ICOS
International Cooperation
On Semiconductors

Challenges in Advanced Computing and Functionalities
International Cooperation on Semiconductors

Presentation of the preliminary ICOS results on International Technology Highlights on Advanced Functionalities

Jyrki Kiihamäki, VTT, Co-creation manager

Markus Pfeffer, Fraunhofer IISB, Prototype Fab Management

Funded by the European Union

SiNANO Institute

Outline

- Overview of current trends and challenges
- Deep Dive
  - Sensors
  - Semiconductor-based photonics
  - Energy harvesting
  - Power devices
- Short Screening of research activities in other areas of advanced functionalities
- Conclusion and first ideas for potential fruitful research collaboration

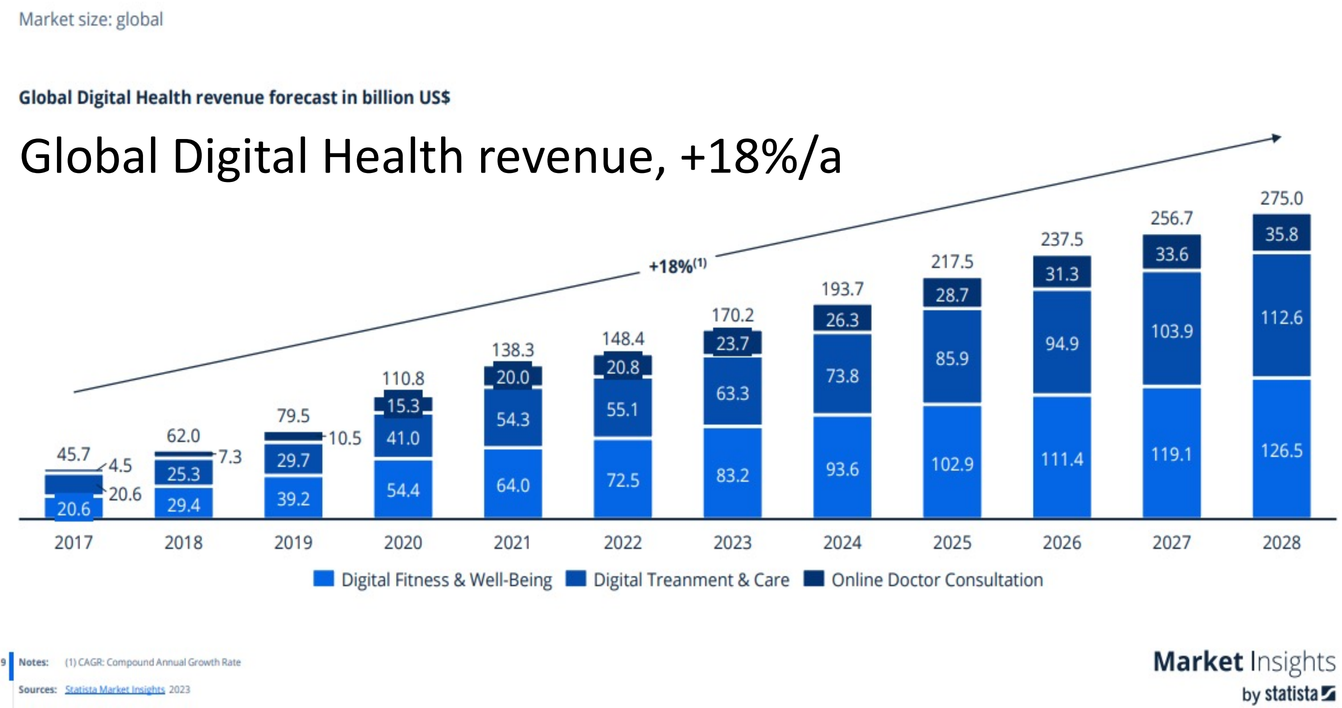
Overview of current trends

Trends and drivers

- **Digitalization**, analogue measurement results are immediately digitized on-site
- **Wireless connectivity** for IoT devices, easy, low cost installation of sensor devices
- **Autarctic systems,** wireless connectivity and (desired) freedom from disposable batteries increase the need for energy harvesting
- Access to powerful computation **(Edge) AI** increases the usage for data producing sensors
- **Fusion of sensor data** from different sources enable new, improved, smarter data to be available for users
- **Data security and reliability**, data should be accurate and reliable, it should not be available to wrong hands, …
- **Electrification of transportation** and **energy conversion** require efficient **power devices**

Applications 1/2

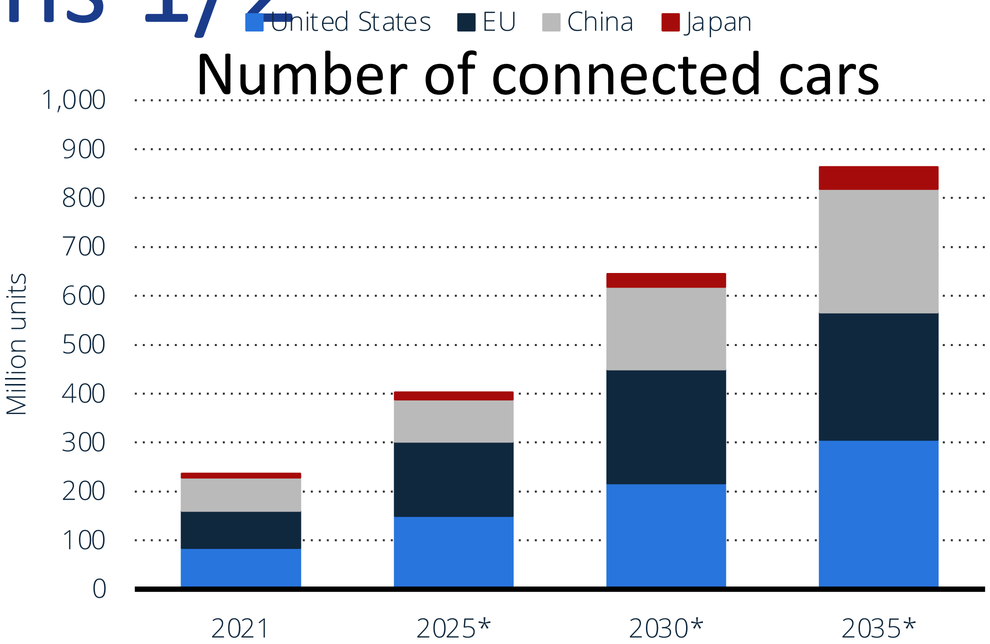
- Automotive/Transport (perception)
- Health / Well being / Vital Signs



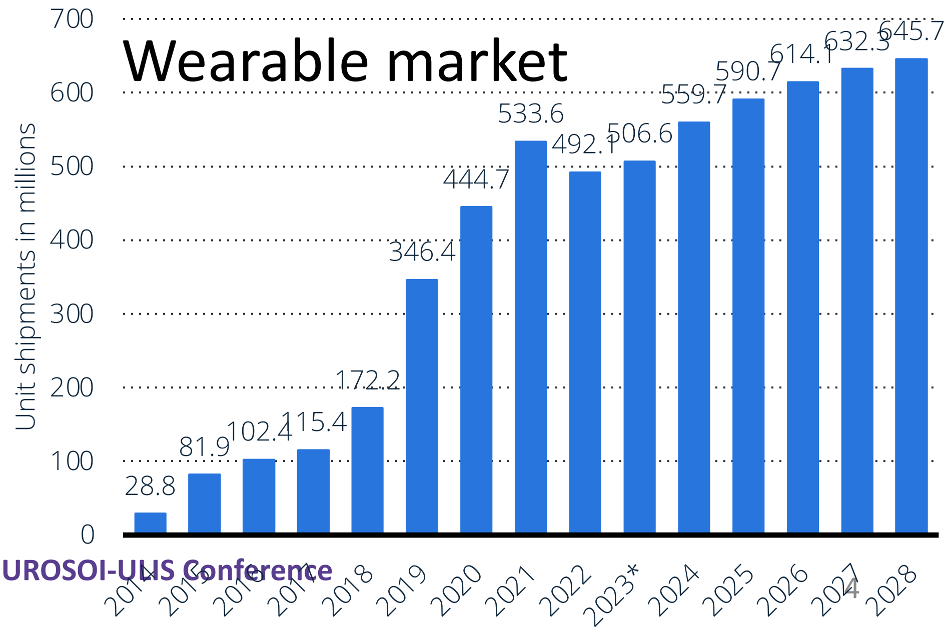
Global Digital Health revenue, +18%/a

Notes: (1) CAGR: Compound Annual Growth Rate

Sources: Statista Market Insights 2023



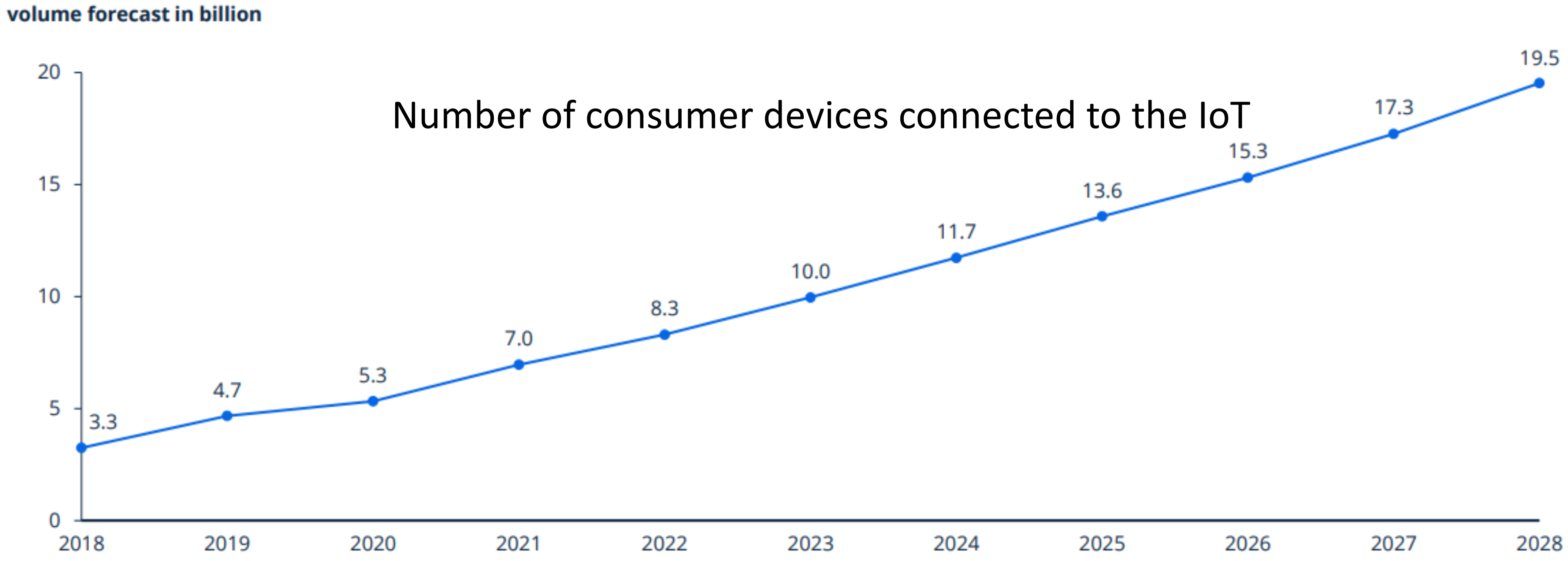
Number of connected cars



Wearable market

Applications 2/2

- Environmental /Built environment
- Industry / Robotics
- Aerospace/Defense/Security
- Consumer
- IoT



Number of consumer devices connected to the IoT

Notes: (1) CAGR: Compound Annual Growth Rate

Sources: Statista Market Insights 2023

Market Insights by statista

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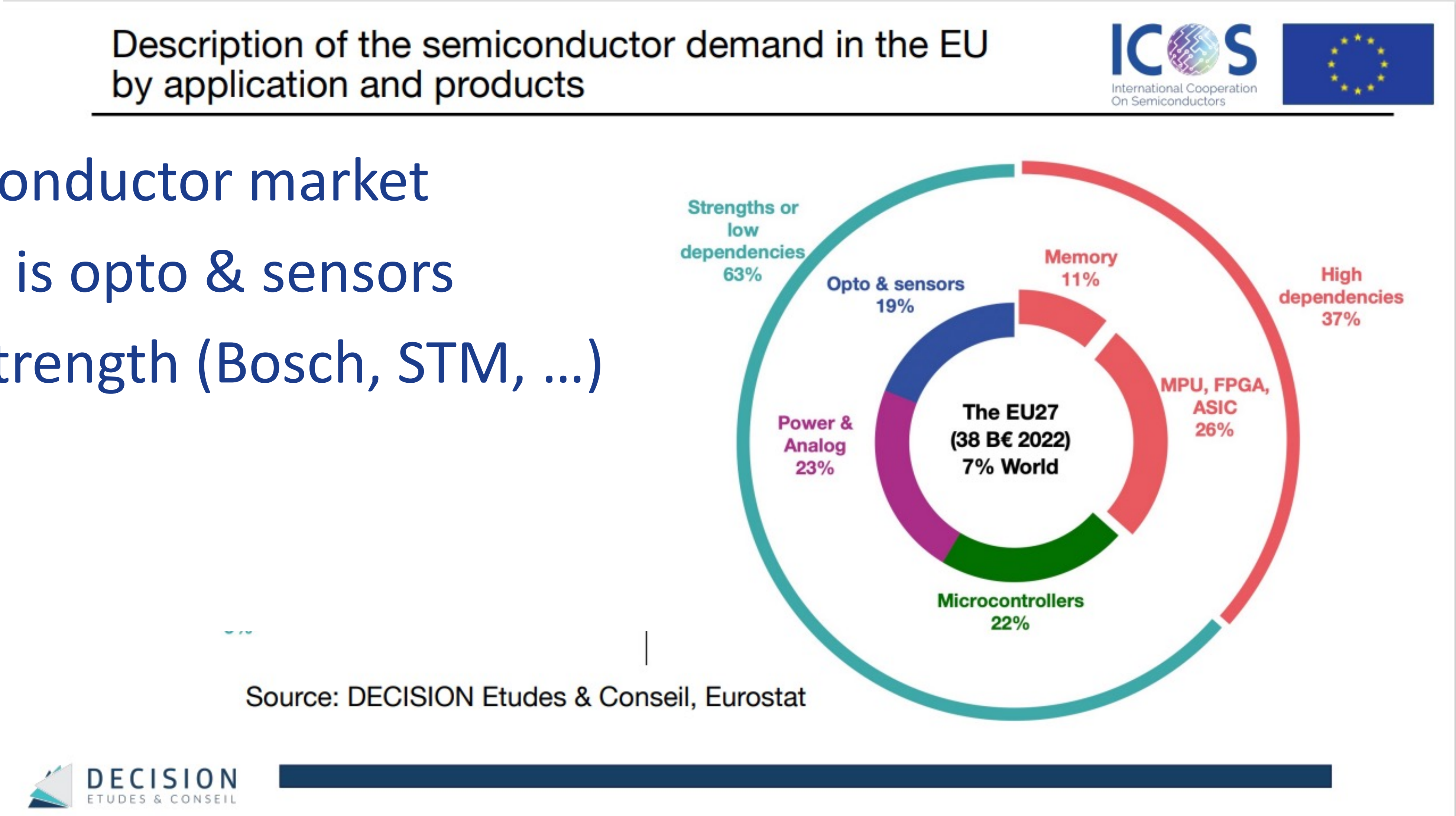
Sensors

- Inertial sensors (accelometers, gyroscopes)
  - Bosch, STM, Murata
- Acoustics (microphones, loudspeakers, ultrasonic transducer)
  - Piezoelectrically driven MEMS are emerging
- Photonics/imaging (camera, spectral sensing, hyperspectral, lidar, …)
- RF (radar, JCAS)
- Others (temperature, pressure, flow, …)

EU market

- 38B€ semiconductor market
- 19% of that is opto & sensors
- European strength (Bosch, STM, …)

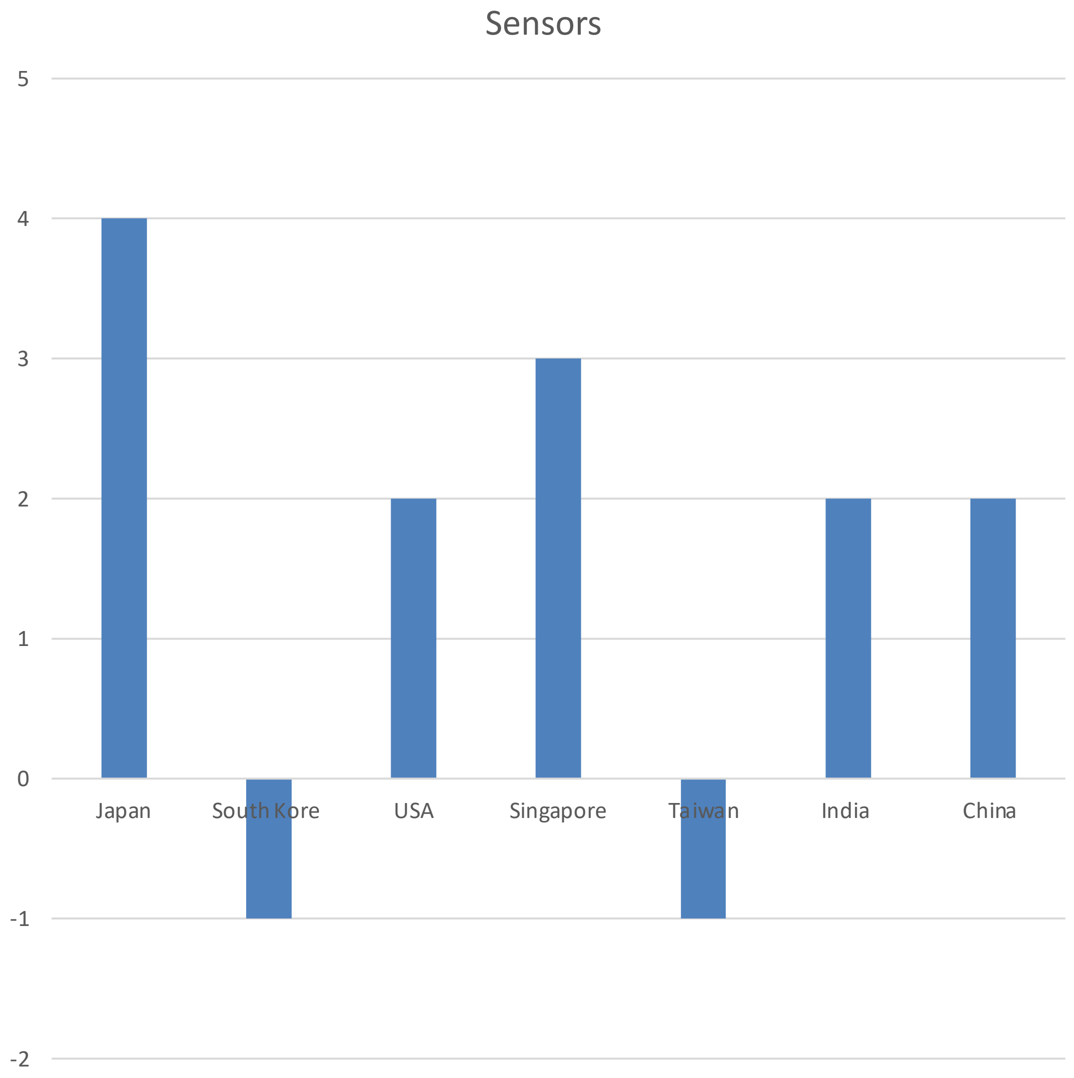


Description of the semiconductor demand in the EU by application and products

Source: DECISION Etudes & Conseil, Eurostat

International comparison

- Relative strength of different countries in sensing technologies
- Scoring 1-5, -1= no data
- (data picked from presentation by Paolo Motto Ros at ICOS workshop January 2024)

