NanoElectronics Roadmap for Europe: Identification and Dissemination

Presentation in the Speaker's Corner at EFECS

Brussels, December 6, 2018

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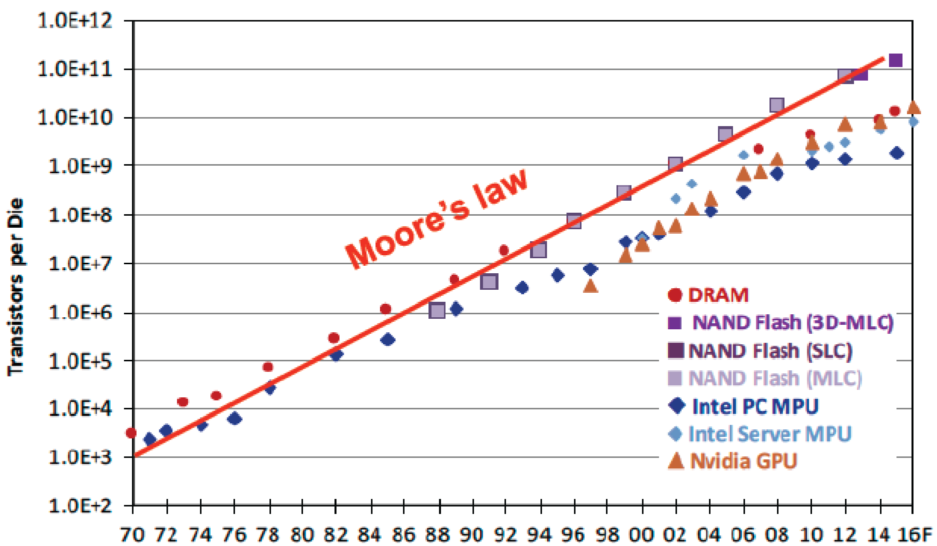
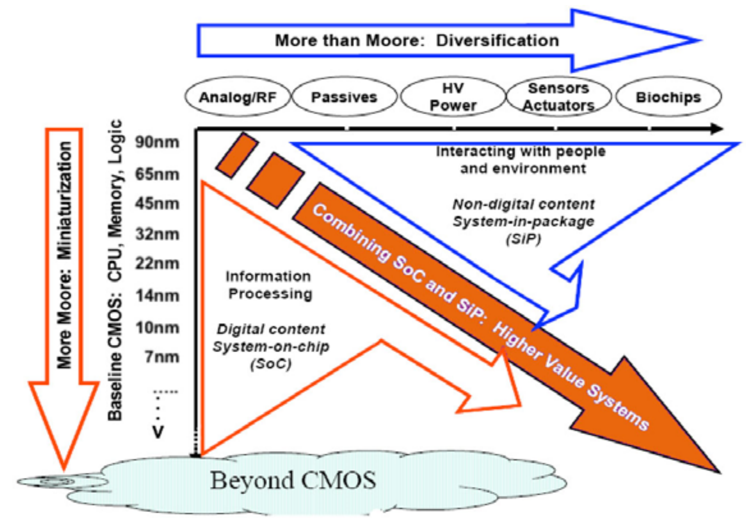
ICT-CSA: Micro- and Nano-Electronics Technologies
Grant Agreement n° 685559

Change of paradigm

From More Moore … … to … More than Moore and heterogeneous integration





• From device density …	… to …	… functionality increase
• From device cost driven …	… to …	… system cost driven
• From single figure of merit …	… to …	… multiple parameters
• From Technology push …	… to …	… Application pull
		… full supply chain
		… sustainability

NEREID Roadmap Flow

From Applications …

different

different

E C S

INTERNATIONAL ROADMAP FOR DEVICES AND SYSTEMS

Roadmap

Different Timescale,
Topics, Method,
Figures of Merit

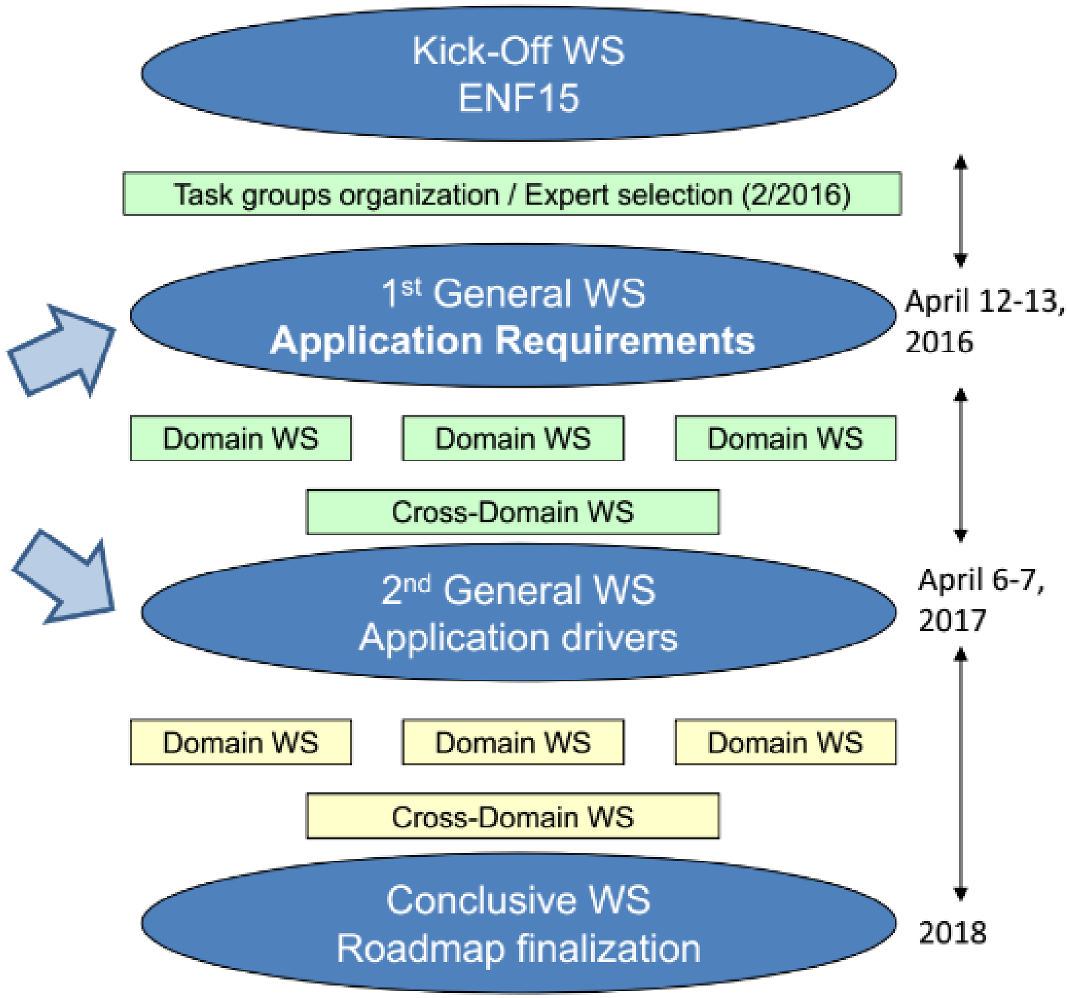
Different focus:
Computing vs
non Computing

