs (and Manos?)	13.03.2025	Student presentations on Theoretical part, students can choose the topic or pick an example below: Exercise 1: Solve exercise: Use data to extra (one solvable and one open question) Exercise 2: solve LCAO matrix in 1D Exercise 3: discuss the effect of these on the efficiency of LEDs: Auger versus leakage? Exercise 4: theorical effect of effective mass on the ionization of dopants - calculate the effect of effective mass on the n- and p-type doping in G
Manos	18.03.2025	**Transition from shallow to deep donor/acceptor…. And discussions** Strain effects on the band structure, effective masses. Current topics in theoretical characterization of nitride semiconductors and materials discovery
Manos	20.03.2025	**Heterojunctions/heterostructures** Brief introduction to band alignment Quantum confinement: quantum wells, nanowires, quantum dots. Case of Nitride semiconductors: Polarization fields, spontaneopus and piezoelectric. Effects of polarization in devices: carrier separation, 2DEG, doping. Switching the polarization: ScAlN and nitride ferroelectrics
Part III - Optoelectronic devices		
Nicolas	25.03.2025	Optical properties and basics
TAs	27.03.2025	Student presentations on Optoelectronic part, students can choose the topic or pick an example below: Exercise 5: Quantum engineering: hot to enginneer quantum struvctures for efficient devices (for a given wavelenths) - couplage entre puits, ICL - p Exercise 6: literature review and techniques to probe the bandgap of a semiconductor Exercise 3 - live: draw the band alignement/band structure for various structures (p-n junction, heterojunctions, contact) Exercise 4 - live: draw the band alignement/band structure for various structures (QW, heterostructures). first try to simulate, but the solution might not be correct - give a counter example from a paper - ask to repeat the exercise
Nicolas	01.04.2025	LEDs and lasers basics of III-Nitride LEDs and lasers, EQE, IQE, laser etc…
TAs at Laspe	03.04.2025	Lab's visit (LASPE) - someone at laspe
Nicolas	08.04.2025** deplacer 09.04.2025 a 17h	Current trends in optoelectronic devices - state of the art Give some state of the art on LEDs, Lasers - performance x wavelength recent advances in the literature in GaN optoelectronics (state of the art, micro LEDs, DEEP UV LEDs, long wavelength LEDs, VCSELS etc..)
Elison and TAs	10.04.2025	Student presentations on Optoelectronic part, students can choose the topic or pick an example below: Exercise 7: literature review: in your view what are the potential big applications of the future - they will be challenged Exercise 8: Research presentation: particular aspect of III-Nitride optoelectronic device
Part IV - Electronics		
Elison	15.04.2025	**Electronic Devices** Electronic and transport properties Basics for electronics: HEMTs
Elison and TAs	17.04.2025	Student presentations on Electronics part - band structures, students can choose the topic or pick an example below: Exercise 9: Simulate the effect of AlGaN barrier, different barriers on ns and explain its effect on mobility Exercise 10: Literature review: Quantum engineering to imporve electron mobility - propose solutions
Elison	29.04.2025** deplacer 02.05.2025 a 10h	**Lateral devices: comparison between MOSFETs and HEMTs** Examples of GaN HEMTs **Radio frequency devices** equivalent circuit how to measure FOM: important aspects
Elison and TAs	01.05.2025	Student presentations on Electronics part , students can choose the topic or pick an example below: Exercise 11: review the literature and present the latest device concepts in III-N for RF applications Exercise 12: explain the characterization of RF devices in details - how to do, deembeding, etc…
Elison	06.05.2025*** deplacer 09.05.2025 a 10h	**Power devices** vertical devices FOM PIN and Schottky diodes transistors
TA at POWERLAB	08.05.2025	Lab's visit (Powerlab)
Elison	13.05.2025	**Power devices** lateral power devices e- and d-mode devices high voltage current commercial devices
Elison and TAs	15.05.2025	Exercise 13: review the literature and present the latest device concepts in III-N for lateral power applications Exercise 14: review the literature and present the latest device concepts in III-N for vertical power applications
Elison	20.05.2025	**Current trends - state of the art** recent advances in the literature in GaN electronics superjunctions
Elison and TAs	22.05.2025	Exercise 15: literature review: in your view what are the potential big applications of the future - they will be challenged Exercise 16 - Novel concepts: ex: superjunction devices
	27.05.2025	Exercise 17: tbd Exercise 18 - tbd

Course structure:

- 24 theoretical lectures in classes
- 18 student presentations – Groups of 3 will present 3 times (marked in green)
- A few dates are not available for the professors: a replacement date is offered

Class are on:

TUESDAYS	**15h-17h**	**INF 119**
THURSDAYS	**16h-17h**	**INJ218**

Groups

1	**Chiesa Riccardo**	EL	**A**
2	**Collette Eloi Régis L**	EL	**B**
3	**Conti Vanessa**	EL	**C**
4	**De Giorgio Cristian**	EL	**D**
5	**Domenech Alexandre Germain Philippe**	MT	**D**
6	**Ferraro Giuseppe**	EL	**E**
7	Gardner Asger Brimnes	PH	
8	**Gür Hakan Cankat**	EL	**A**
9	**Iaconeta Andrea**	EL	**B**
10	**Ji Xinru**	PH	**B**
11	**Krsic Ivan**	EL	**D**
12	**Li Hao**	PH	**C**
13	**Macaluso Marta**	EL	**D**
14	**Marcantoni Francesco**	MX	**C**
15	**Martinolli Niccolò**	CGC	**E**
16	**Mazzone Luca**	EL	**E**
17	**Reichler Mikael Sebastian**	PH	**E**
18	**Soydal Önder**	EL	**B**
19	**Toschi Anna**	PH	**A**
20	**Wang Junda**	EL	**A**
21	**Wang Xuxin**	PH	**A**
21	**Zong Yuan**	EL	**C**

Suggested Topics (you can also propose a topic of interest)

EPFL

Epitaxy

Topic 1: literature review: presentation on growth - literature review and key breakthrough in III-nitride growth

Topic 2: Research presentation: presentation of experimental results of particular aspects of III-Nitrides

Theory

Topic 3: discuss the effect studied on the efficiency of LEDs: Auger versus leakage?

Topic 4: theoretical effect of effective mass on the ionization of dopants - calculate the effect of effective mass on the n- and p-type doping in GaN

Optoelectronics

Topic 5: Quantum engineering: how to enginneer quantum structures for efficient devices (for a given wavelenths) - present a recent concept

Topic 6: literature review and techniques to probe the bandgap of a semiconductor

Topic 7: literature review: in your view what are the potential big applications of the future in optoelectronics

Topic 8: Research presentation: particular aspect of III-Nitride optoelectronic device

Electronics

Topic 9: Simulate the effect of AlGaN barrier, different barriers (incluing new ones proposed in the literature, such as ScAlN, or quaternary) and explain in details its effects (on ns, mobility, etc..)

Topic 10: Literature review: Quantum engineering to imporve electron mobility - propose solutions

Topic 11: review the literature and present the latest device concepts in III-N for RF applications

Topic 12: explain the characterization of RF devices in details - how to do, deembeding, etc…

Topic 13: review the literature and present the latest device concepts in III-N for lateral power applications

Topic 14: review the literature and present the latest device concepts in III-N for vertical power applications

Topic 15: literature review: in your view what are the potential big applications of the future in electronics

Topic 16 - Novel emerging concepts: ex: superjunction devices