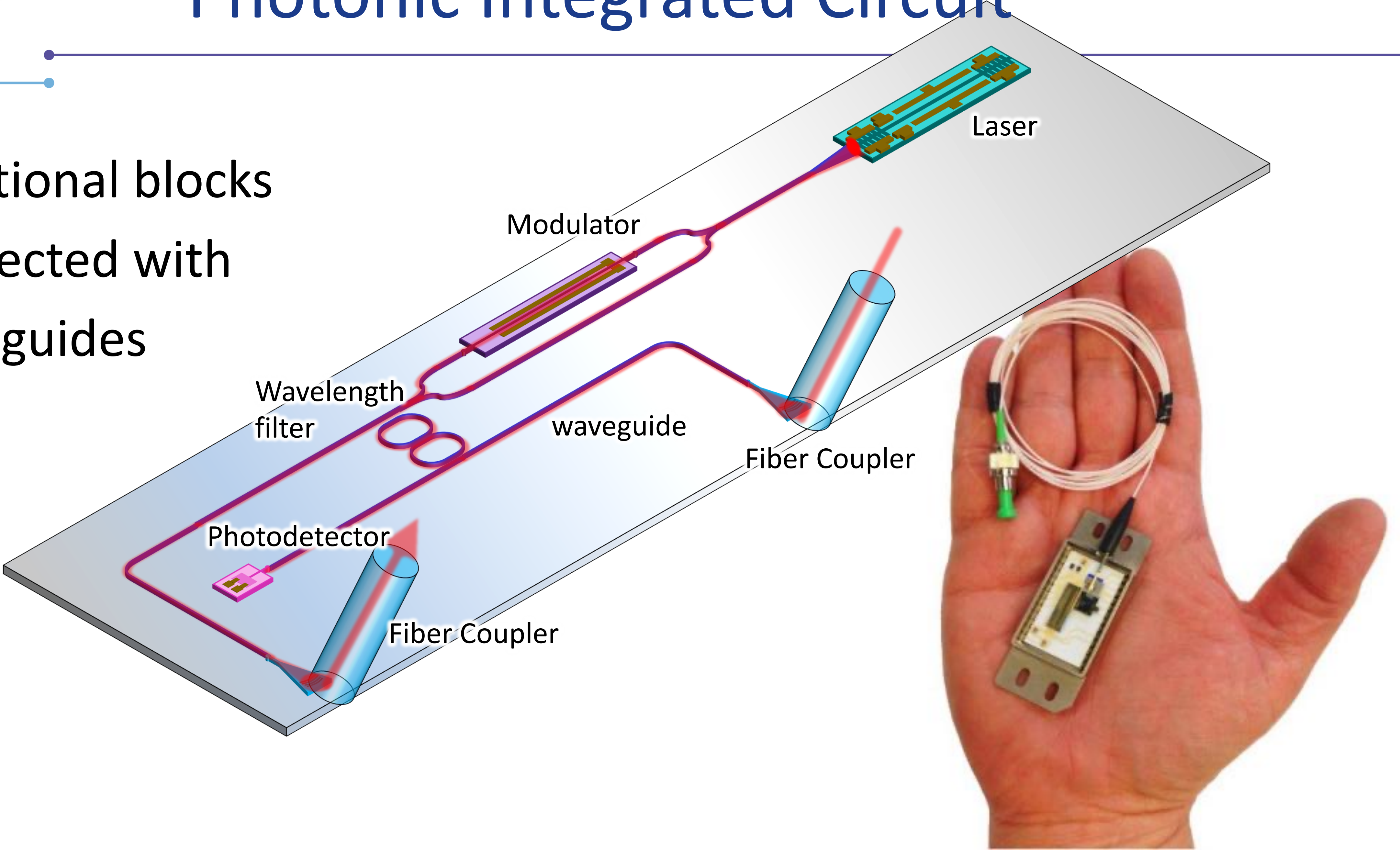


Semiconductor-based photonics

Wim Bogaerts (U Ghent)

Photonic Integrated Circuit

- Functional blocks
- connected with
- waveguides



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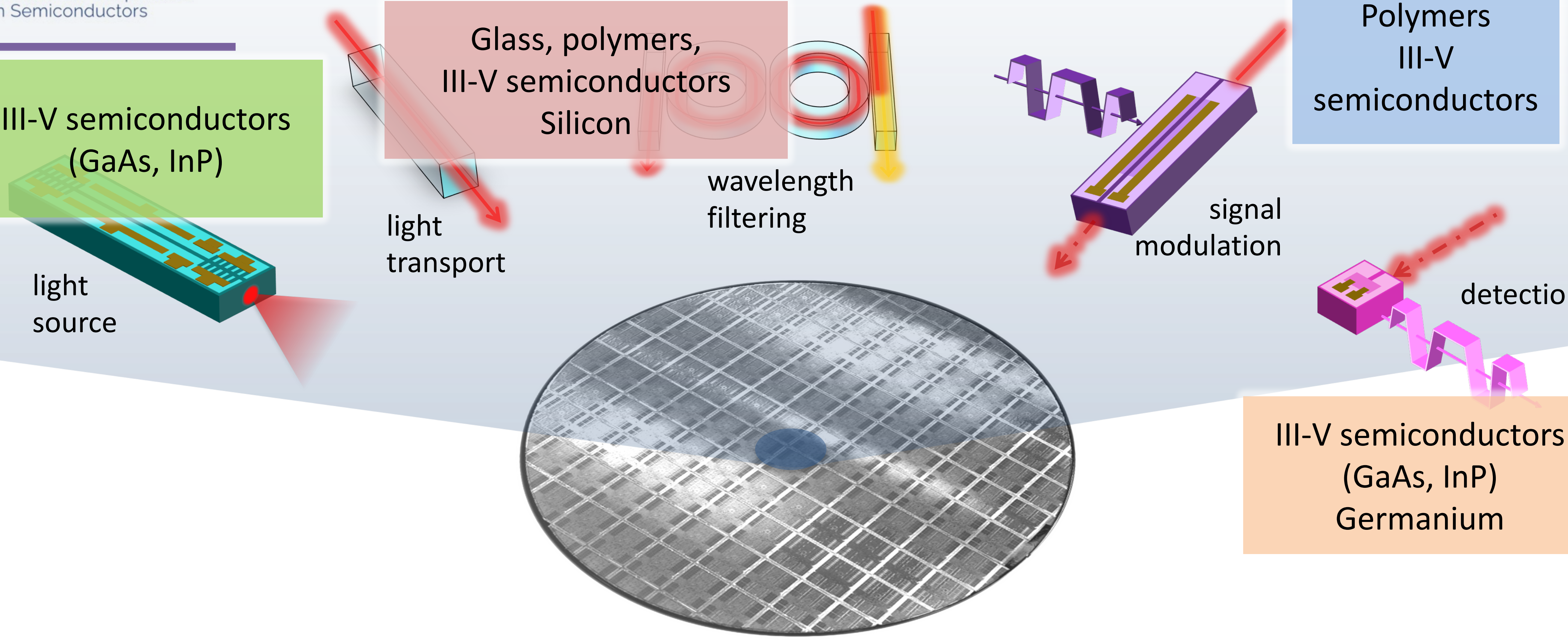
Photonic Integration: A mix of materials



III-V semiconductors
(GaAs, InP)

light
source

Glass, polymers,
III-V semiconductors
Silicon

light
transport

wavelength
filtering

Lithium Niobate
Polymers
III-V
semiconductors

signal
modulation

detection

III-V semiconductors
(GaAs, InP)
Germanium

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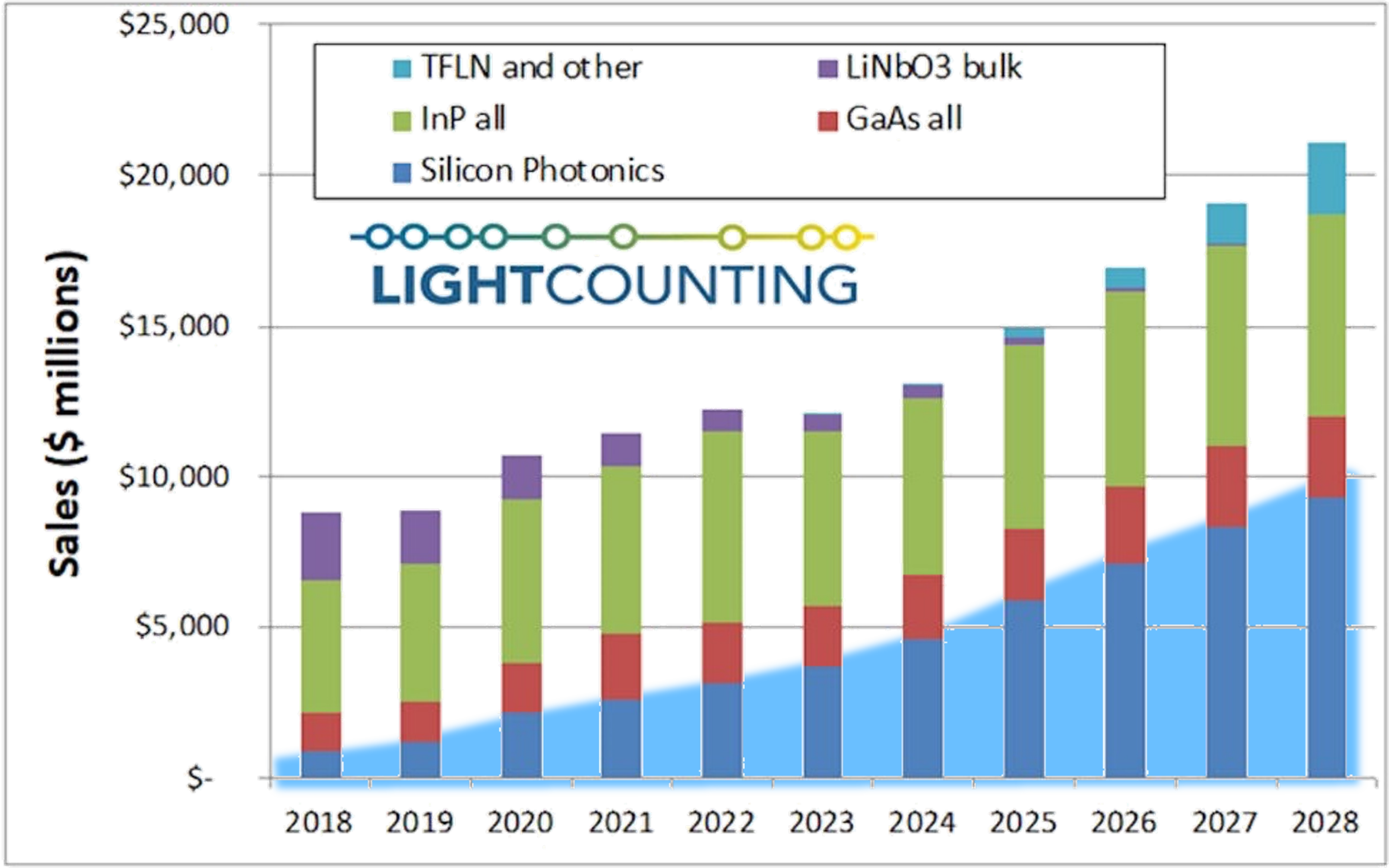
PICs can be made in many materials

- III-V platforms are still dominant
- **Silicon Photonics** is driving the growth



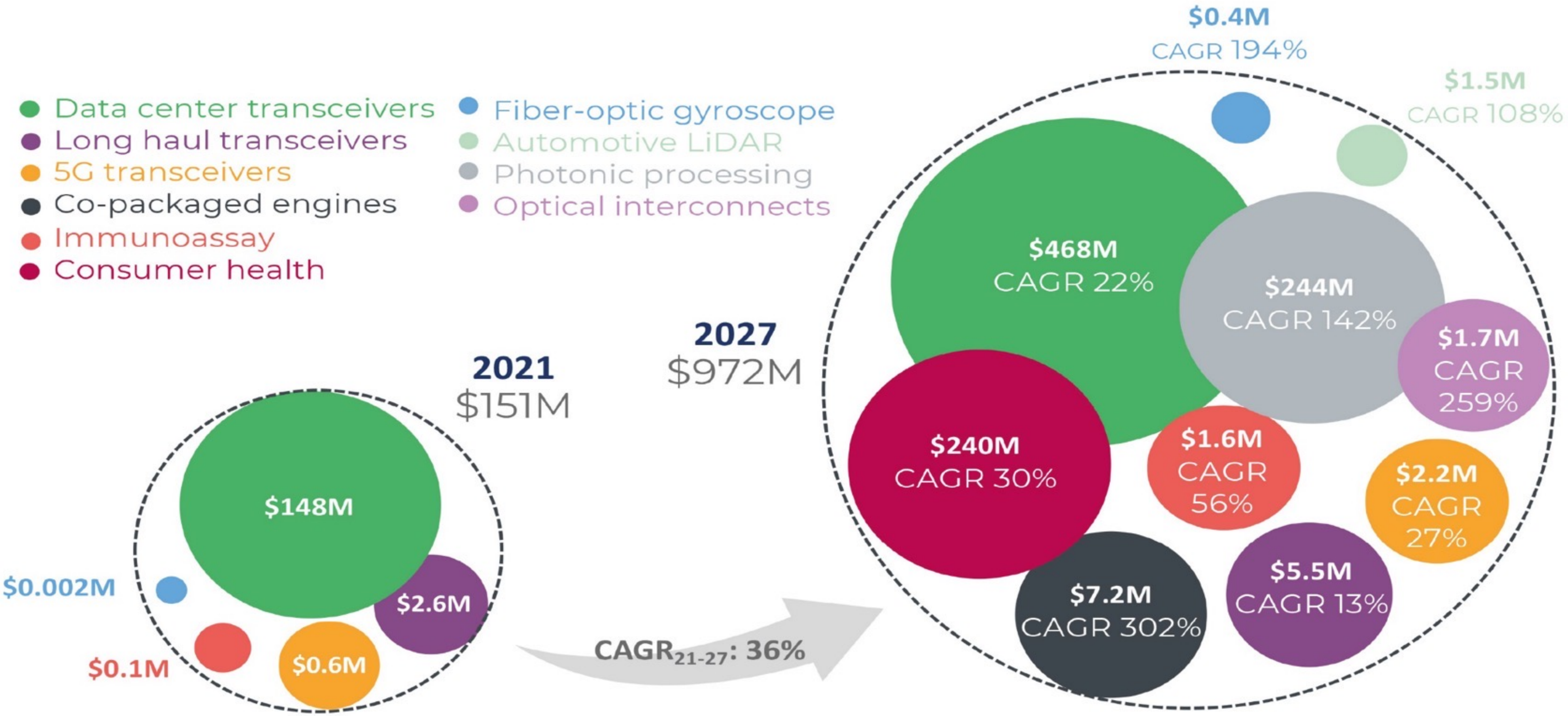
The driver today: Data Centers

For a typical data center:

- 100K to 1M servers
- multiple optical fiber connections per server
- 100’s MWatt energy consumption

2021-2027 SILICON PHOTONIC DIE FORECAST BY APPLICATION

Source: Silicon Photonics 2022 Report, Yole Intelligence, 2022



Summary

- Silicon photonics rides on the developments of CMOS
- The main driver today is transceivers (mostly US and Asia)
- No high-end, high-volume foundries in Europe
- Europe has great R&D, design tools, packaging, …
- Performance needs are driving heterogeneous integration

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Some challenges

- Sensors
  - **Design tools**, sensor design requires multi-physics simulation in challenging geometrical dimensions and scales
  - **Packaging and integration**, sensors can be sensitive to packaging and interferences. Materials properties sometimes not known well enough. Some packaging technologies and materials not easily available in Europe.
  - **Market is fragmented** to small segments, sometimes cost of sensor design, manufacturing and packaging is prohibitely expensive
- Photonics
  - III-Vs still needed for light sources
  - Photonic packaging is difficult and expensive
  - Long product development cycles

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Energy Harvesting: review of the main EU and international activities and technologies

Gustavo Ardila (IMEP-LaHC)

ICOS WORKSHOP – May 13-14th 2024, Athens – EUROSOI-ULIS Conference

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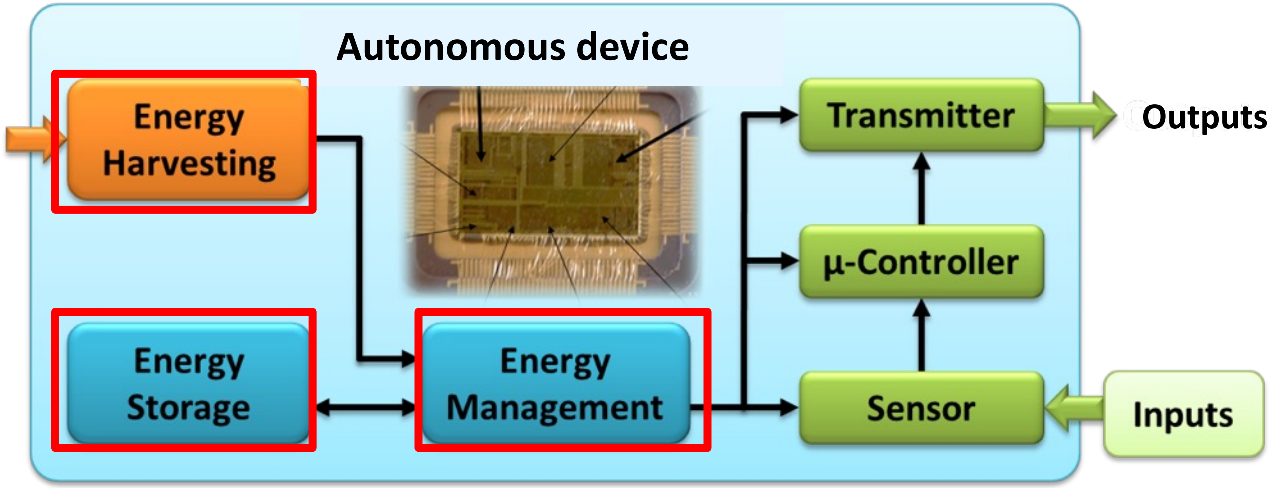
Energy Harvesting - Importance

- Market growth on connected devices : IoT (estimated 40 billion devices by 2025), healthcare, wearables, home automation…
- Energy supply is essential (<mW, tens of µW) → Energy Harvesting
- EH is important in applications with specific requirements : simple battery is not enough, cords would increase the cost / complexity, too many devices, harsh environment, implants…