… to European strategic programs

NEREID Roadmap Process

- From European application needs to specific technical workshops

- Automotive
- Medical
- Security
- Energy
- Industrial
- IoT
- Mobile convergence



- Large participation of (>100 !) experts (internal, external ; application, technology) from leading European academic and industrial institutions in Workshops

NEREID Structure & coordination with other regions

Management

Communication & Dissemination

Beyond CMOS

Advanced Logic and Connectivity

Functional diversification

System Design & Heterogeneous Integration

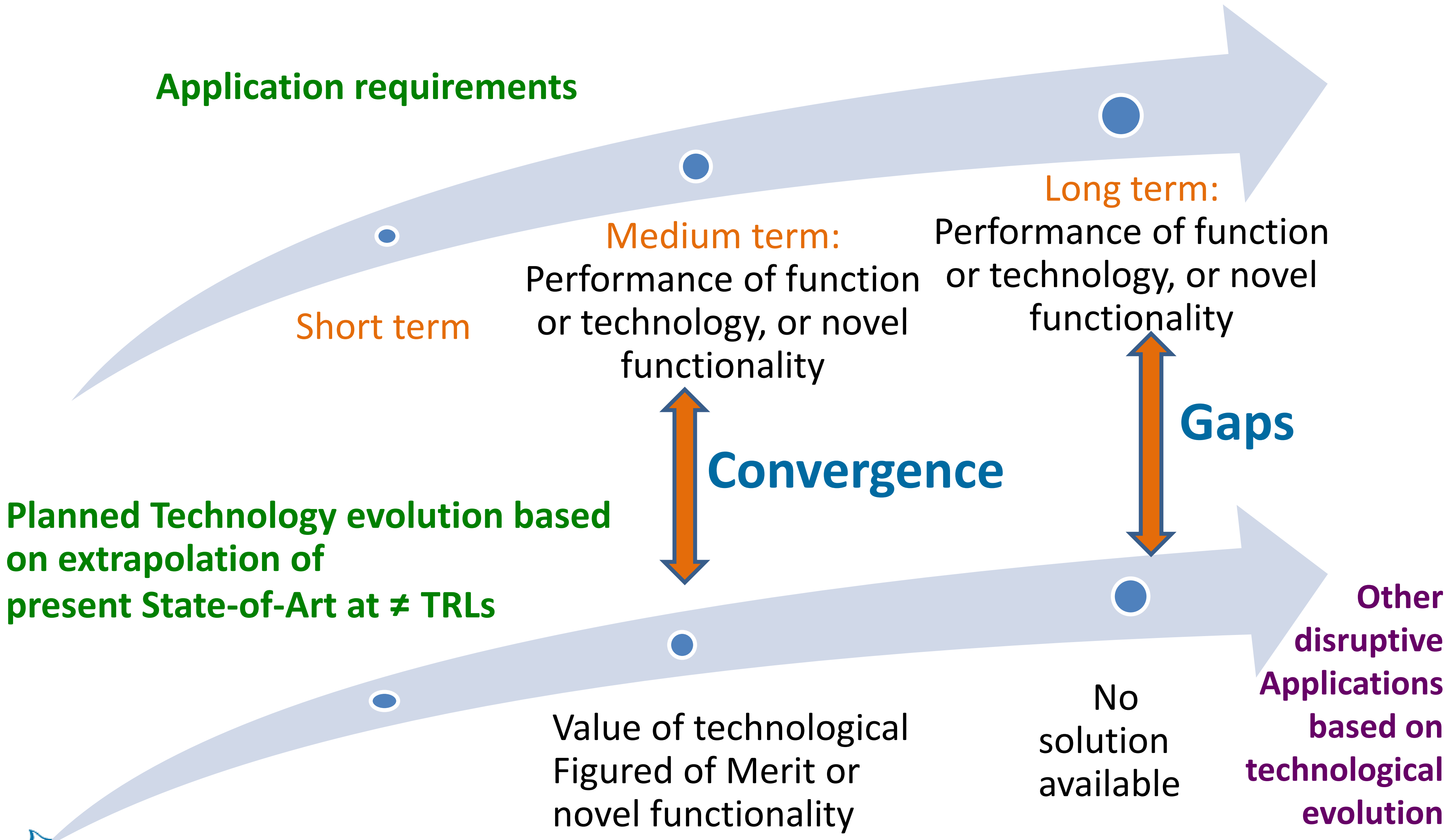
Equipment & Manufacturing Science

Coordination with roadmap initiatives

Advisory Committee

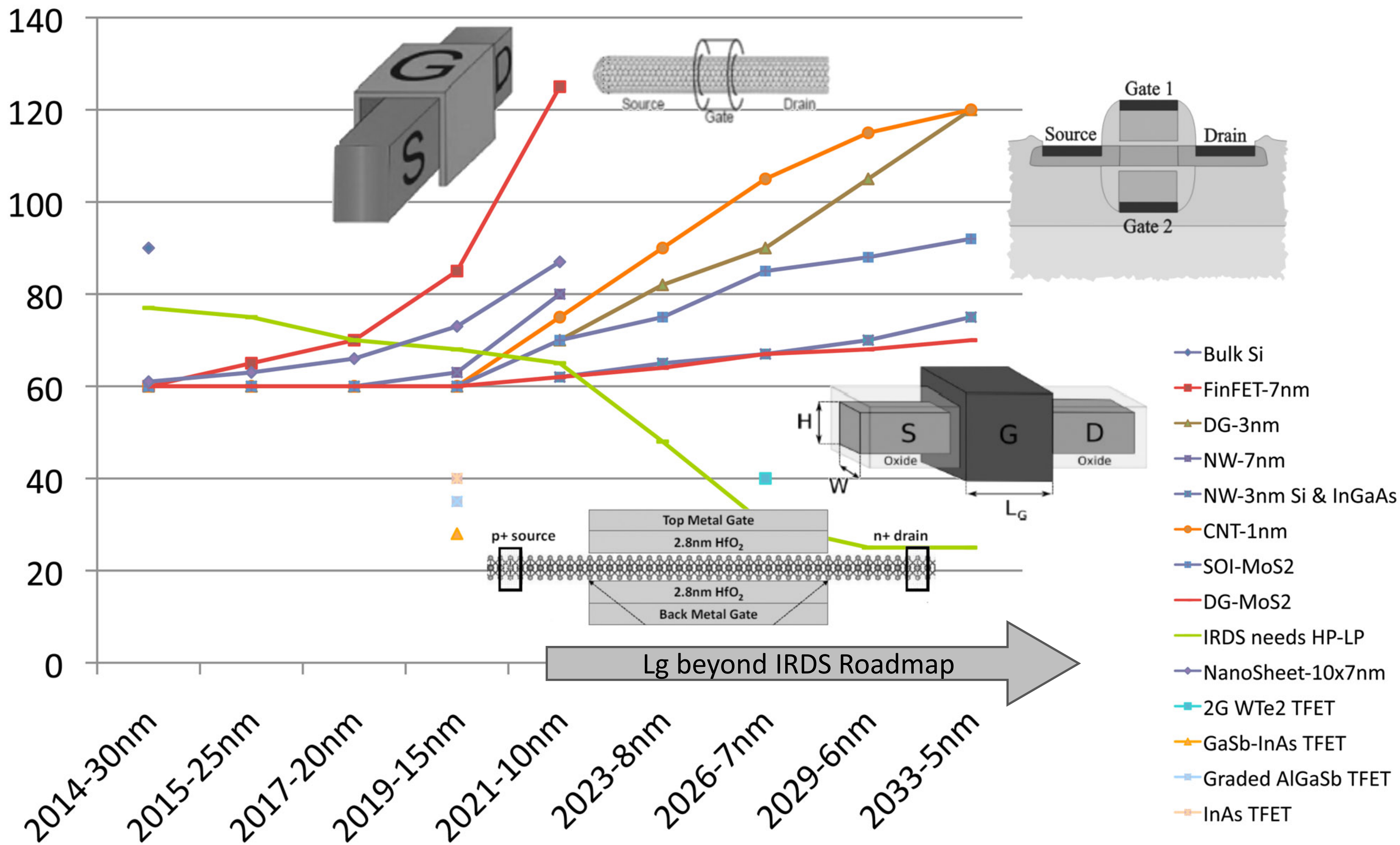
10-15 high level members:
Europe, USA, Asia