➢ **Mechanical**

➢ **Electromagnetic**

➢ **Thermal…**



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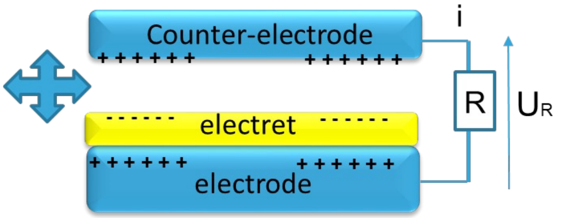
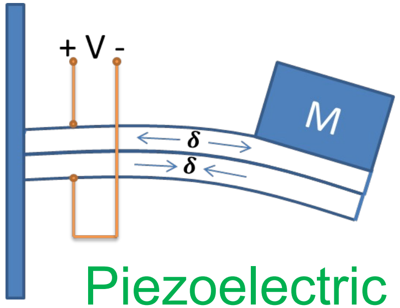
Energy Harvesting – Possibilities

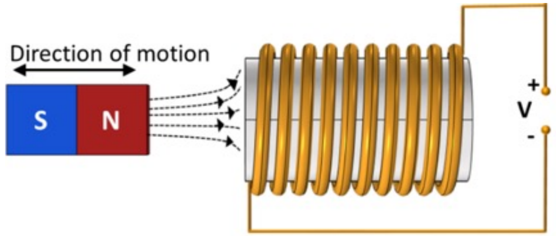
Mechanical EH



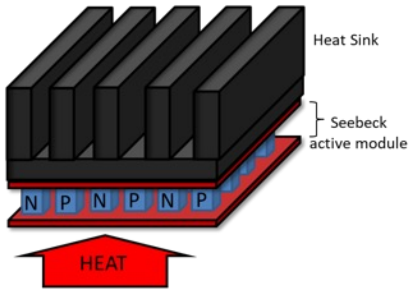
Electrostatic



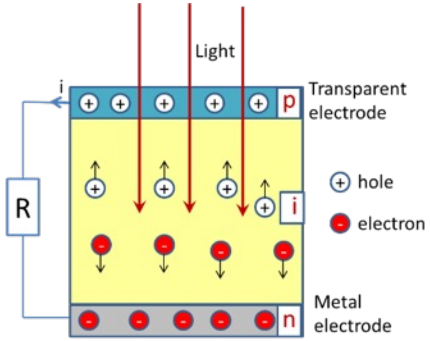
Piezoelectric



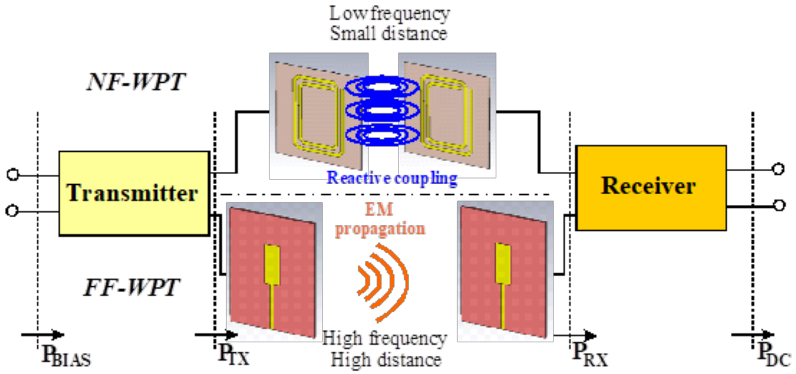
Electromagnetic



Thermal EH



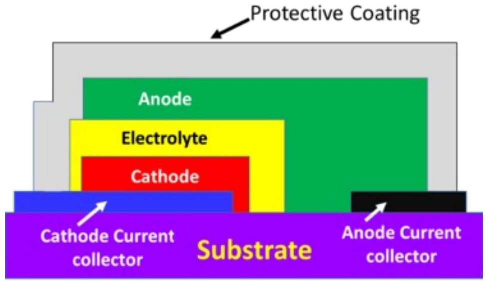
Solar EH



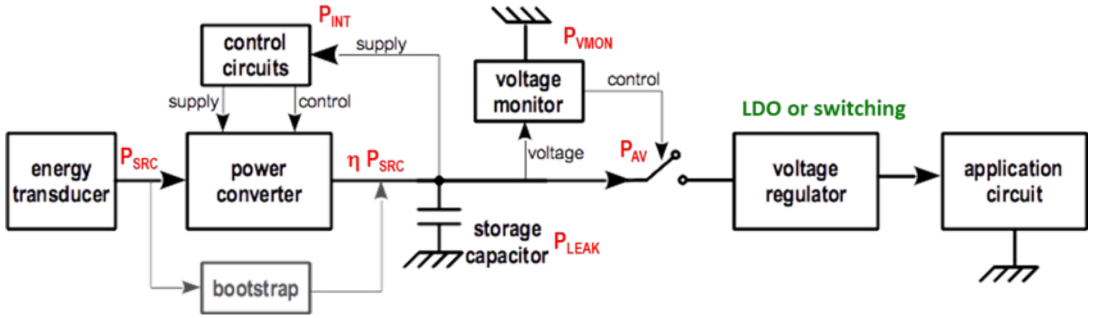
RF EH / wireless power transfer

IEEE
Advancing Technology for Humanity

IRDS
INTERNATIONAL ROADMAP FOR DEVICES AND SYSTEMS™



Energy storage (µbatteries)



Micro power management

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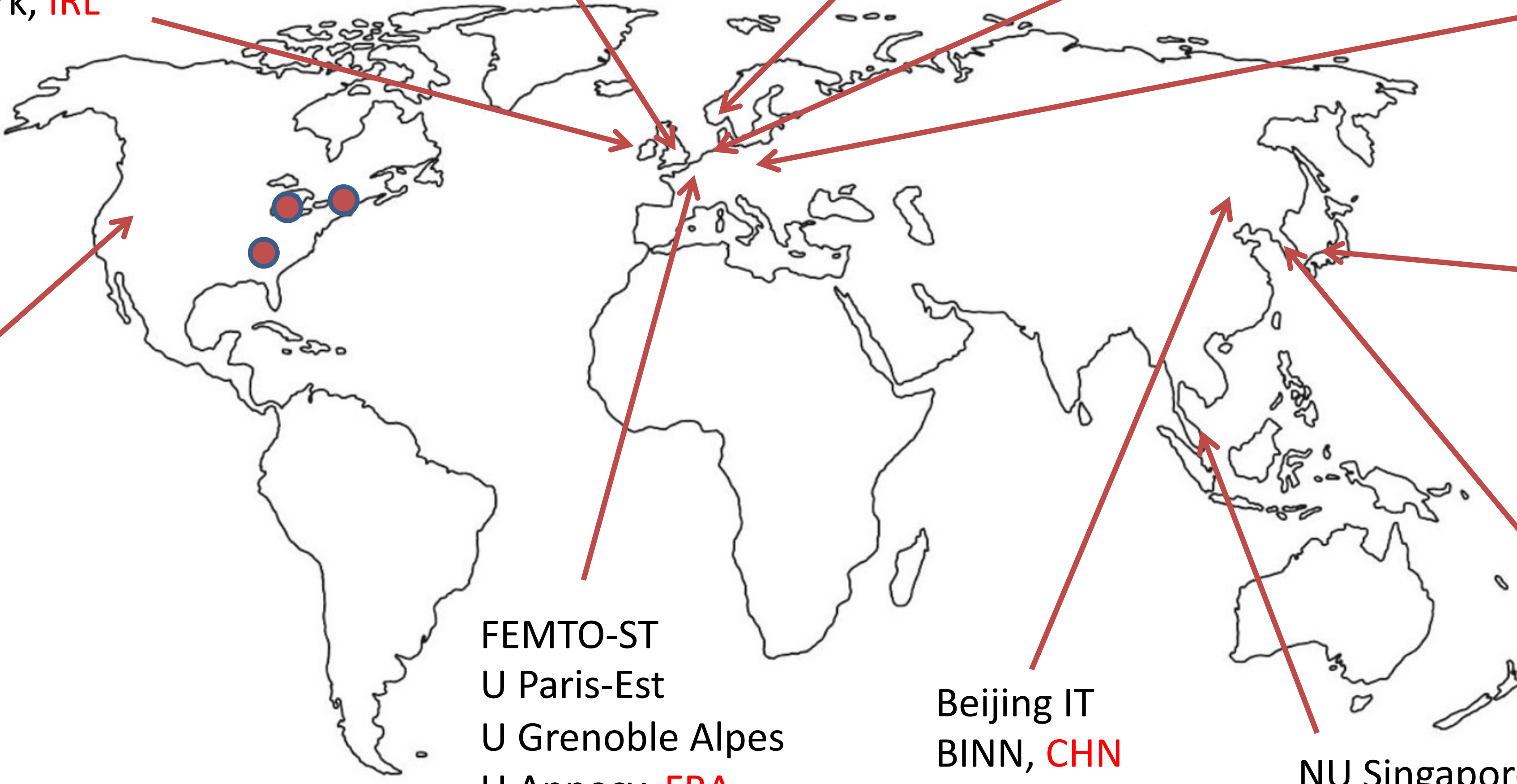
Mechanical EH: Most active universities / RTO



Tyndall
U. College Cork, IRL

Imperial College, BGR

USN-Norway, NOR

Fraunhofer-ISIT, GER

Warsaw U
CEZAMAT, POL

U Tokyo
Kobe U
Gunma U
Kanazawa U
CRIEPI
U Tohoku, JPN

U Michigan
Georgia Tech
MIT
U Utah, USA

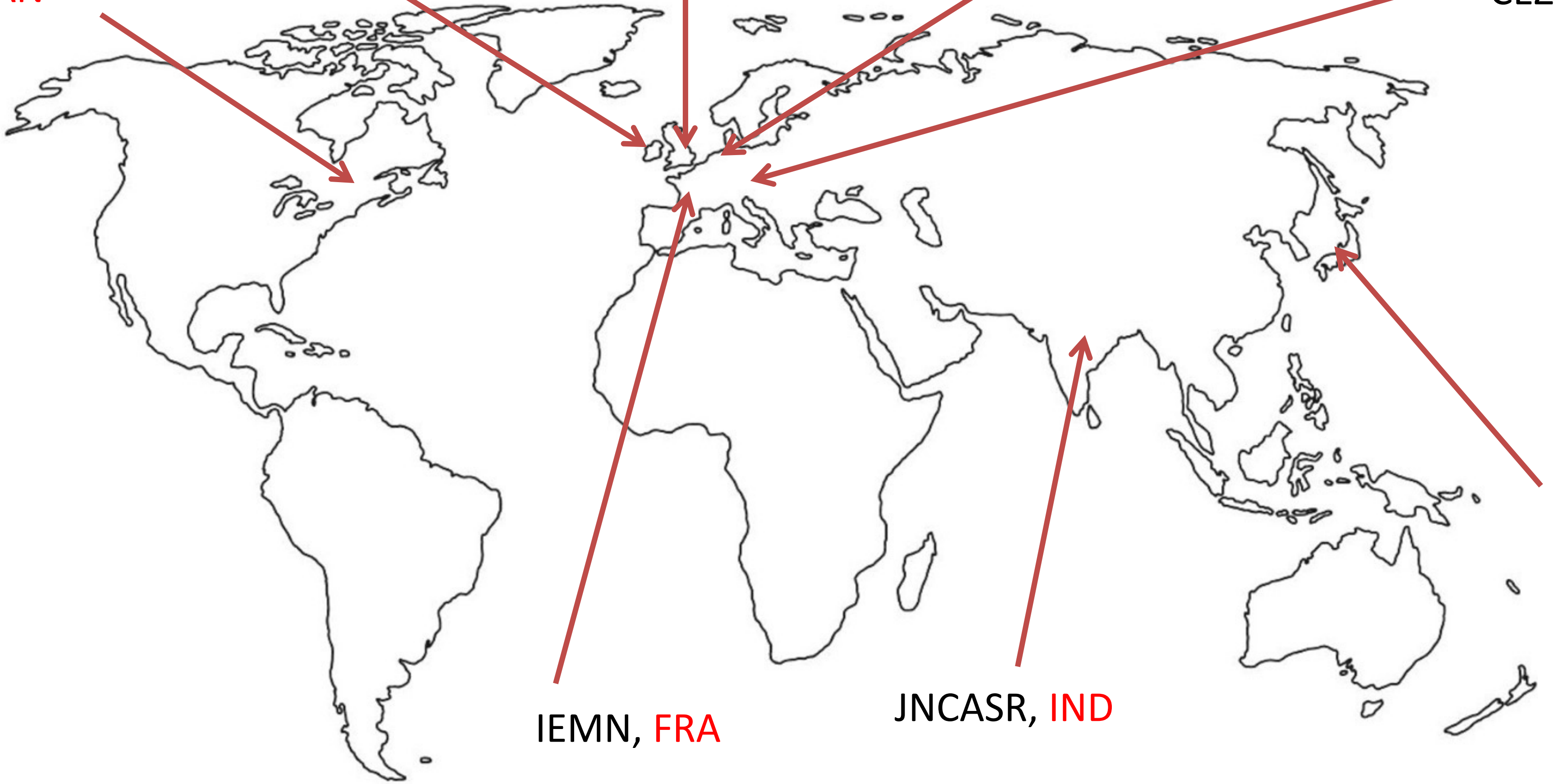
FEMTO-ST
U Paris-Est
U Grenoble Alpes
U Annecy, FRA

Beijing IT
BINN, CHN

NU Singapore, SGP

U Yonsei, KOR

Thermal EH: Most active universities / RTO



U Sherbrook, CAN

Tyndall, IRL

Imperial College
U. Southampton, BGR

U. Freiburg
IFW Dresden, GER

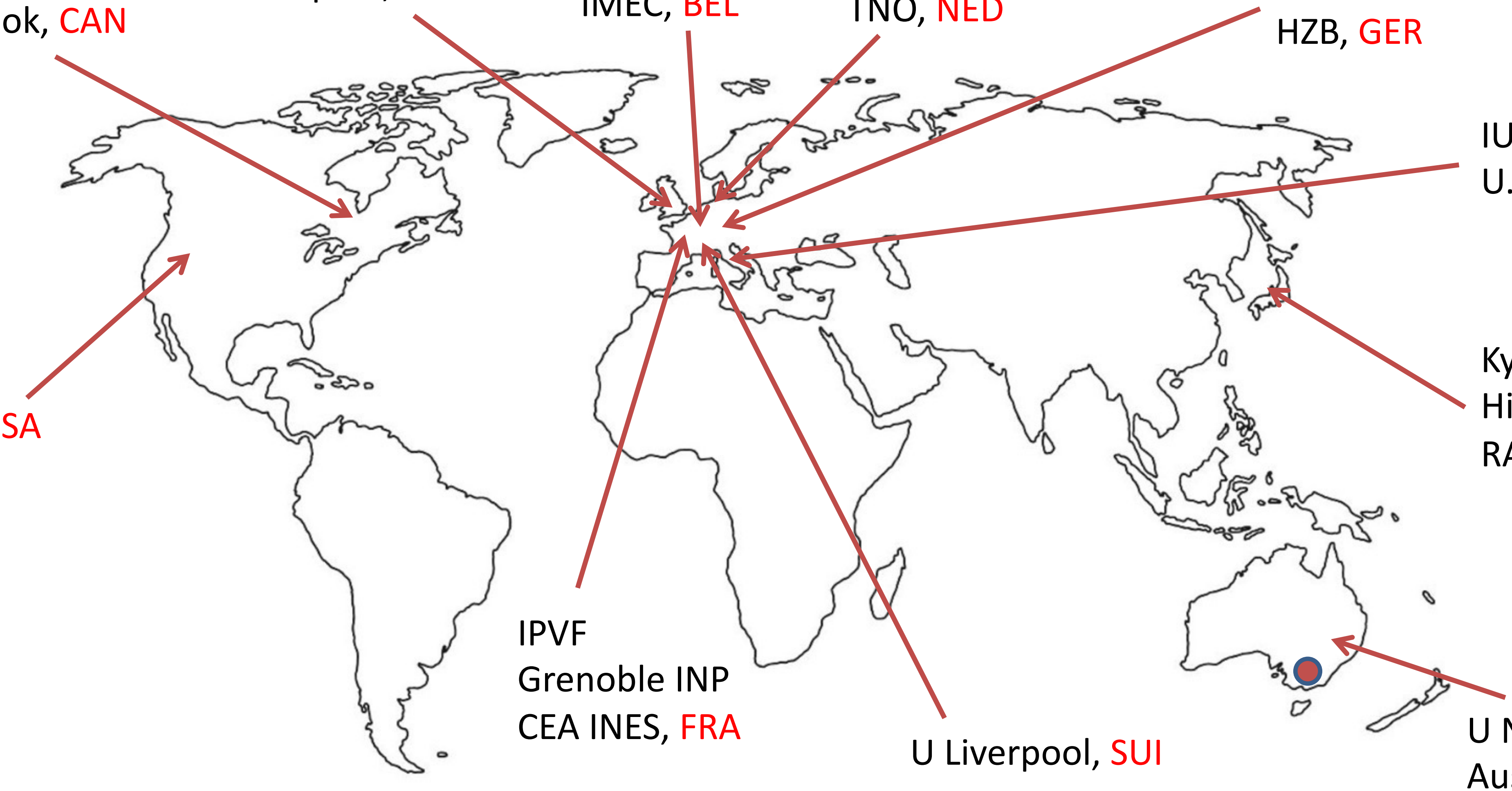
Warsaw U
CEZAMAT, POL

NIMS
Waseda U
AIST
Osaka Met. U
Nagoya U
Kyushu U
Kyoto Inst. Tech.
U Tsukuba
U Tokyo, JPN

IEMN, FRA

JNCASR, IND

Photovoltaic EH: Most active universities / RTO



U Sherbrook, CAN

U Liverpool, BGR

IMEC, BEL

TNO, NED

Fraunhofer ISE
HZB, GER

IUNET
U. Modena, ITA

Kyoto U
Hiroshima U
RATO, JPN

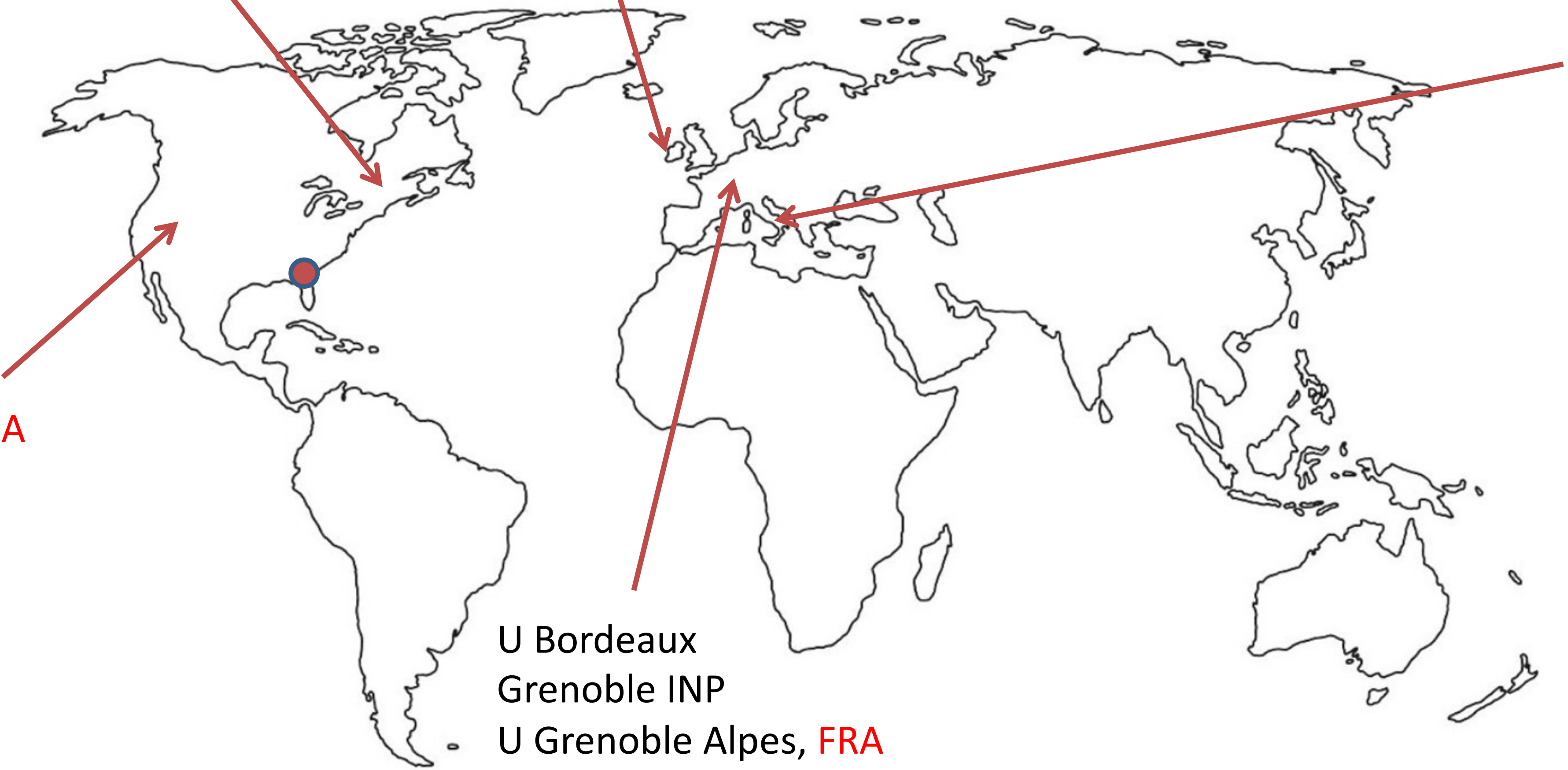
NREL, USA

IPVF
Grenoble INP
CEA INES, FRA

U Liverpool, SUI

U New South W
Australian N U, AUS

RF EH/wireless power transfer: Most active …



Ecole Polytechnique, CAN

Tyndall, IRL

IUNET
U. Bologna, ITA

U Florida
U Utah, USA

U Bordeaux
Grenoble INP
U Grenoble Alpes, FRA

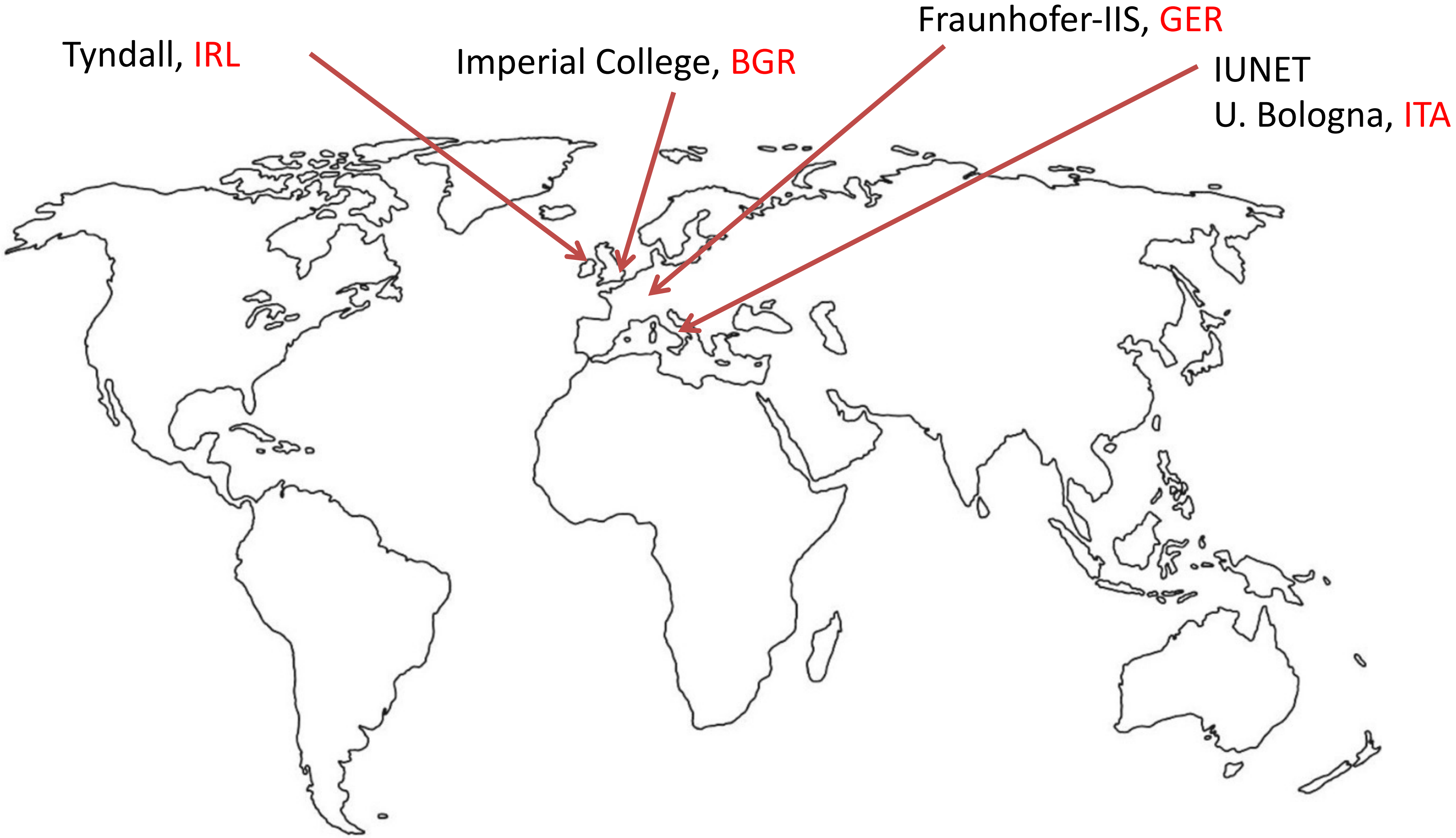
Energy storage: Micro-batteries: Most active …

Tyndall
U. College Cork, IRL

U. Tsinghua, CHN

UC Berkeley, USA

Micro-power management: Most active …



Tyndall, IRL

Imperial College, BGR

Fraunhofer-IIS, GER

IUNET
U. Bologna, ITA

Energy Harvesting - Summary

- The improvement of the EH performance/efficiency is as important as the development of "green" materials. Replacing toxic/rare materials used nowadays (lead based piezoelectrics, Bi_2Te_3 for thermoelectrics, NdFeB - neodymium, for electromagnetic conversion).
- The use of nanotechnologies is foreseen to increase the performance of all the concepts in general.
- Flexible and low cost approaches for wearable applications (i.e. e-health) should be developed as well.
- The comprehensive system design combining all aspects of the fabrication process, harvester structure, power conversion circuits and storage will be the potential solution for increasing the power generation efficiency.

Energy Harvesting - Contributors

International Roadmap for Devices and Systems

MORE THAN MOORE WHITE PAPER

Energy Harvesting team

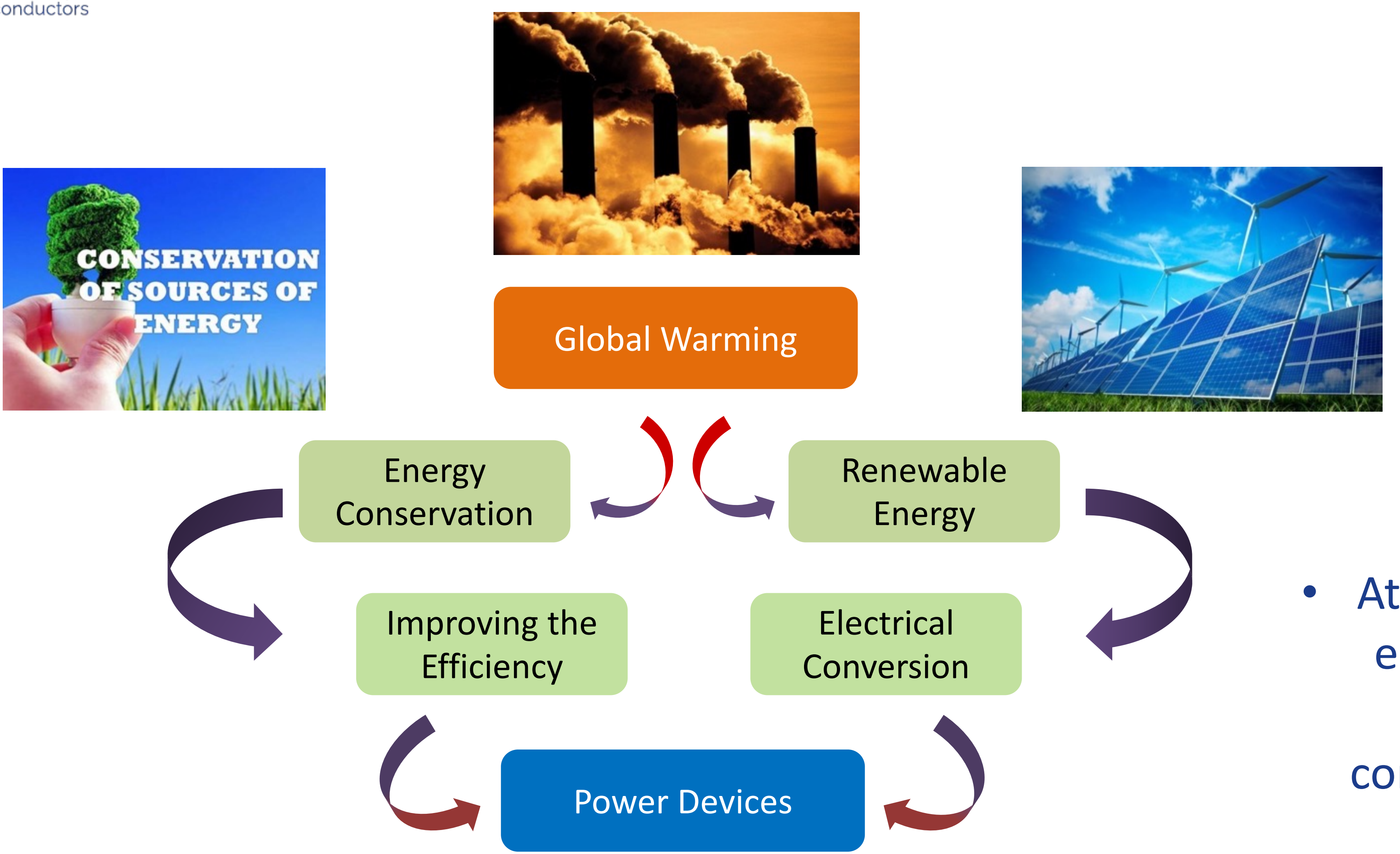
- **Gustavo Ardila**, Grenoble Alpes Univ./Grenoble INP (Team leader)
- **Aldo Romani**, IUNET/Univ. of Bologna (co-leader)
- **Hiro Akinaga**, National Institute of Advanced Industrial Science and Technology (AIST)
- **Philippe Basset**, Univ. Gustave Eiffel
- **Alessandro Bertacchini**, IUNET/Univ. of Modena and Reggio Emilia
- **Alessandra Costanzo**, Univ. of Bologna
- **Mike Hayes**, Tyndall
- **Maciej Haras**, Warsaw Univ. of Technology
- **Anne Kaminski**, Grenoble INP

- ☐ **Michail Kiziroglou**, Imperial College London
- ☐ **Ivona Mitrovic**, Univ. of Liverpool
- ☐ **Yoshiyuki Nonogushi**, Kyoto Institute of Technology
- ☐ **Alessandro Piovaccari**, Univ. of Bologna
- ☐ **Kafil M Razeeb**, Tyndall
- ☐ **James Rohan**, Tyndall
- ☐ **Saibal Roy**, Tyndall
- ☐ **Thomas Skotnicki**, Warsaw Univ. of Technology
- ☐ **Hiroshi Toshiyoshi**, Univ. of Tokyo
- ☐ **Eric Yeatman**, Imperial College London

Power Devices: review of the main EU and international activities and technologies

Mikael Östling KTH Royal Institute of Technology, Markus Pfeffer Fraunhofer IISB

Our Great Societal Challenge



Global Warming

Energy Conservation

Renewable Energy

Improving the Efficiency

Electrical Conversion

Power Devices

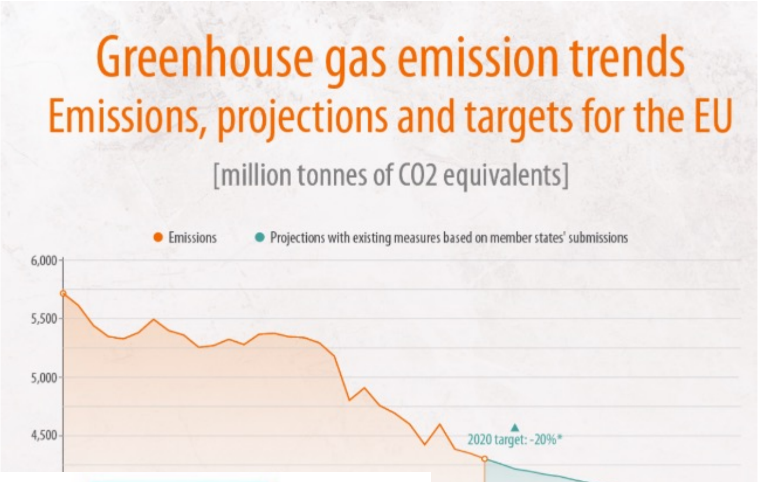
- At least 50 % of the electricity used in the world is controlled by Power Devices.

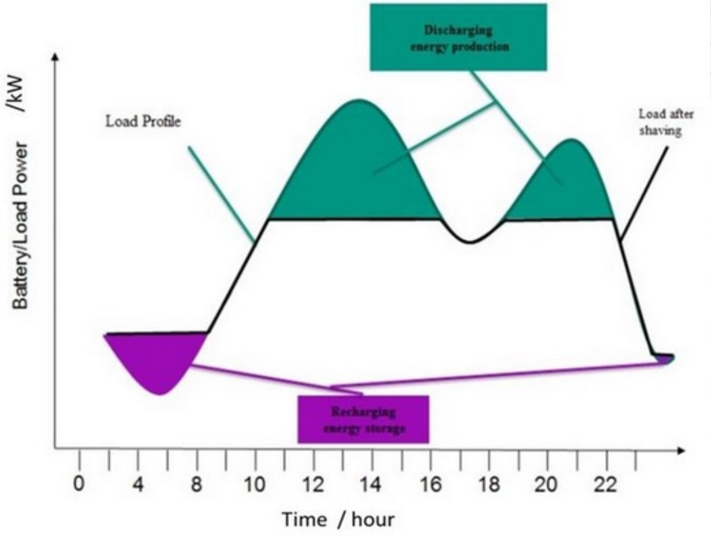
B.J. Baliga, Advanced High Voltage Power Device Concepts, Springer

Power Devices - Introduction

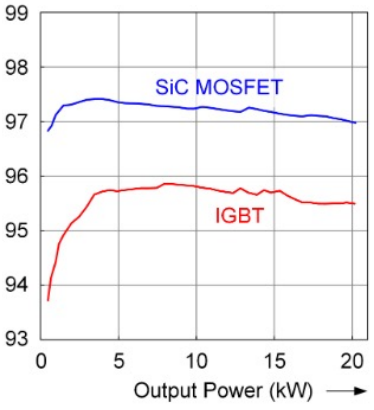
- Energy efficiency contributes to EU’s CO_2 goals
  - Ecological and economical implications
    - Laws and regulations (compare Monitors)
    - Prestige and responsibility for companies

- SiC (WBG) converters offer excellent partial load properties
  - Up to 10% more efficiency compared to silicon topologies
  - Every time energy is transferred
    - Generation
    - Storage (Recuperation)
    - Consumption
  - Applicable to any source of electrical energy consumption (broad range)

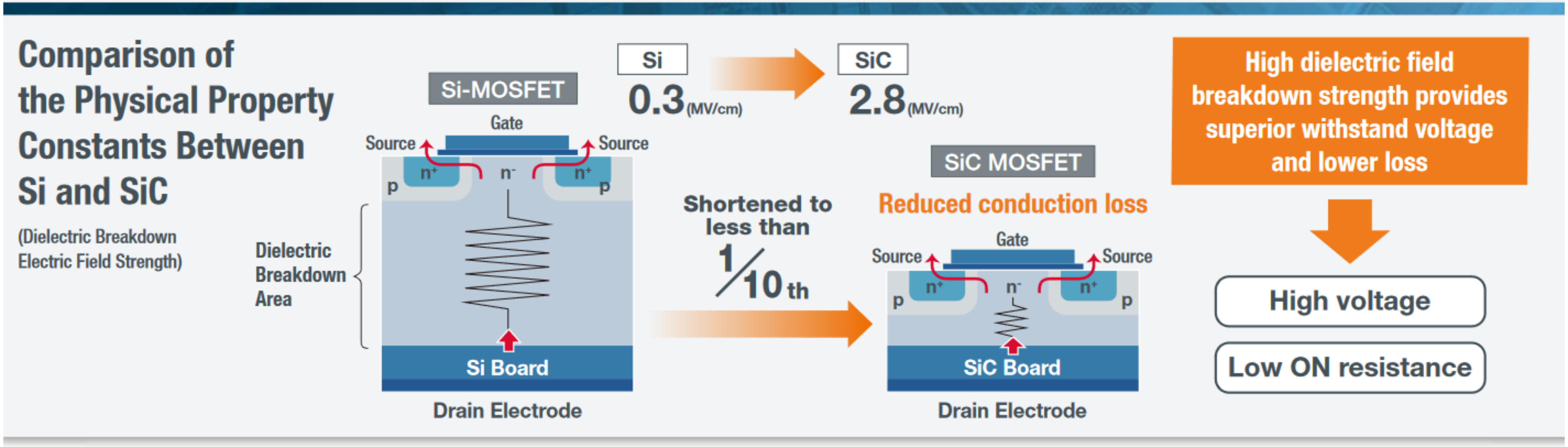




Boyouk N. et al., ISGT-Europe 2018, Sarajevo



M. Nitzsche et al.,
PCIM 2019, Nuremberg



Comparison of the Physical Property Constants Between Si and SiC

(Dielectric Breakdown Electric Field Strength)

Si 0.3 (MV/cm) → **SiC** 2.8 (MV/cm)