The NEREID Approach



Advanced Logic and Connectivity
Nanoscale FETs

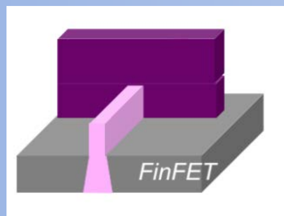
Sub. Swing vs Year / Lg (mV/dec) *(Sim.)*



Nanoscale FETs: Research highways

10nm | 7nm | 5nm | 3nm

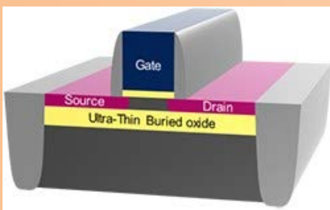
Fin-FET



- Co-integration of different channel materials
- Improve analog performance
- Subthreshold slope control
- Variability control

22nm | 14nm | 10nm | 7nm

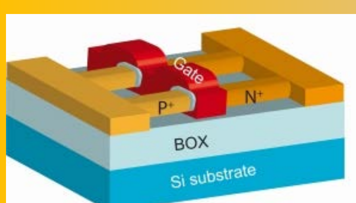
FD-SOI



- Compatibility with different options
- Integration of new materials
- Ultra-Low Power design
- 3-D integration

7nm | 5nm | 3nm | 2nm | 1nm

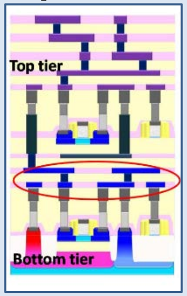
NW-Nanosheet



- New materials
- New geometries
- Strain engineering
- 3-D process control

Nanoscale FETs: Research highways

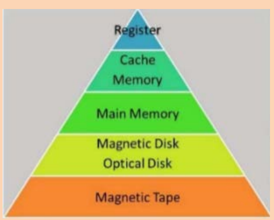
Sequential 3D



- Ultra-fine grain interconnections between layers
- Thermal management/self-heating mitigation
- Design Tools for place and route
- Manufacturing challenges

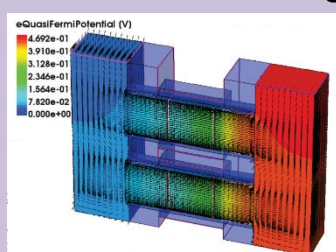
Non Charge-based memories

OxRAM
CBRAM
FeRAM
MRAM
PCRAM



- Threshold spread and variability control
- Reliability and thermal stability
- Cell architectures for scalability
- New materials

Charact. & Modelling

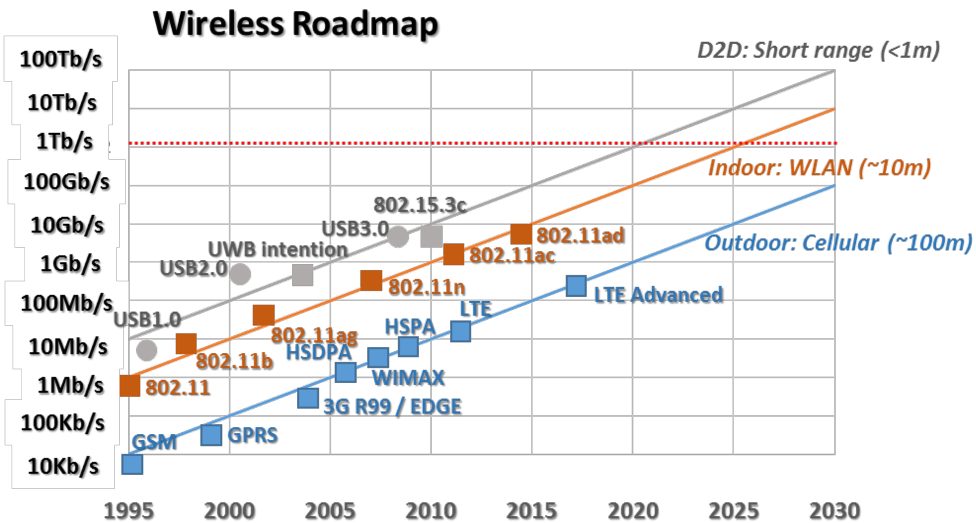


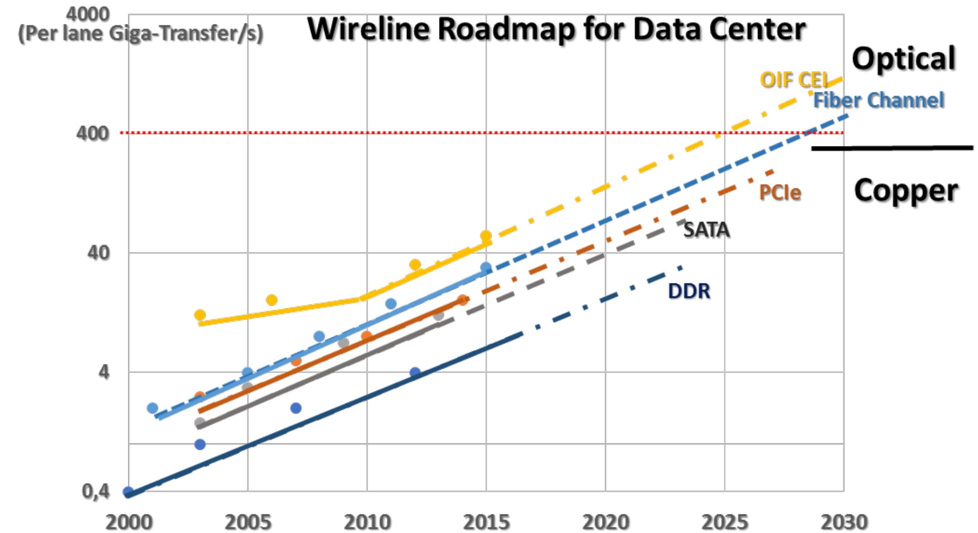
- Modelling and charact. of new materials, including confined ones (2D, 1D)
- Modelling and charact. of technology and process including 3D
- Modelling and charact. of variability and reliability
- Models and charact. of novel device concepts