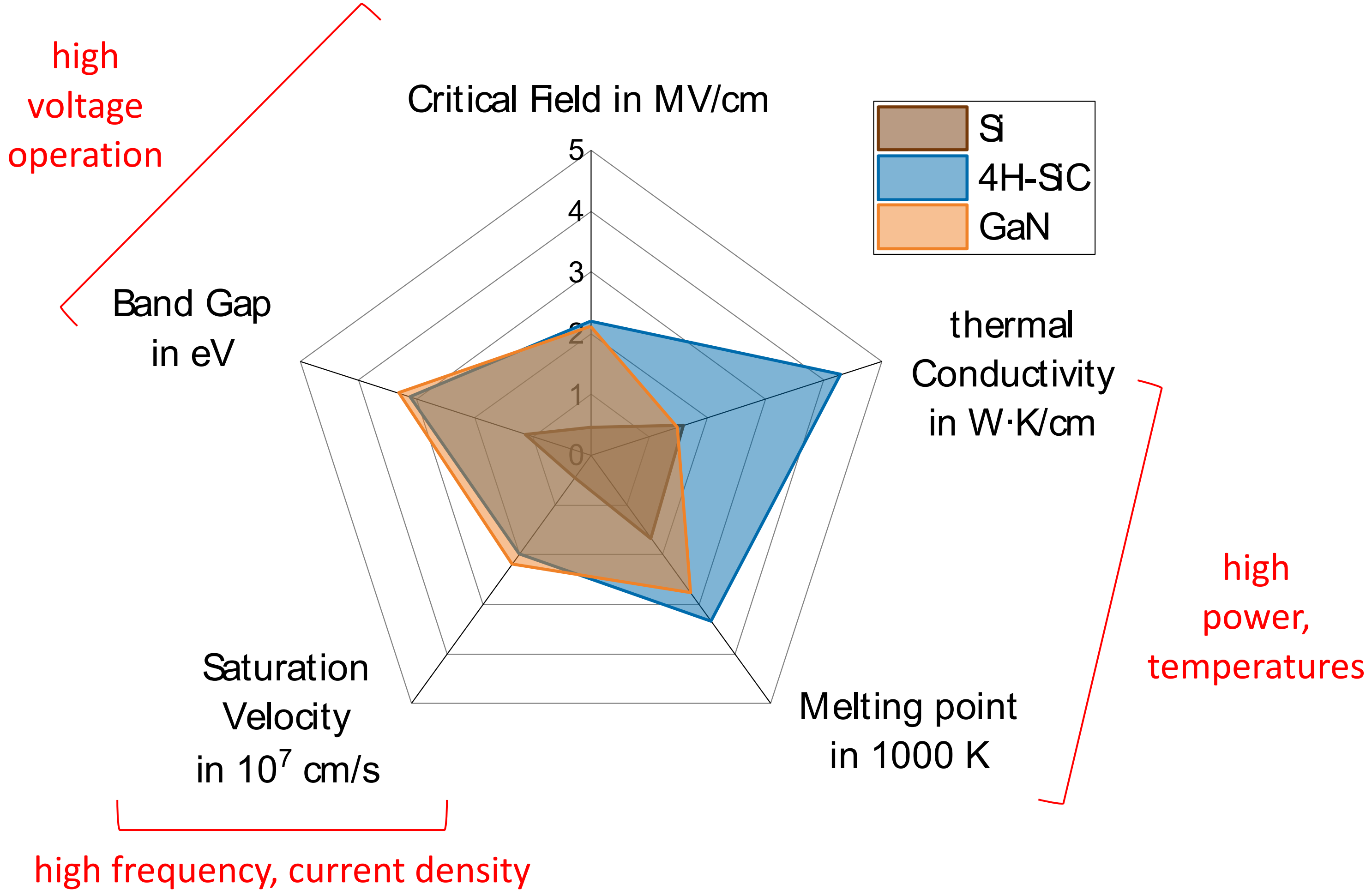
High dielectric field breakdown strength provides superior withstand voltage and lower loss

- High voltage
- Low ON resistance

Shortened to less than 1/10th

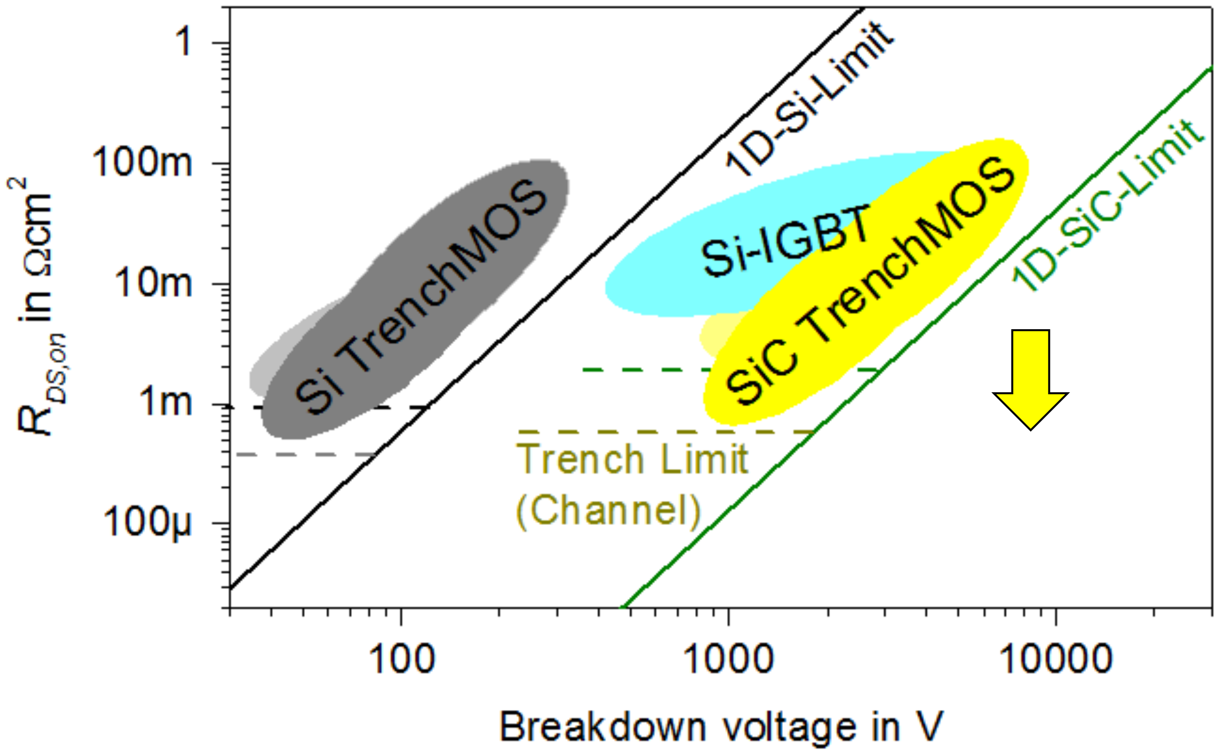
Reduced conduction loss

Materials Properties of SiC



Evolution of Power MOS Technolog

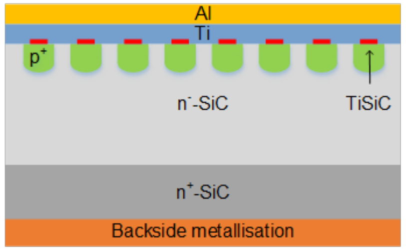
- Task 1: Reduction of On-State resistance to minimize die size/cost
  - Technology development depends on voltage rating

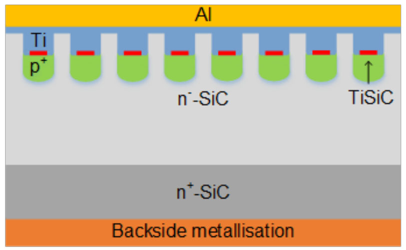


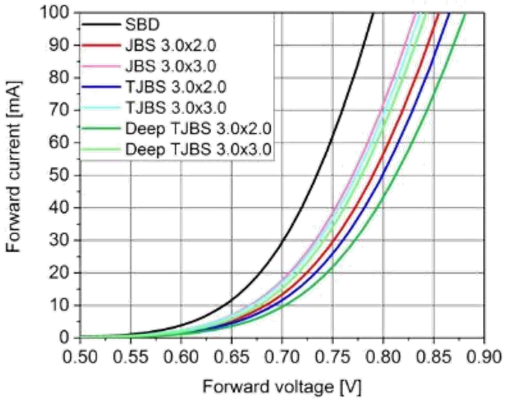
Power Devices on SiC

- Bipolar and MOS Power Devices

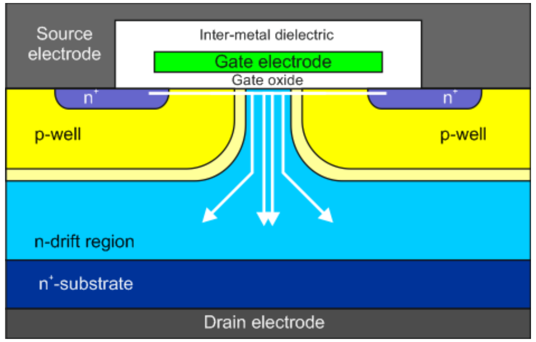
Merged Schottky/pn Diodes

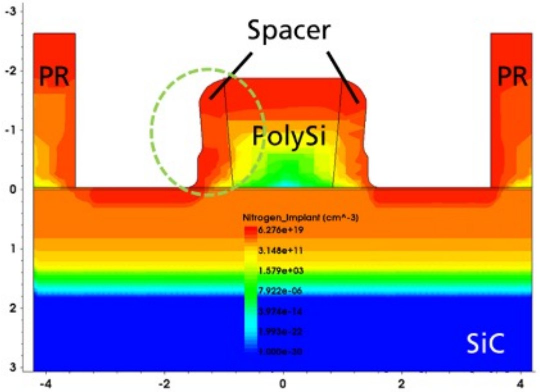


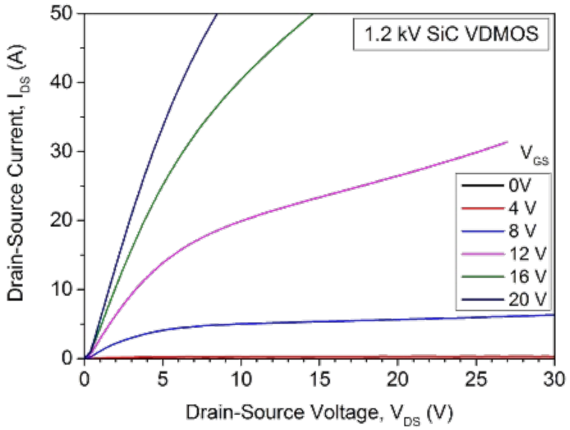


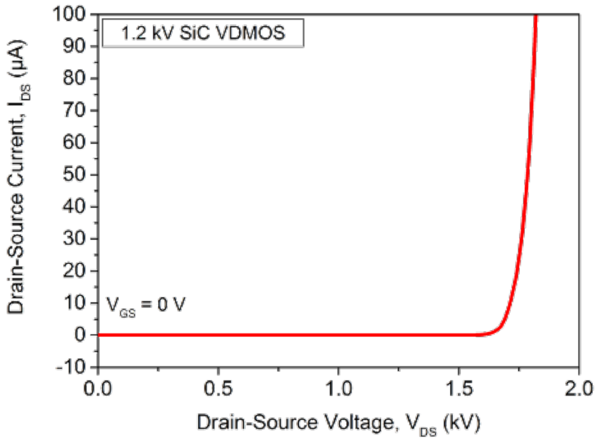


1.2 kV VDMOS (planar)









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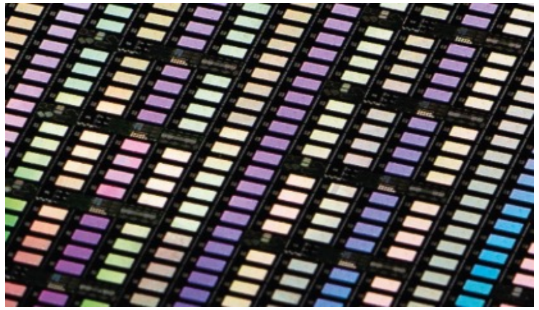
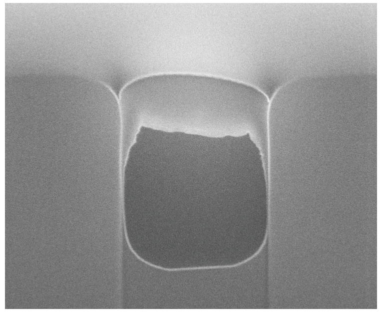
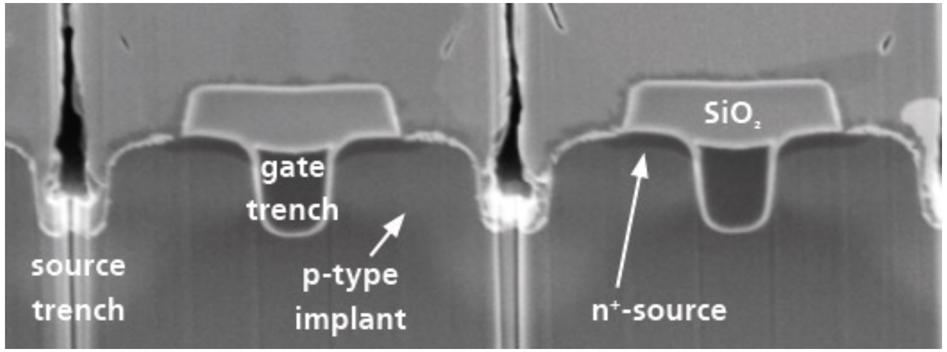
Power Devices on SiC

- Advanced Trench Technologies

1.2 kV TrenchMOS


Devices on wafer

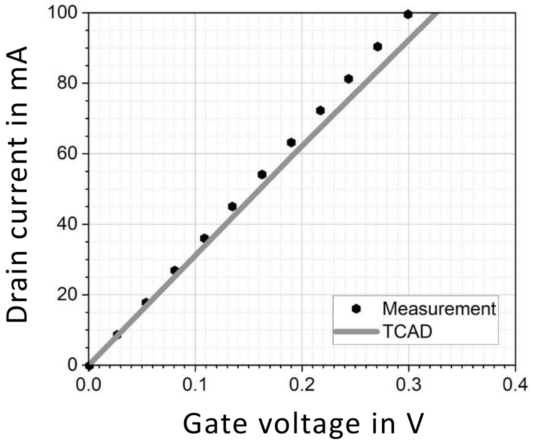

Poly-Si-plug with oxidation



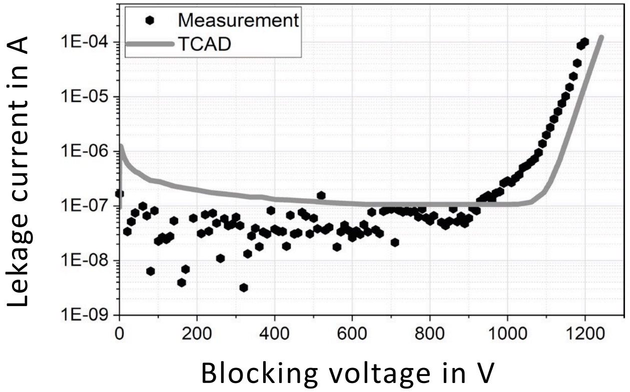
FIB cross-section of active area

Electrical Performance

Transfer characteristics (lin.)



Reverse operation



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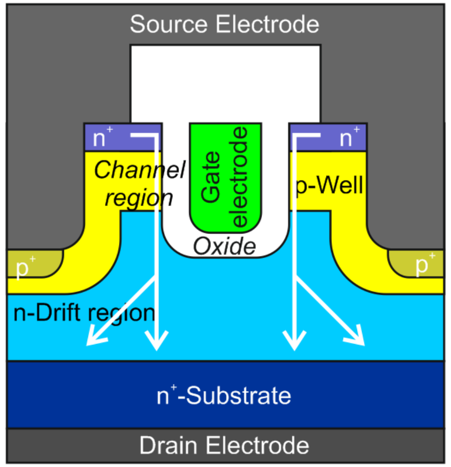
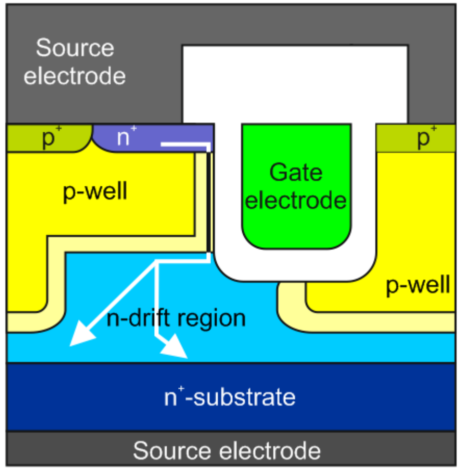
Evolution of Power SiC MOS Technolog

- Task 1: Reduction of On-State resistance
  - Implementation of trench gates
    - Increased channel mobility along (1 1 -2 0) orientation
    - Vertical channel → Pitch reduction compared to VDMOS
  - Shielding of trench bottom oxide vital!