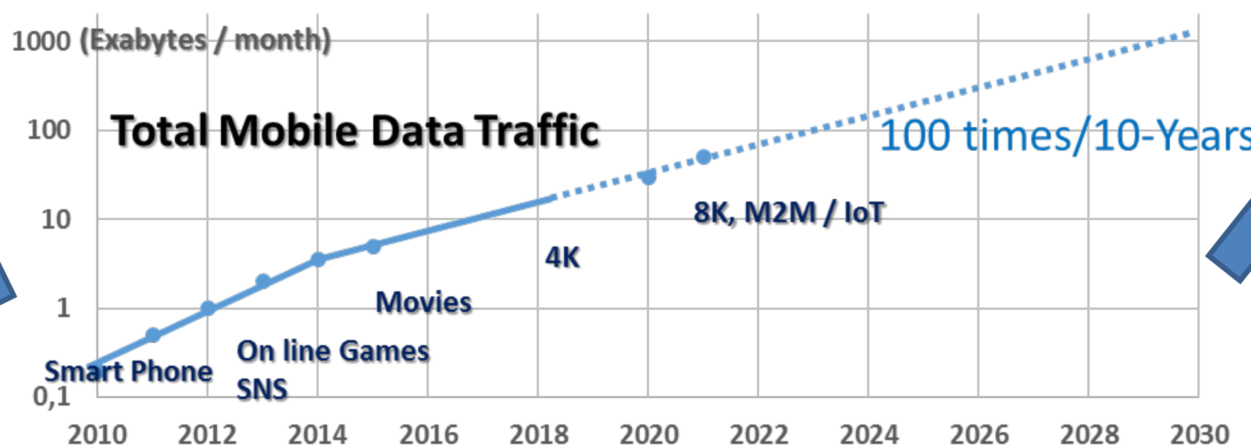
Advanced Logic and Connectivity

Connectivity

Connectivity Roadmap







Next 5 years Connectivity Challenges

WLAN/WPAN/WBAN:
mmW & 10s Gbs

WSN: µW & Security

Localization:
Low cost & Wearable

WLAN: 100s Gbs

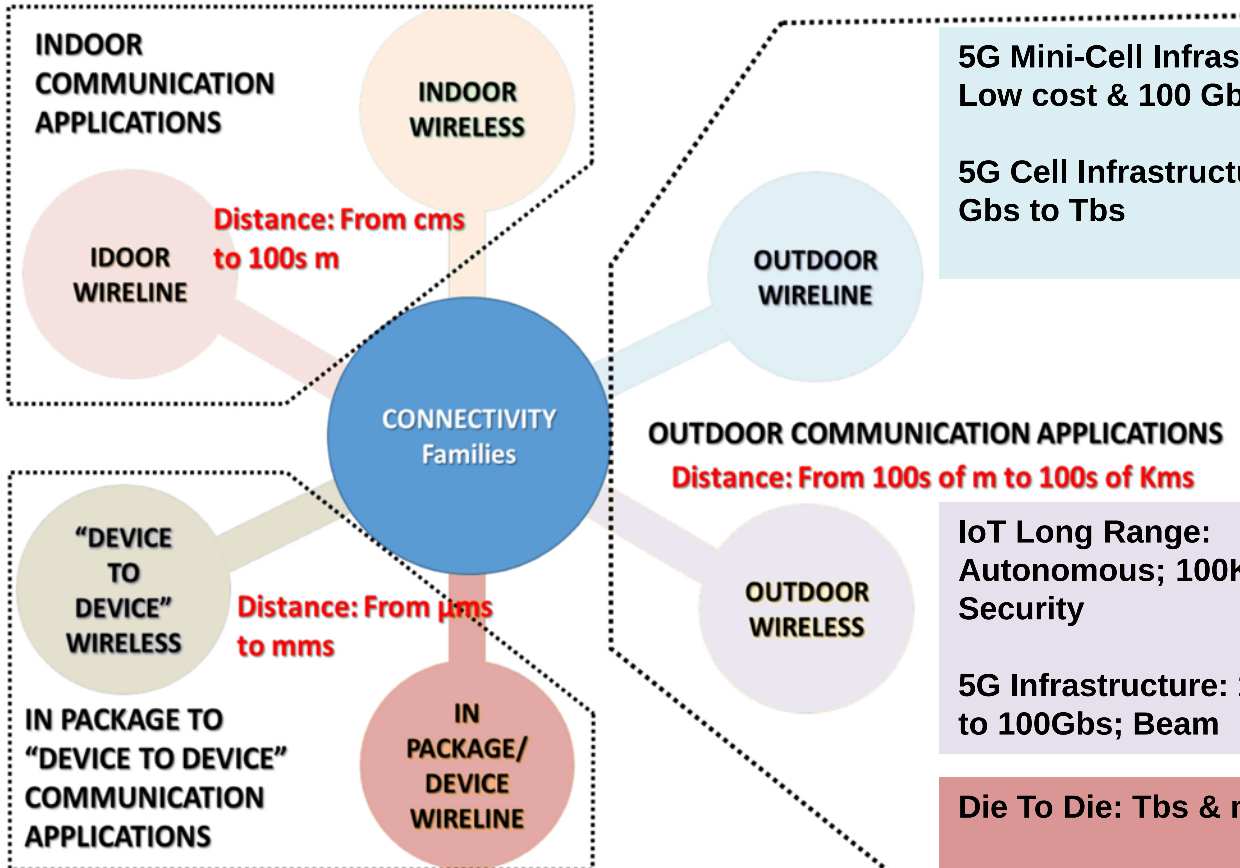
WSN: 100s meters

5G Data Centers Short Range: 10s Tbs

Die to Die & Package to Package: 10Gbs & BER 10^{-15}

NFC: Security

RFID: mmW-100Mbs & Security



5G Mini-Cell Infrastructure: Low cost & 100 Gbs

5G Cell Infrastructure: 400 Gbs to Tbs

IoT Long Range: Autonomous; 100Km & Security

5G Infrastructure: 10s Gbs to 100Gbs; Beam

Die To Die: Tbs & mm range.

In Module: Tbs & 10s mms range.

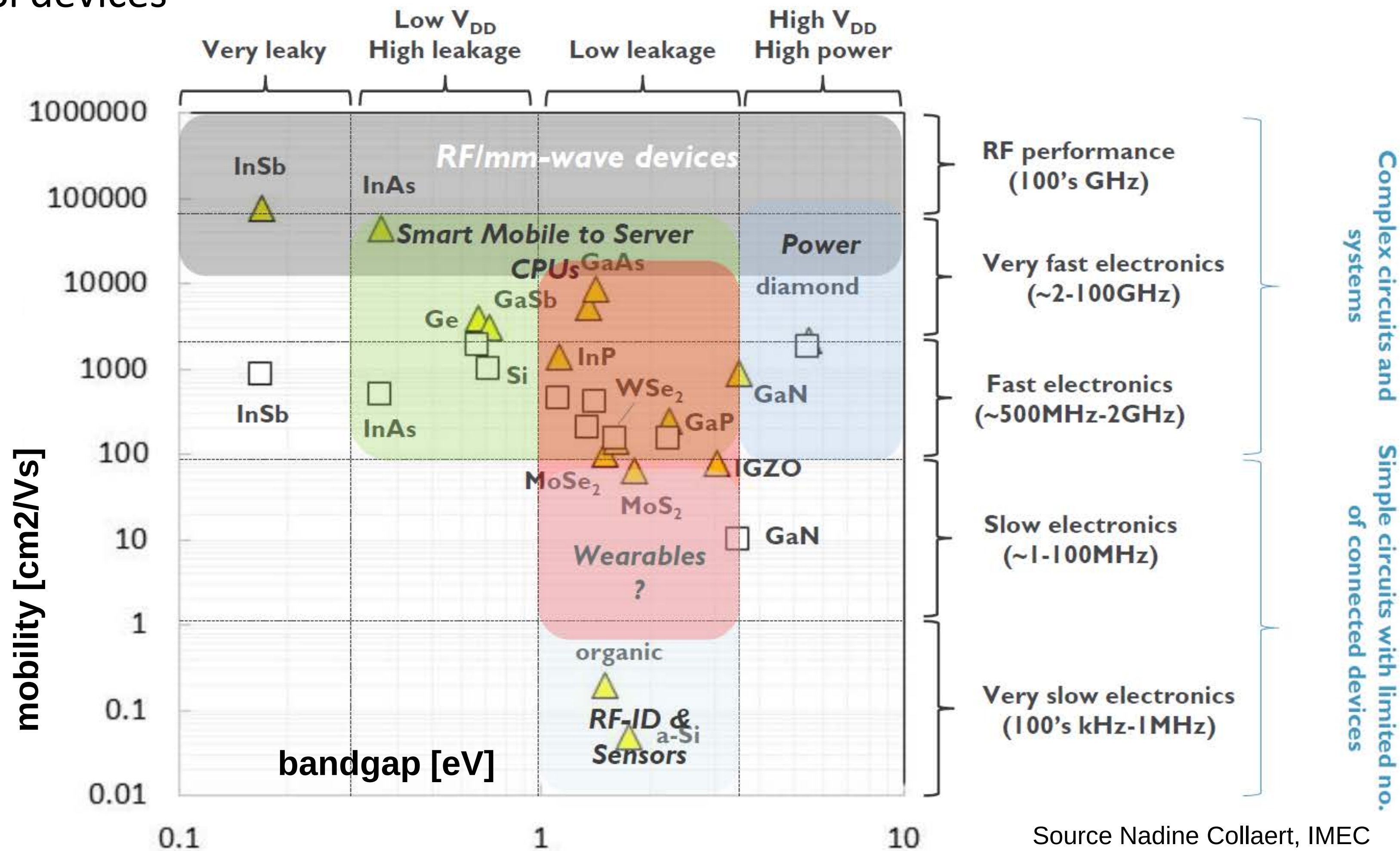
IN Device (phones….):
10s Gbs over 10s cms range.

$$FOM = \frac{Data\_rate(Gbs) \times D^2(m) \times \frac{1}{BER}}{Psupply(W)}$$

Highlights of Connectivity

Organization of a WS at EuMW 17 around RF & mmW connectivity and III-V devices compared to Si devices

Channel Carrier Mobility & Applications



Source Nadine Collaert, IMEC

Functional Diversification

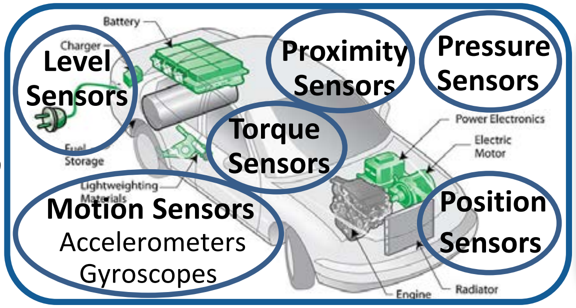
Smart Sensors

Smart Sensors - Roadmap

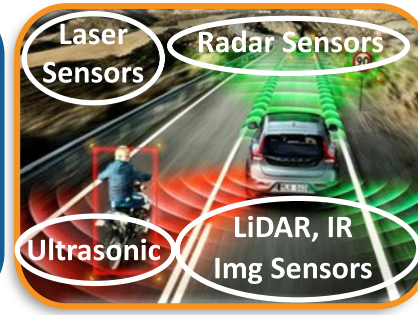
Automotive

sensors to *reduce pollution, energy consumption and to improve safety & security*

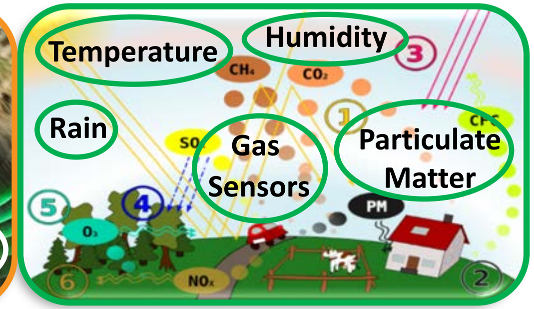
Automotive performance sensors: Inertial and motional sensors



Advanced Driver Assistance System: ADAS



Environmental monitoring : Pollution & Climate status



- Improve accuracy
- Share manufacture infrastructure costs with other applications

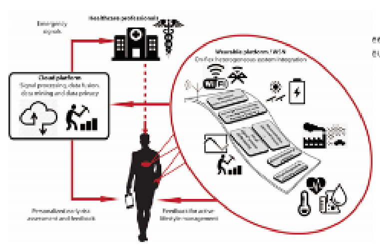
Medical and healthcare

sensors are developing very fast.