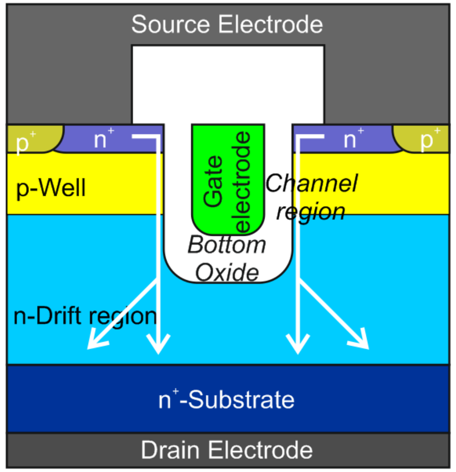
Examples of practical SiC Trench MOS concepts



Rohm / MaxPower Double Trench



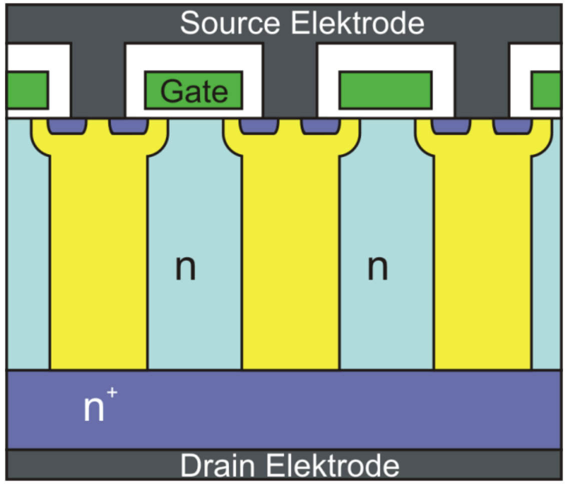
Peters et al., Power-Mag 3 (2017)

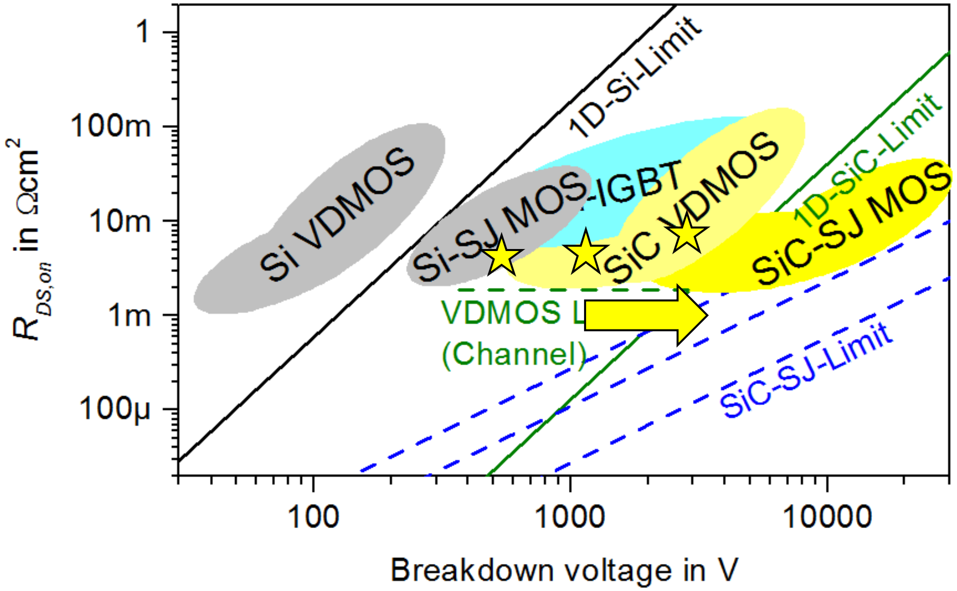


Banzhaf et al. MSF 858 (2016) 848-851

Evolution of Power SiC MOS Technolog

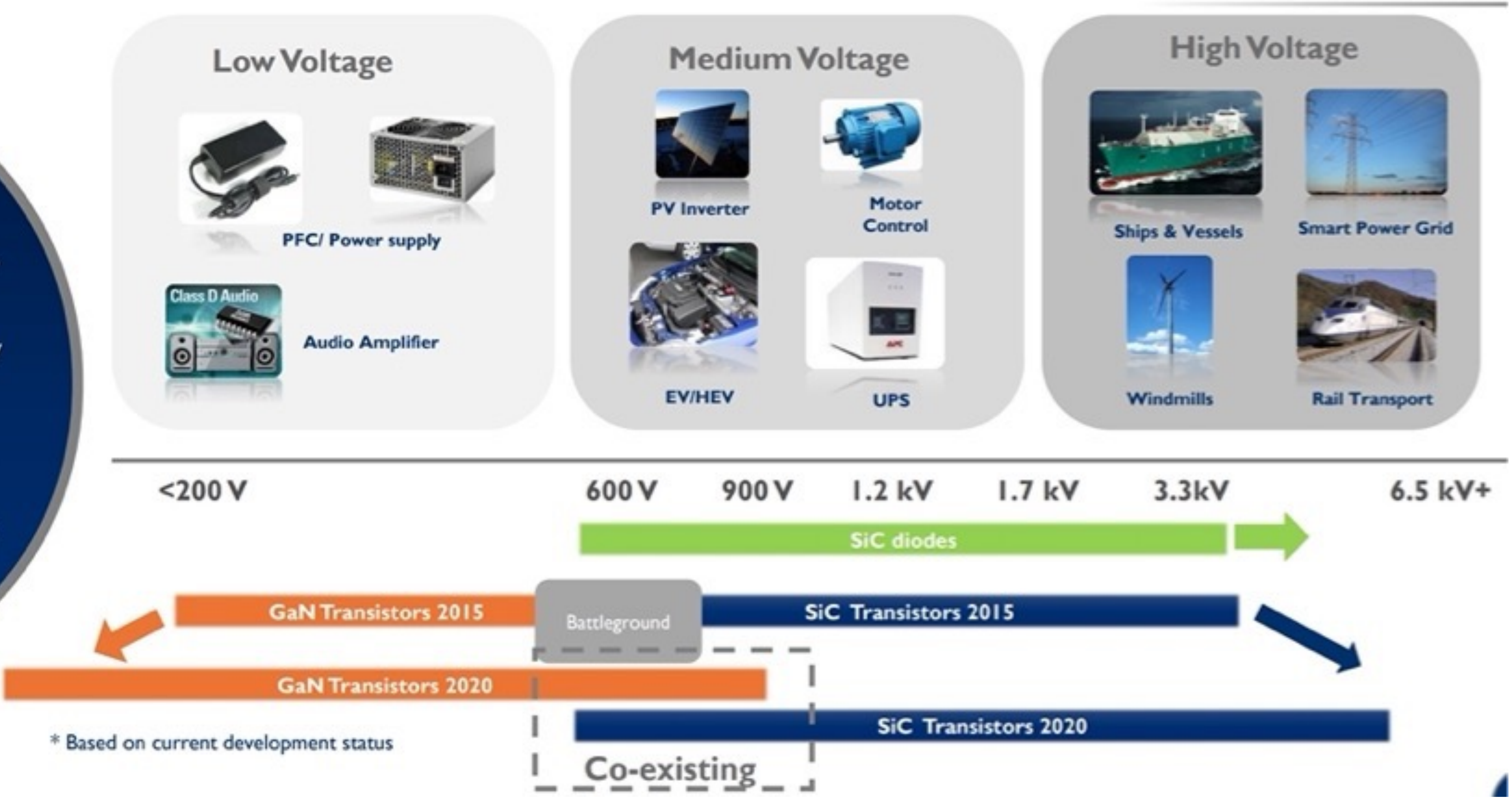
- Challenges for further advancements
  - Unipolar high voltage devices
  - Superjunction device topology using vertical pillar structure (approx. 60µm @ 10kV)
  - Concepts (similar to Infineon / Toshiba solutions in Silicon):
    - Mid-energy ion implantation and epitaxial overgrowth (rinse & repeat)
    - High-energy ion implantation (e.g. filter implantation)
    - Deep trench etching and epitaxial refill





The WBG Device Landscape

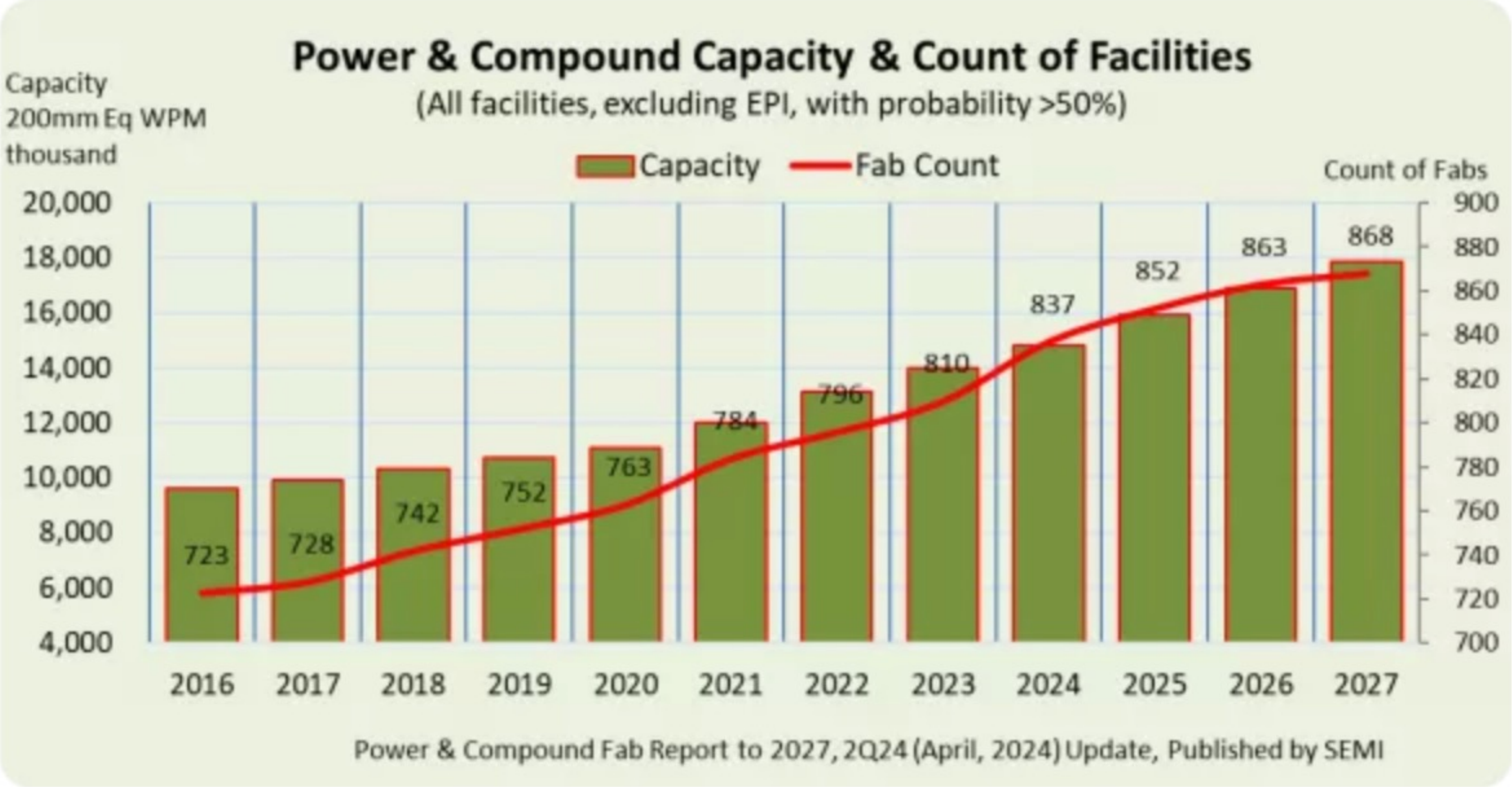
While SiC is used for high-voltage applications, GaN is mainly used for low voltage. The 600 - 900V range will be the battleground.



* Based on current development status

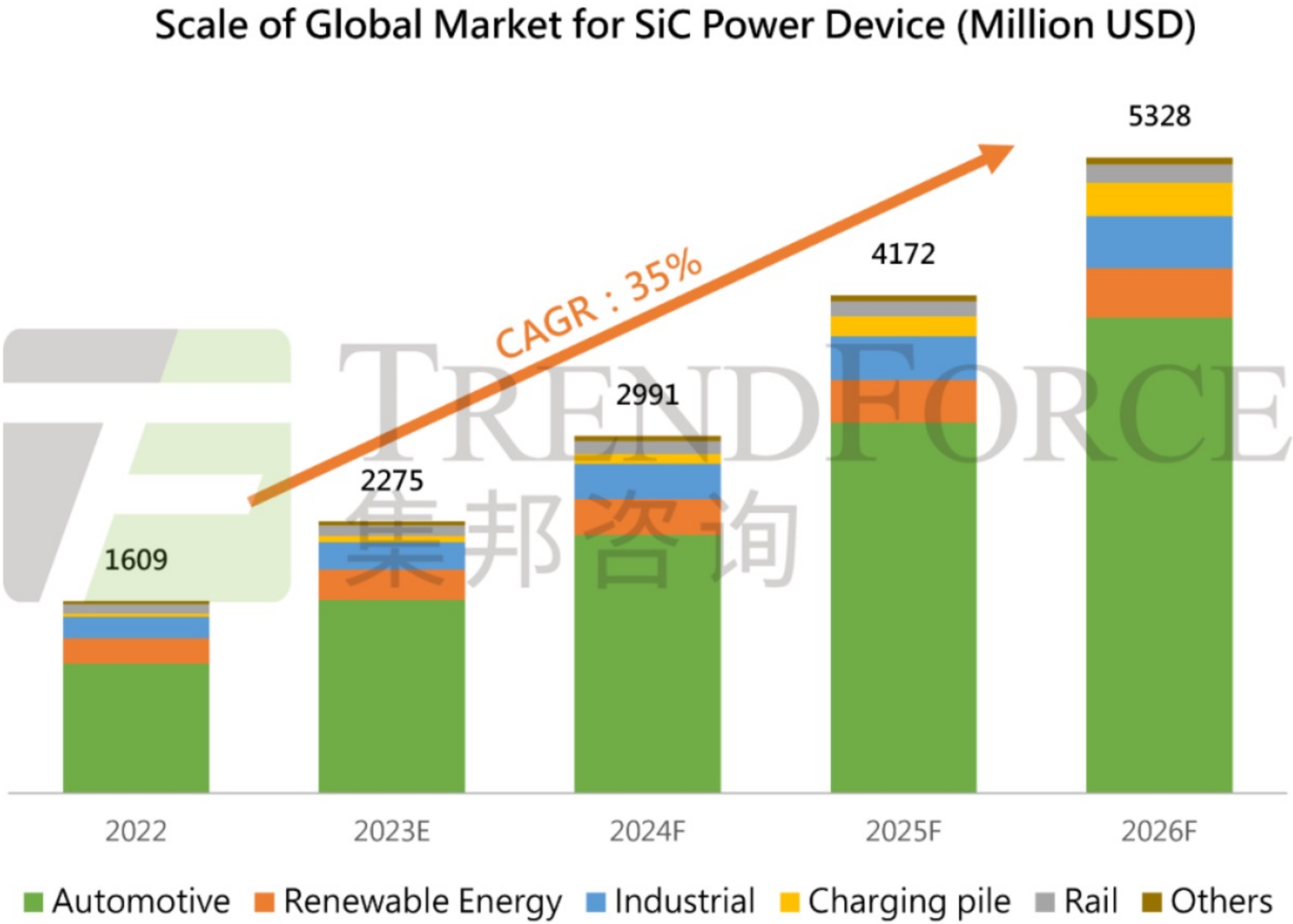
YOLE

Market Outlook



SEMI

Market Outlook



Scale of Global Market for SiC Power Device (Million USD)

Annoucements (some examples)

Corporate Manufacturing

STMicroelectronics to build integrated Silicon Carbide substrate manufacturing facility in Italy

Oct 5, 2022 Geneva, Switzerland

STMicroelectrincs

Infineon to build the world's largest 200-millimeter SiC Power Fab in Kulim, Malaysia, leading to total revenue potential of about seven billion euros by the end of the decade

Aug 3, 2023 | Business & Financial Press

Infineon

TOKYO, Japan, May 17, 2022 — Renesas Electronics Corporation ("Renesas", TSE:6723), a premier supplier of advanced semiconductor solutions, today announced that it will conduct a 90-billion-yen worth investment in its Kofu Factory, located in Kai City, Yamanashi Prefecture, Japan. While the Factory was closed in October 2014, Renesas intends to reopen the fab in 2024 as a 300-mm wafer fab capable of manufacturing power semiconductors.

Renesas

Corporate, Power

Wolfspeed Announces Plan to Construct World's Largest, Most Advanced Silicon Carbide Device Manufacturing Facility in Saarland, Germany

Feb 01, 2023

Wolfspeed

TOKYO, March 14, 2023 - Mitsubishi Electric Corporation (TOKYO: 6503) announced today that it will double a previously announced its investment plan to approximately 260 billion yen in the five-year period to March 2026 mainly for constructing a new wafer plant to increase production of silicon carbide (SiC) power semiconductors.

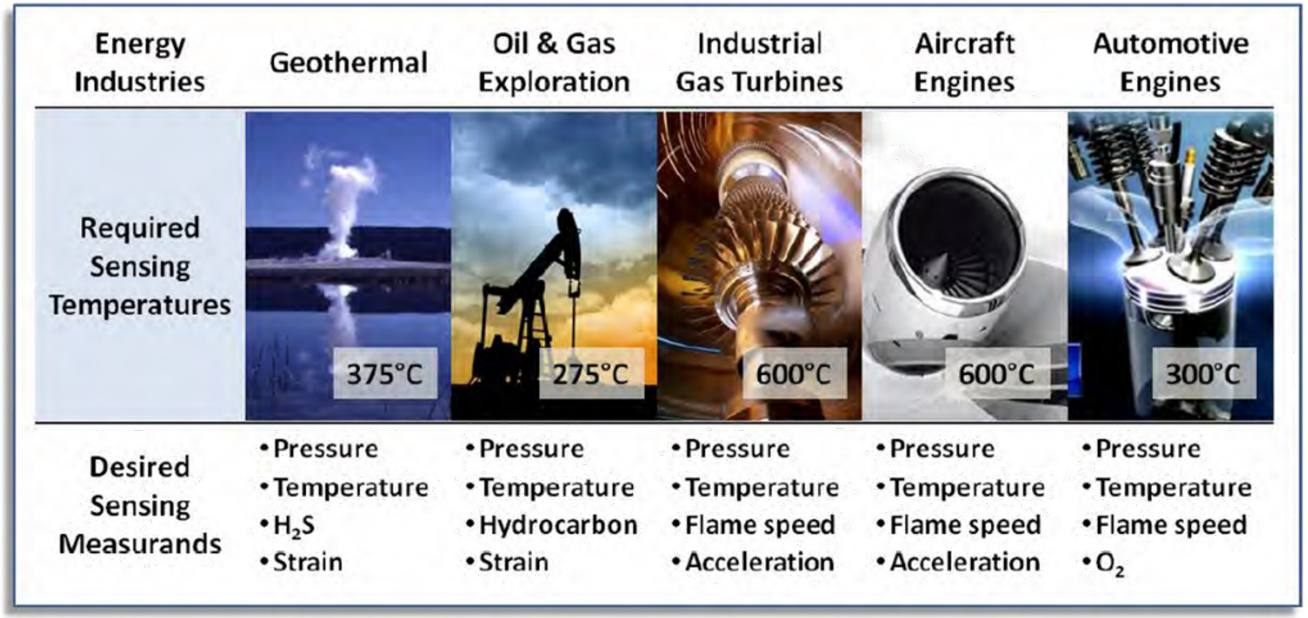
Mitsubishi

Research activities in other areas

- SiC CMOS Technology for harsh environments
- EU Chips Act – Pilot Line(s)
- Ultra Wide Band Gap semiconductors (UWBGs)

High-Temperature SiC Circuits

- Operation > 500°C



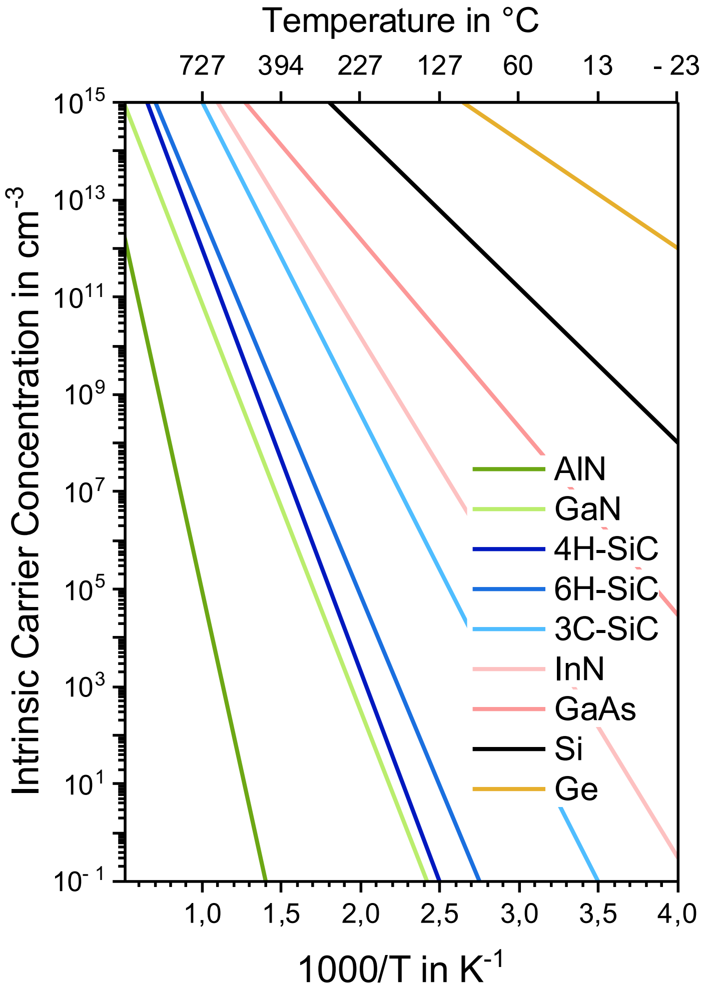
Energy Industries	Geothermal	Oil & Gas Exploration	Industrial Gas Turbines	Aircraft Engines	Automotive Engines
Required Sensing Temperatures	375°C	275°C	600°C	600°C	300°C
Desired Sensing Measurands	• Pressure • Temperature • H_2S • Strain	• Pressure • Temperature • Hydrocarbon • Strain	• Pressure • Temperature • Flame speed • Acceleration	• Pressure • Temperature • Flame speed • Acceleration	• Pressure • Temperature • Flame speed • O_2