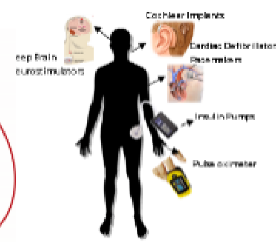
Applications

- Drug Development
- Patient Monitoring
- Clinical Operation
- Clinical Imaging
- Fitness & Wellness

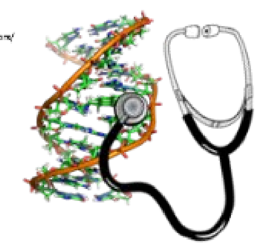
Devices



mHealth
Wearable Sensors



Bionics
Implantable Sensors



Molecular diagnosis

End Users

- Patients
- Biotech companies
- Research labs of pharma
- Healthcare providers & players
- Government authority

- Cost and convenience (for the patient, the hospital, etc.)
- Long and tedious development stage

Highlights of Smart Sensors

Healthcare and automotive are of **high relevance for European industry and research**. In this sectors **quality** is even more important than the **price.**

- **Well-penetrated healthcare systems**
- Dominates the **autonomous vehicle market** with major technology manufactures and early commercialization of **ADAS systems**.

Some of the smart sensor identified gaps by 2030 concern: ***manufacturability and cost*** *(hybrid integration),* ***low power consumption*** *(energy efficiency, zero-power or self-powered sensors),* ***robustness*** *(stability) of design and in production* ***reliability****.*

- ❖ **Lack of metrology & standards:** clinical validation, FDA approvals…
- ❖ **Lack of regulations:** reduce emissions, dependence in oil…
- ❖ **Auto-calibration** or self-calibrated sensors
- ❖ Sensor packaging, compatibility and CMOS integration
- ❖ **Connected objects** and Internet of things (IoT)
- ❖ **Sensor Fusion/** Wireless Sensor Network (WSN)

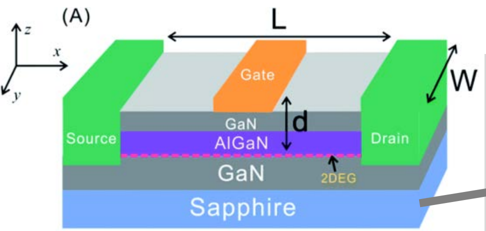
Sensors relevant in other segments:

- consumer electronics: **motion MEMS**
- industrial: **image sensors**
- infrastructure: **air quality sensors**
- defense: **LiDAR**
- etc.

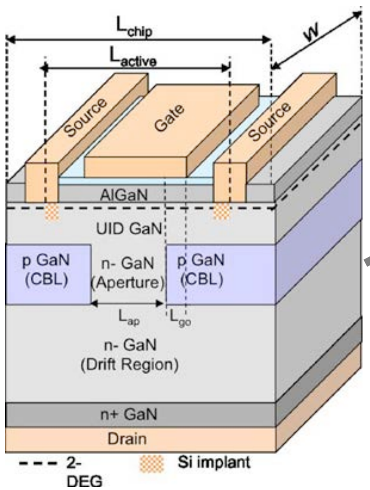
Functional Diversification

Smart Energy

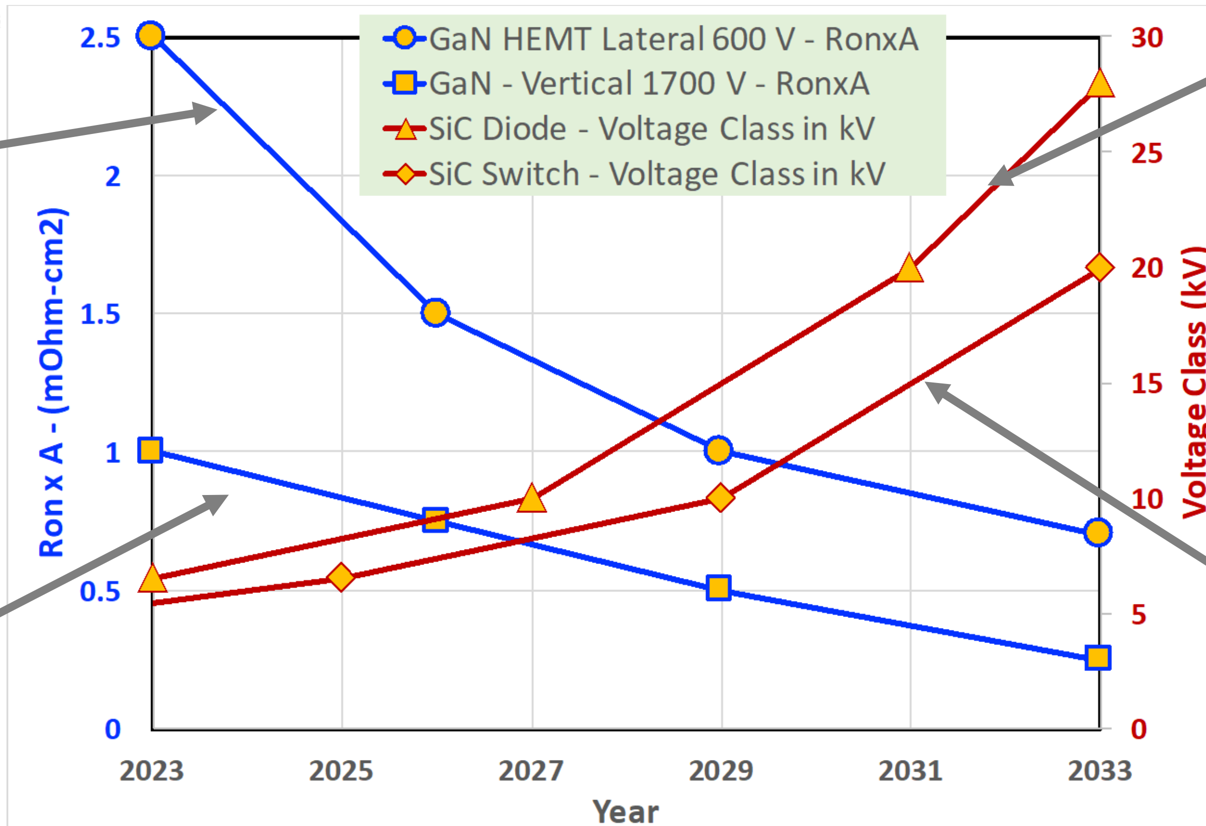
Smart Energy - Roadmap

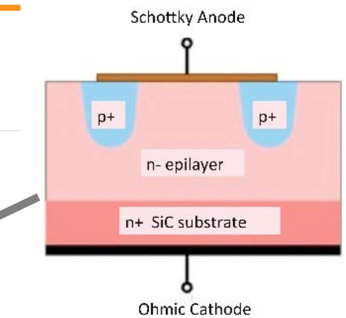


GaN HEMT (Lateral)