Harsh Environment Sensor Cluster, University of California, San Diego

Power Electronics

Integrated Gatedriver:
- Current
- Temperature

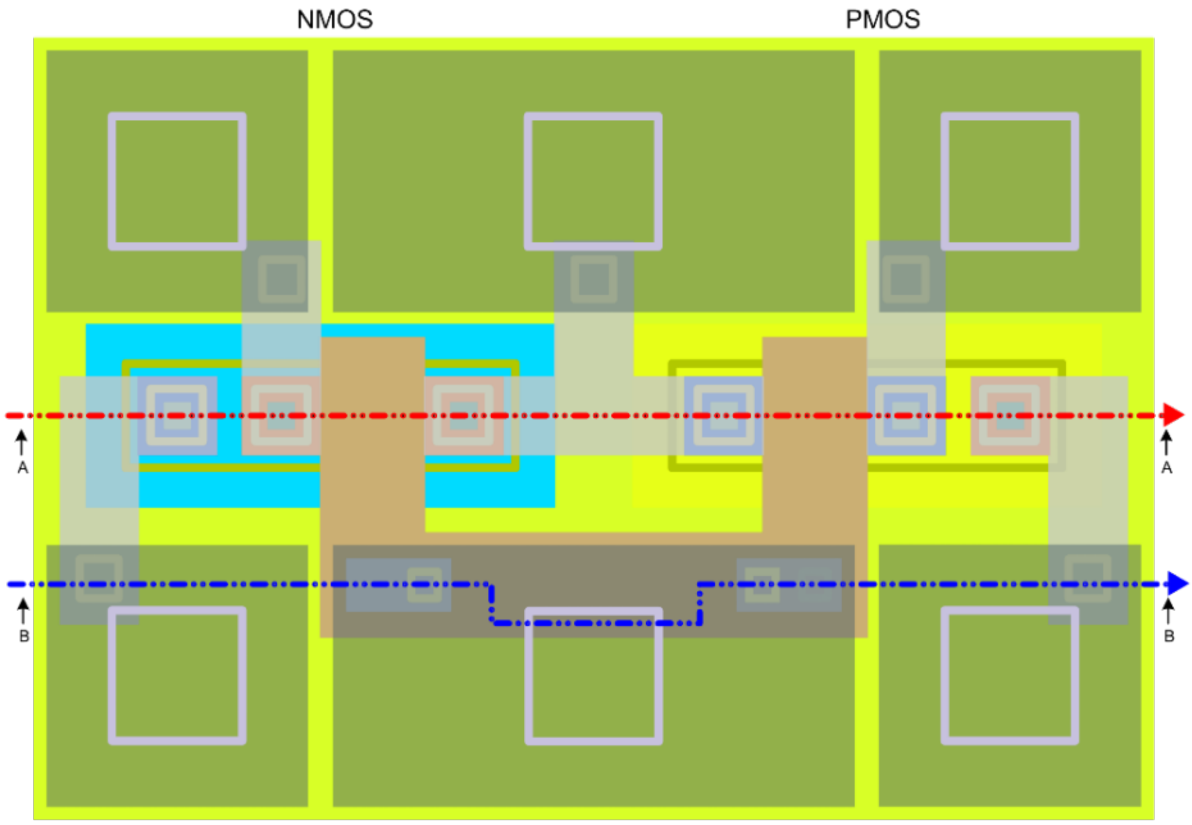
- High switching frequencies
- reliabilty

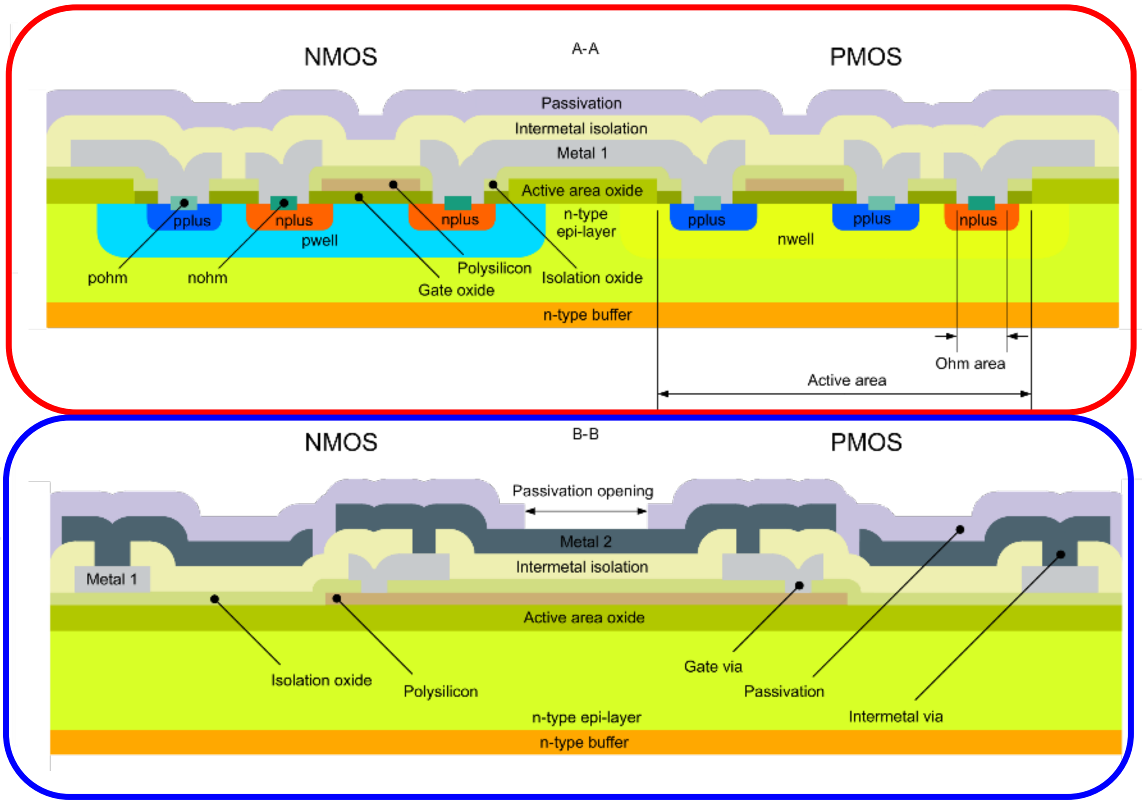


High-Temperature SiC Circuits

- Technology overview

Top View of Circuit Blocks





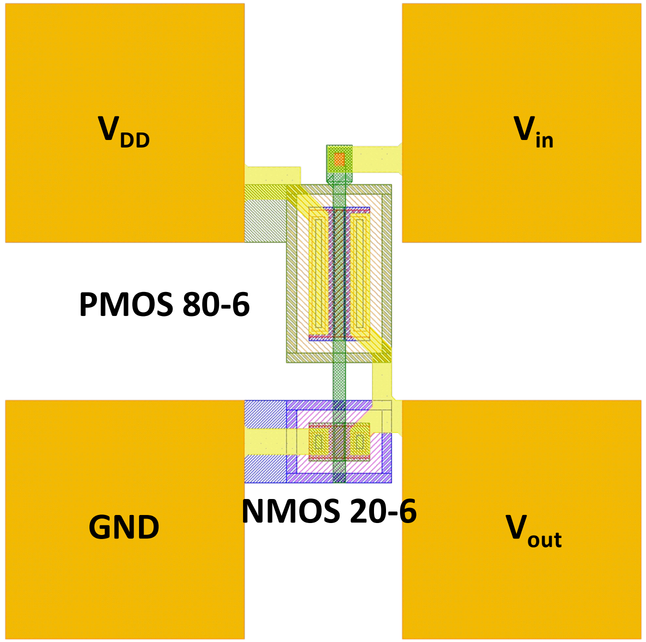
Circuit Cross-Cuts

Funded by the European Union

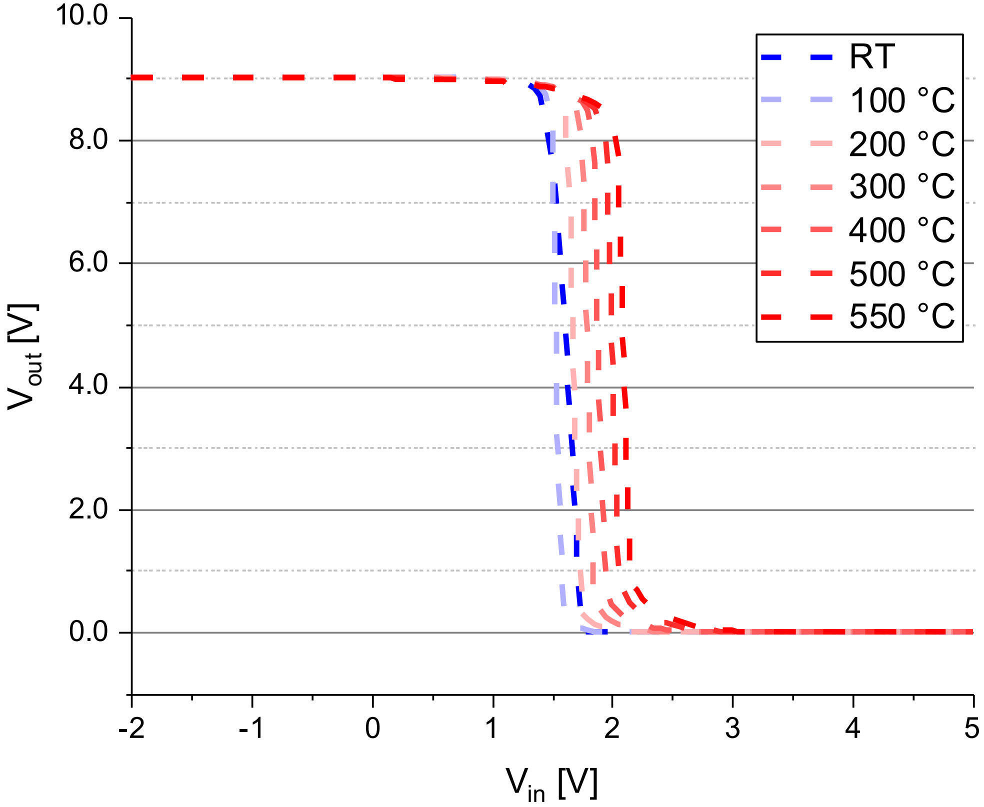
High-Temperature SiC Circuits

- CMOS inverters up to 550 °C

Inverter Layout



Temperature Dependence of Transfer Characteristics

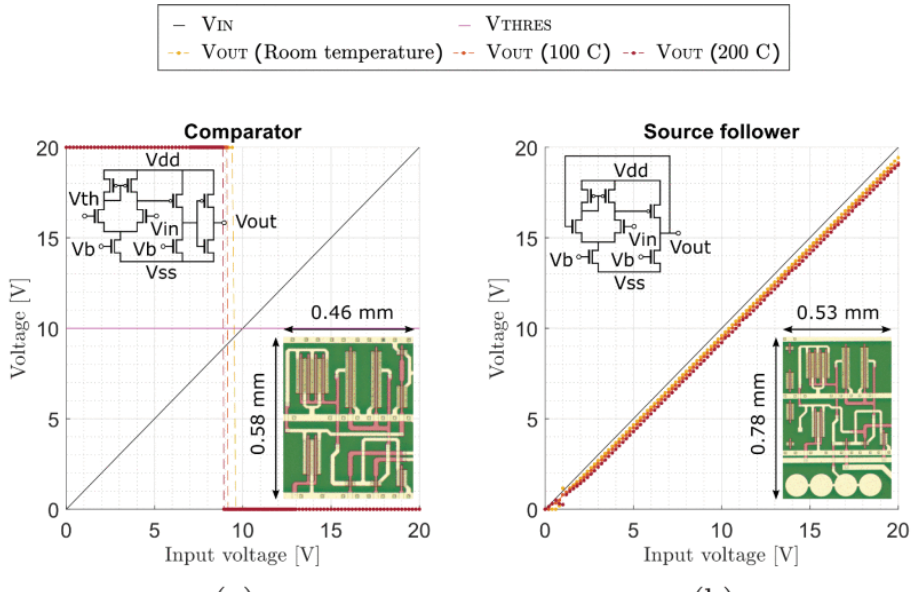


High-Temperature SiC Circuits

in cooperation with TUDelft
Delft
University of
Technology

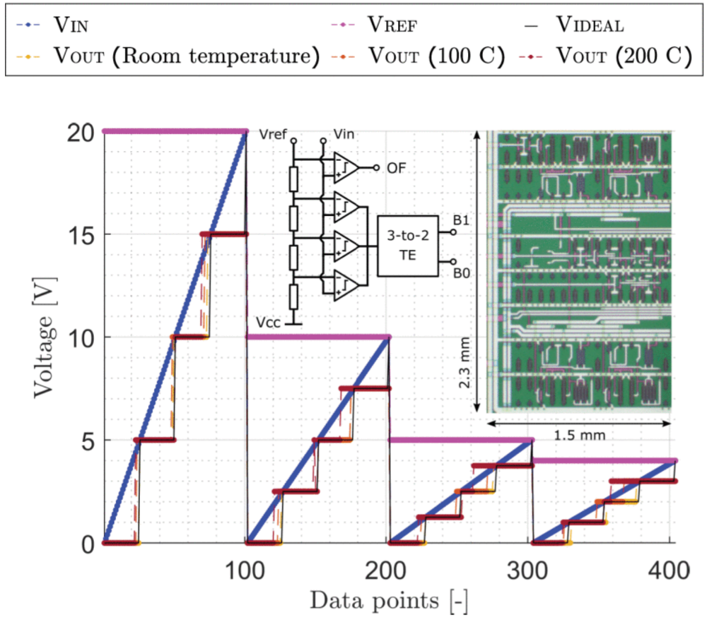
- Development of System Building Blocks

Comparator & source follower

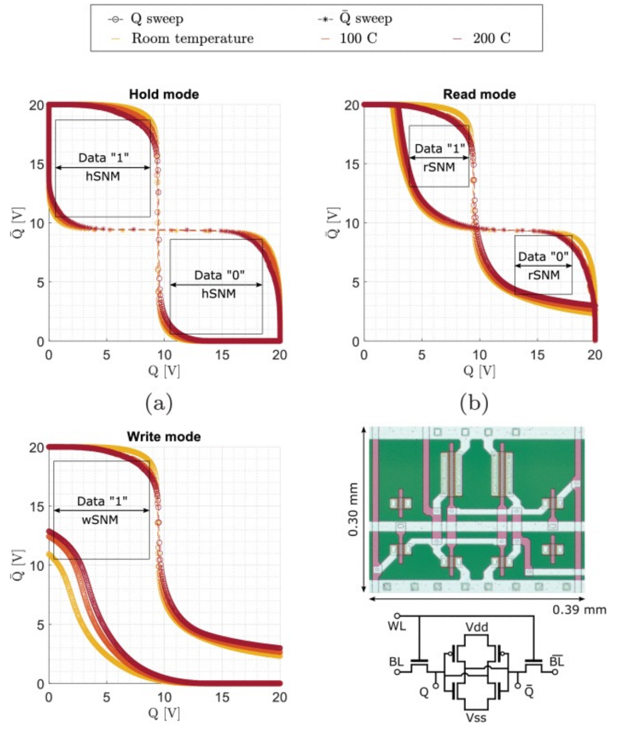


(a) (b)

2-bit ADC



SRAM cells



(a) (b)

(c) (d)

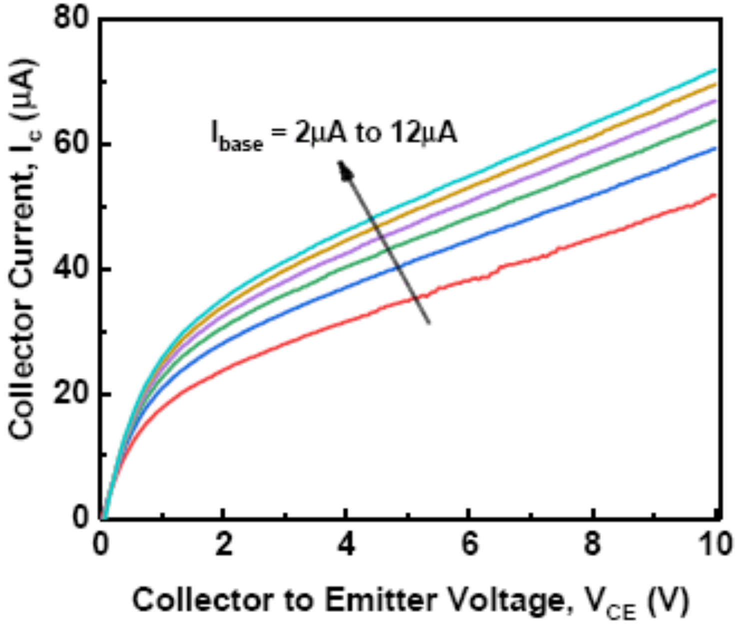
Integrated Digital and Analog Circuit Blocks in a Scalable Silicon Carbide CMOS Technology
Romijn et al. *IEEE Transactions on Electron Devices*, 2022

High-Temperature SiC Circuits

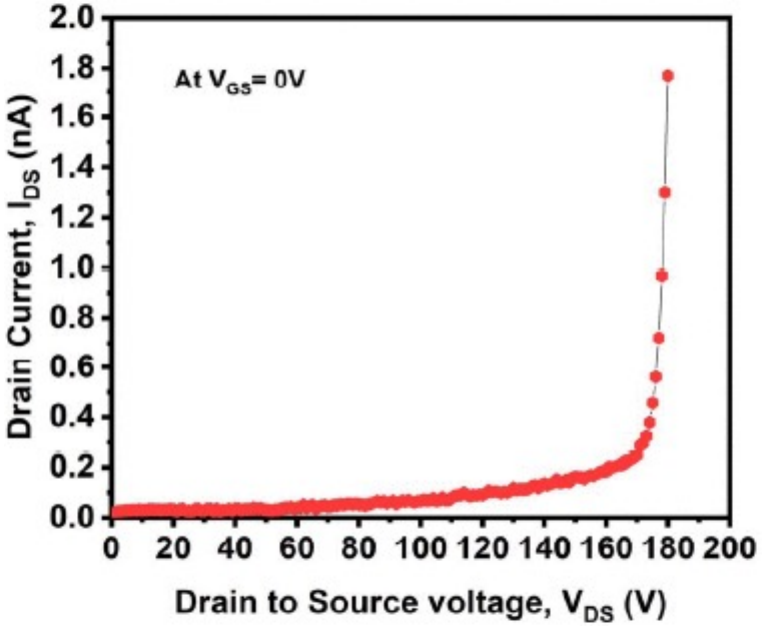
in cooperation with UNIVERSITY OF ARKANSAS