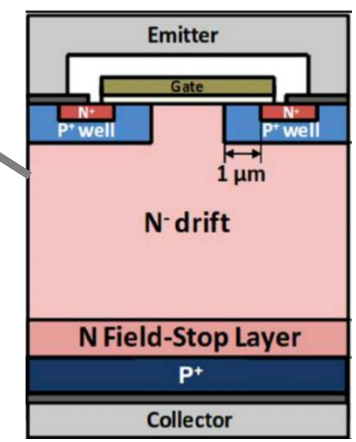


GaN Vertical





SiC Diode

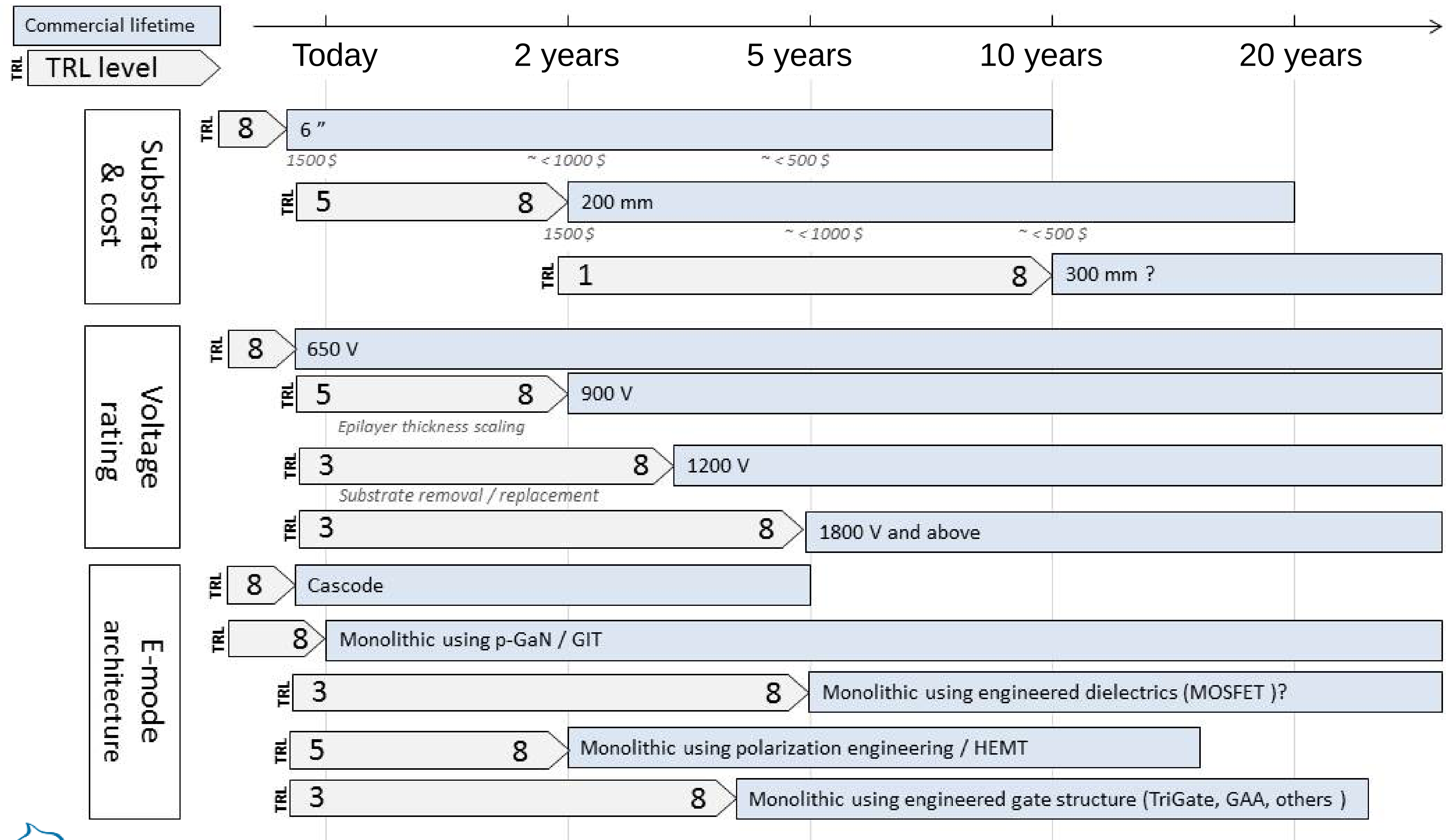


SiC Switch

GaN/SiC Roadmap

Smart Energy - Roadmap

➢ *GaN-on-Si Roadmap*



Smart Energy devices open issues

- **Fast switching is the key for size and weight reduction** with WBG power semiconductors leading to several issues:
  EMC, low parasitic inductances of the **packaging** and interconnection technologies, power losses related to **passive** components, need for system **integration solutions**, optimized switching cell, integrated drivers, ...

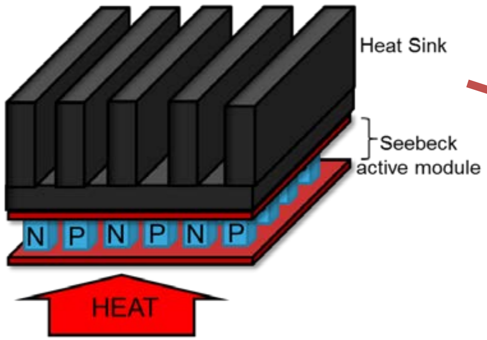
- As a consequence, the extreme miniaturization of power electronic systems leads to **higher power density** which requires **new improved cooling techniques**, but also leads to higher operation (and junction) temperature.

- **Issues related to high temperature power electronics**:
  advanced materials and processes for **packaging** and interconnection (chip level and system level), polymer moulding & encapsulation, substrates, temperature range for passive components, **robustness** and reliability.