- SiC Smart Power Integration

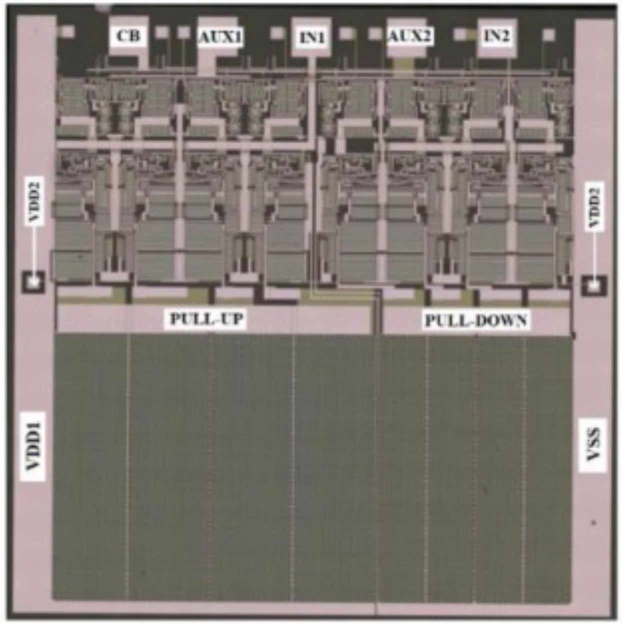
Bipolar Junction Transistor
Output Characteristics



LDMOS (W = 30 μm, L = 5 μm)
Breakdown at RT

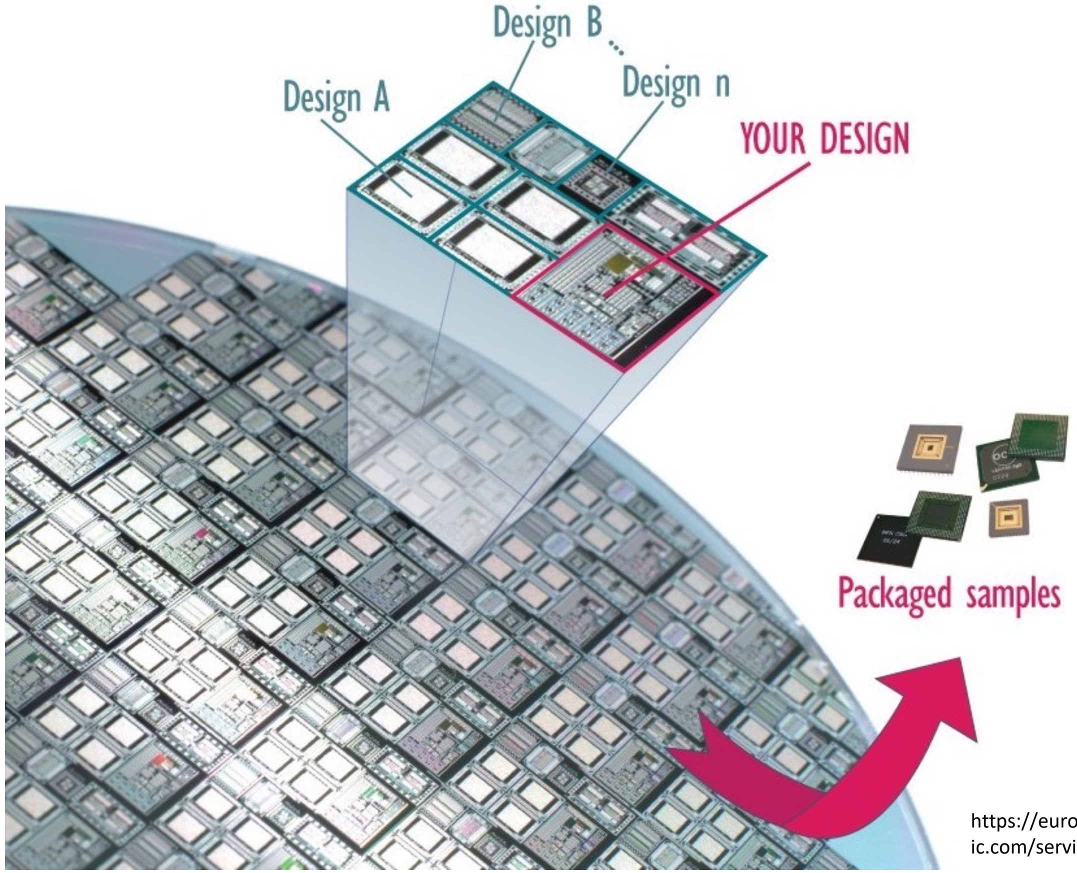


Multi-Level 5 x 5 mm²
Gate Driver



High-Temperature SiC Circuits

- Access
  - Customer designs are combined in a mask set and processed jointly
  - Process cost are distributed according to areal share
  - Each customer gets delivered single chips of their layout
  - Allows for participation in CMOS process flow starting from approx. 5% of total processing cost



https://europractice-ic.com/services/fabrication/

EU Chips Act – Pilot Line(s)

EU Commissioner for the Internal Market, Thierry Breton, spoke of Europe's ambitions to be an industry front-runner, with capabilities in advanced technologies as well as in existing strengths. He praised the world-beating 11 billion euros of investment in R&D through the Chips JU, and confirmed the creation of a European cloud-based design platform and four new pilot lines. These lines will bridge the gap from the lab to the fab in four critical and strategic technologies:

- Extending Moore's law to the Angstrom area
- Scaling down towards 7 nm in FD-SOI technology
- *The integration of several heterogeneous technologies and advanced packaging*
- **Next-generation wide-bandgap materials**

Ultra Wide Band Gap semiconductors (UWBGs) are superior to Silicon

due to their physical properties in the field of power electronic applications

		WBGs		**Ultra WBGs**		
	Silicon	**4H-SiC**	**GaN**	**Ga2O3**	**Diamond**	**AlN**
Bandgap E_g [eV]	1.1	**3.26**	**3.45**	4.85	5.47	6.2
Melting Point [°C]	1420	-	-	1795	-	-
Electron Mobility μ_n [cm^2/Vs]	1350	900	1000	150	4000 (th.)	500
Dielectric constant ε	11.8	9.7	9.5	9.9	5.5	9.1
Thermal Conductivity k [W/cmK]	1.56	**3.7**	1.5	0.1	25	3
Critical Electrical Field E_{cr} [10^6V/cm]	0.2	**3.2**	**3.3**	8	10	16.6


Fraunhofer IISB

Device performance

- Drastically lower transmission losses
- Outstanding dynamic properties
- Potential for higher/lower operating temperatures

System benefits

- Higher efficiency
- More compact systems including
simpler cooling and smaller passive components
- Reduced costs at system level

Funded by the European Union

WBG Pilot Line

Chips-CPL-4: Pilot line on advanced semiconductor devices based on Wide Bandgap materials:

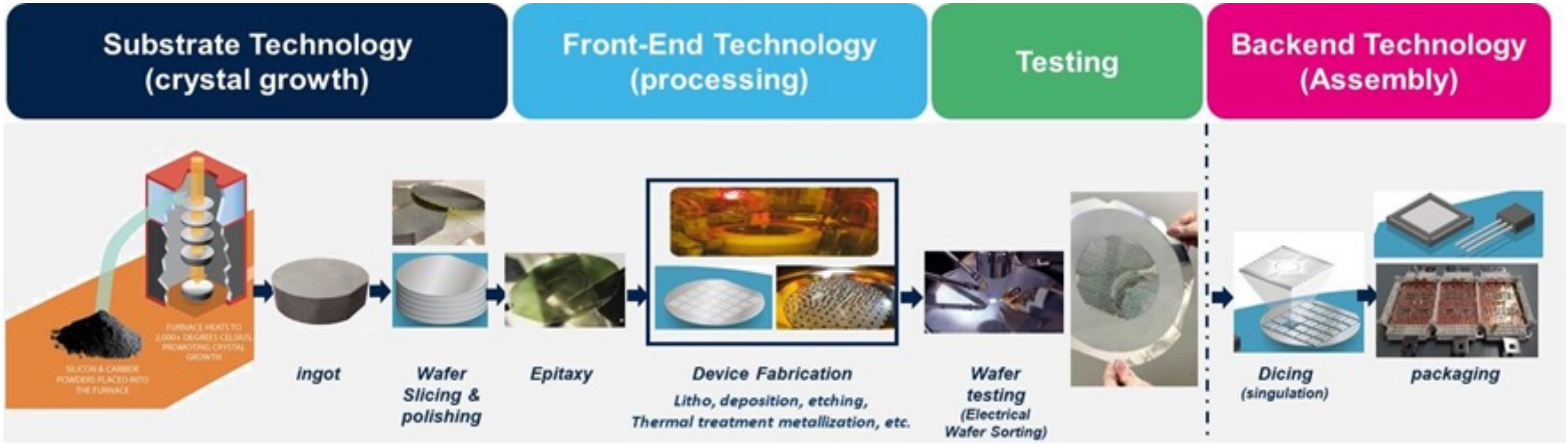
It will focus on two key outcomes:

(i) to extend the maturity level and the impact of ***SiC and GaN technologies***; and

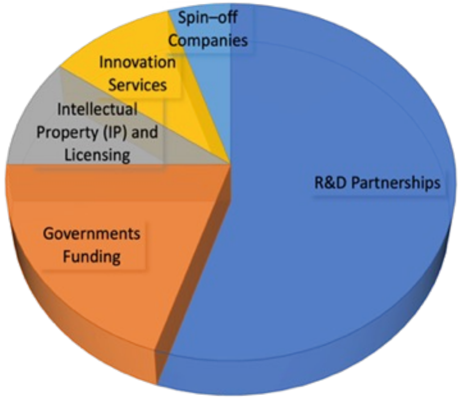
(ii) to ***explore less mature WBG and UWBG semiconductors***, such as cubic polytype of SiC (3C–SiC), low–cost polycrystalline SiC, lattice–matched InAlN or InAlGaN for RF heterostructures, bulk gallium nitride or gallium oxide (Ga_2O_3) or aluminium nitride (AlN).

Vision of the WBG Pilot line:

The R&D activities aim to improve the efficiency and power density capabilities of WBG–based power devices must cover the entire chain, from the crystal growth to the front–end, testing and back–end technology



General idea, vision and topical coverage of the WBG Pilot Line

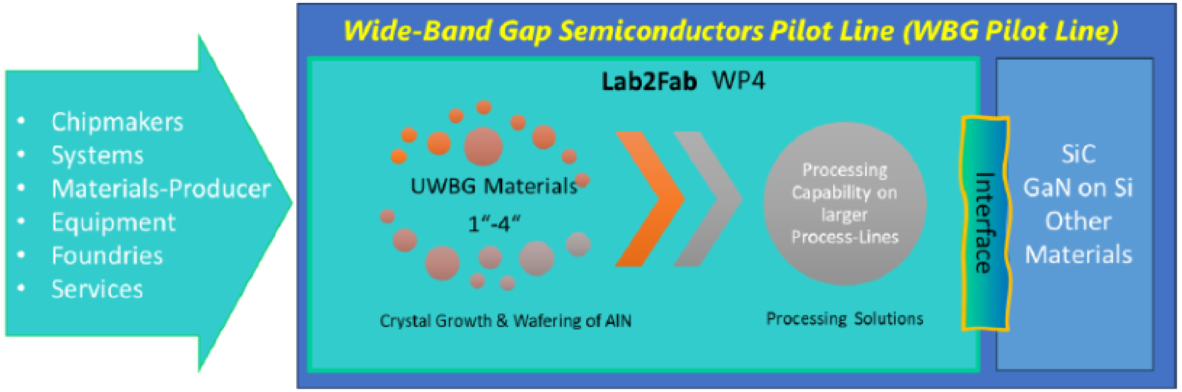


Income prospect of WBG PL business model

WBG Pilot Line - contribution by FhG-IISB

Ultrawide band gap semiconductors for next generation power devices = UWBG4NGP

Lab2Fab initiative for a faster bridging of the „valley of death“



- Chipmakers
- Systems
- Materials-Producer
- Equipment
- Foundries
- Services

Wide-Band Gap Semiconductors Pilot Line (WBG Pilot Line)

Lab2Fab WP4

UWBG Materials
1"-4"

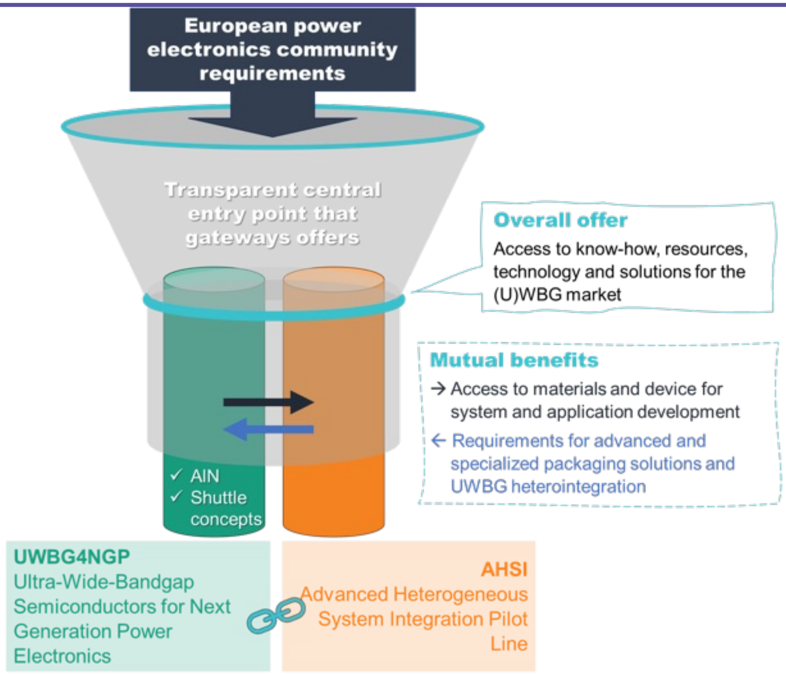
Crystal Growth & Wafering of AlN

Processing Capability on larger Process-Lines

Processing Solutions

Interface

SiC
GaN on Si
Other Materials



European power electronics community requirements

Transparent central entry point that gateways offers

Overall offer
Access to know-how, resources, technology and solutions for the (U)WBG market

Mutual benefits
→ Access to materials and device for system and application development
← Requirements for advanced and specialized packaging solutions and UWBG heterointegration

✓ AlN
✓ Shuttle concepts

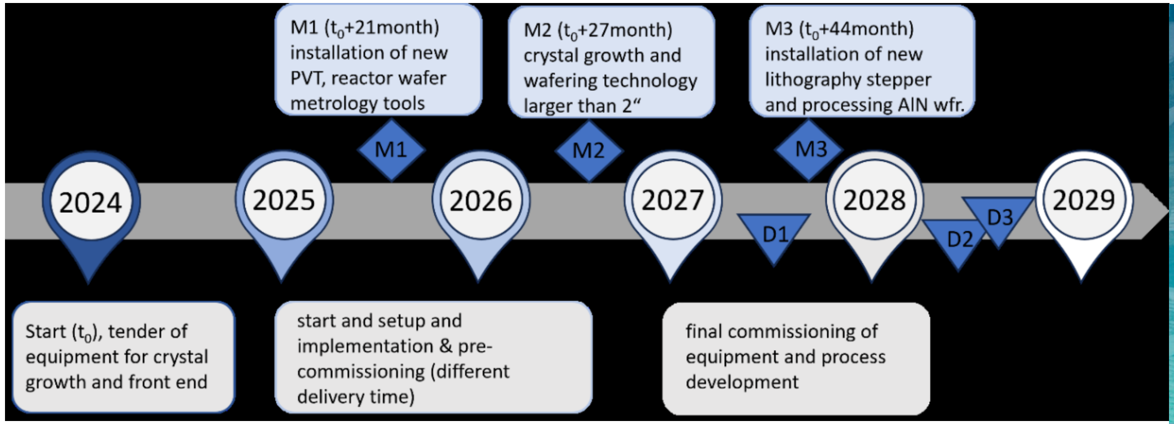
UWBG4NGP
Ultra-Wide-Bandgap Semiconductors for Next Generation Power Electronics

AHSI
Advanced Heterogeneous System Integration Pilot Line

The German contribution aims to fulfil the following targets:

- Creation of synergies within Germany and Europe for AlN but also GaN and Ga2O3 based device supply chains
- Capabilities inside Europe for technology development of power devices based on UWBG materials on low TRL level like AlN, unlock the potential of these new semi-conductors and raise their maturity. → **Lab2Fab**
- **Ensuring the availability of AlN** wafers and related process equipment from within Europe
- Securing **technology autonomy for AlN** and leading the way for Next-Generation Power Semiconductors in Germany

Planned timeline and outcome for AlN inside PL4 by FhG-IISB



M1 (t_0+21month) installation of new PVT, reactor wafer metrology tools

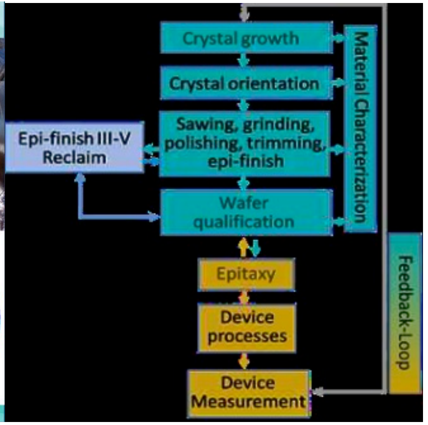
M2 (t_0+27month) crystal growth and wafering technology larger than 2“

M3 (t_0+44month) installation of new lithography stepper and processing AlN wfr.

Start (t_0), tender of equipment for crystal growth and front end

start and setup and implementation & pre-commissioning (different delivery time)

final commissioning of equipment and process development



AlN will be very far-reaching and AlN will be able to function as a next-generation semiconductor with a wide range of applications in automotive and industry such as:

- Electronics for extreme environmental conditions such as radiation-resistant and cold electronics for satellites, aerospace, and quantum electronics
- Energy-efficient power electronics for automotive and data centers
- Power Transistors for radio frequency (RF) and communication applications
- Energy-efficient UVC LEDs for disinfection purposes

Summary – Power Devices

- Global research and development in the field of advanced power devices
- Investments are on the way
- Market for WBG (SiC, GaN) and UWBG (AlN, Ga_2O_3, diamond)
- Enable Access via Pilot Lines for universities, SMEs and fast followers
- Electronics for harsh environment
  - Available via EUROPRACTICE

THANK YOU!

This project has received funding from the European Union's Horizon Europe research and innovation programme under GA Nº 101092562

icos-semiconductors.eu