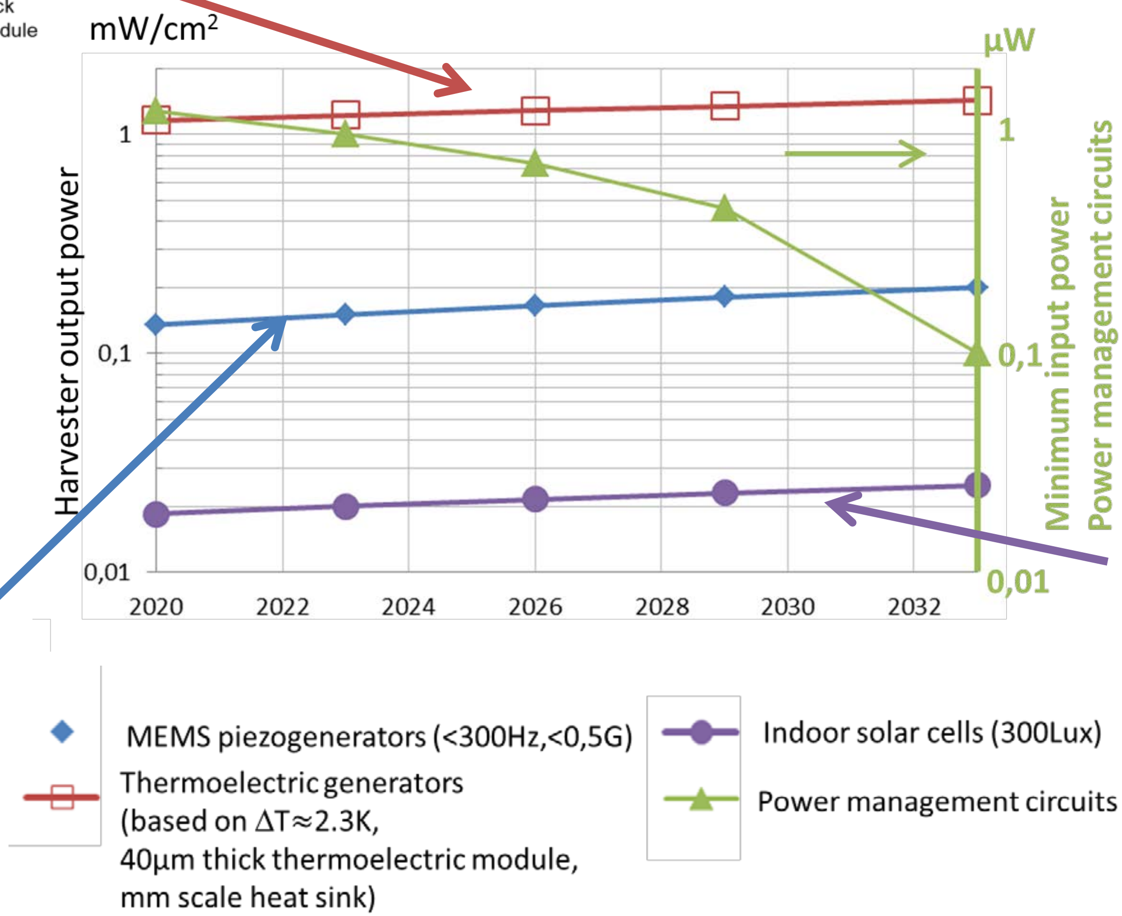
Functional Diversification

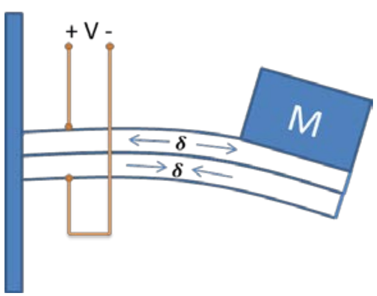
Energy for autonomous systems

Energy for autonomous systems - Roadmap

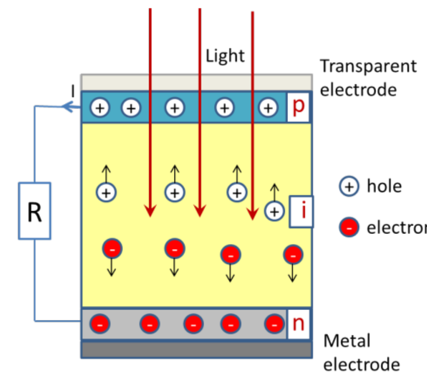


Thermoelectric generators





MEMS Piezogenerators



Solar cells

Highlights of Energy for autonomous systems

- IoT and energy harvesting are application-driven today, so projects should mainly focus on the development of a complete application (from harvesting to the use case)
- The improvement of energy harvesters performance and efficiency is as important as the development of “green” materials.
- The use of nanotechnologies is foreseen to increase the performance of all the concepts in general.
- Increasing the bandwidth at a low frequency target (below 100Hz) will help to fit applications for vibration based mechanical energy harvesters.
- Power management circuits key issues: inductors size reduction, develop planar alternatives to inductors, reduce leakages.

System Design
and
Heterogeneous Integration

Application drives the choices for the system

Functionalities

- Specs, Interfaces/Communication, Computing/Storing, Sensing, Learning, Autonomy, Speed

Physicalities

- Energy/power, response time, form factor, environment, temperature, EM effects, technology nodes, robustness

Criticalities & Opportunities

- Manufacturability, Cost, System Level Reliability, Lifecycle, OoS, Compatibility/Standard, Security(hacking), Privacy, Safety, Designer Education

Design Paradigms

- HW/SW, re-configurability, energy aware/driven, design for IP, Open source/cores, Automated

Design Activities

- Verification, testing & validation, multi-physics, multi-parameter, optimisation, prototyping, constraints aware design, design for maintenance, network synthesis

Implementation Qualities

Energy Autonomy

Connectivity

Sensor Integration

Miniaturisation

Reliability & Lifecycle

Functional Safety, Privacy & Security

Functionalities

Applications to be considered

Implantables

Autonomous Driving

Europe‘s competitive profile

Wearables

Environmental Monitoring Systems

Example: Implantable Systems (I)

Everything is application driven. The application drives the choices.		
The Key Functionalities to be considered Capture importance and the anticipated TRL focus at 5+ and 10+	The Implementation Qualities required for implementing the Functionalities. Measured in 5+ and 10+ importance.	Criticalities & Needs indicating the challenges and the needed technologies in 5+ and 10+ horizon What needs to be achieved in terms of anticipated technologies/solutions?

Example: Implantable Systems (II)

Everything is application driven. The application drives the choices.

IMPLANTABLE BIO-SYSTEMS

FUNCTIONALITIES (*** = Very Important) (TRL to be reached)		IMPLEMENTATION QUALITIES (*** = Very Important Quality/Concept)				CRITICALITIES & NEEDS (*** = Very Important to solve/implement it)		
			FoM 5+	FoM 10+	Link to other WPs	List of Criticalities and/or needs	FoM 5+	FoM 10+
		PHYSICAL & TECHNOLOGICAL REQUIREMENTS						
		Technology Nodes/Impact on Technology	**	***	2	Technical (investing in technical manufacturability)	**	***
		Low power electronics	***	***	4	Design and production of ultra-low power electronics	< μW (circuit consumption)	< nW (circuit consumption)
		Energy storage (e.g., solid state)	***	***	4	Duration	> 10 years	> 30 years
						Recycling	***	***
		Energy Harvesting (e.g., new materials)	***	***	4	Production of efficient energy harvesters	μW	mW
		Energy/Power efficient algorithms	***	***	4	Implementation of efficient energy-aware hw/sw co-design algorithms	**	***
		DESIGN METHODS & TOOLS						
		Automated Design Space Exploration & System Synthesis	*	*	4	Implementation of automated tools for exploring optimal solutions for lowering energy consumption	**	***
						Focus of System Synthesis for optimising energy consumption	**	**
Energy Autonomy	*** 5+: TRL 5 10+: TRL 8	Verification	***	***	4	Verification of system functionalities in case of not stable or critic energy levels	***	***
		Profile of Energy Sources	***	***	4	Design tools for implementing profiling and monitoring of energy sources	***	***
		Constraint Propagation	***	***	4	Tools for propagation of constraints deriving from energy sources, considering their impact on system performances/functionalities	***	***
		DESIGN PARADIGMS						
		Machine Learning Capabilities/Artificial Intelligence	*	**	4	Design for implementing Machine Learning algorithms for optimising power consumption (for example Machine Learning applied in the	*	**

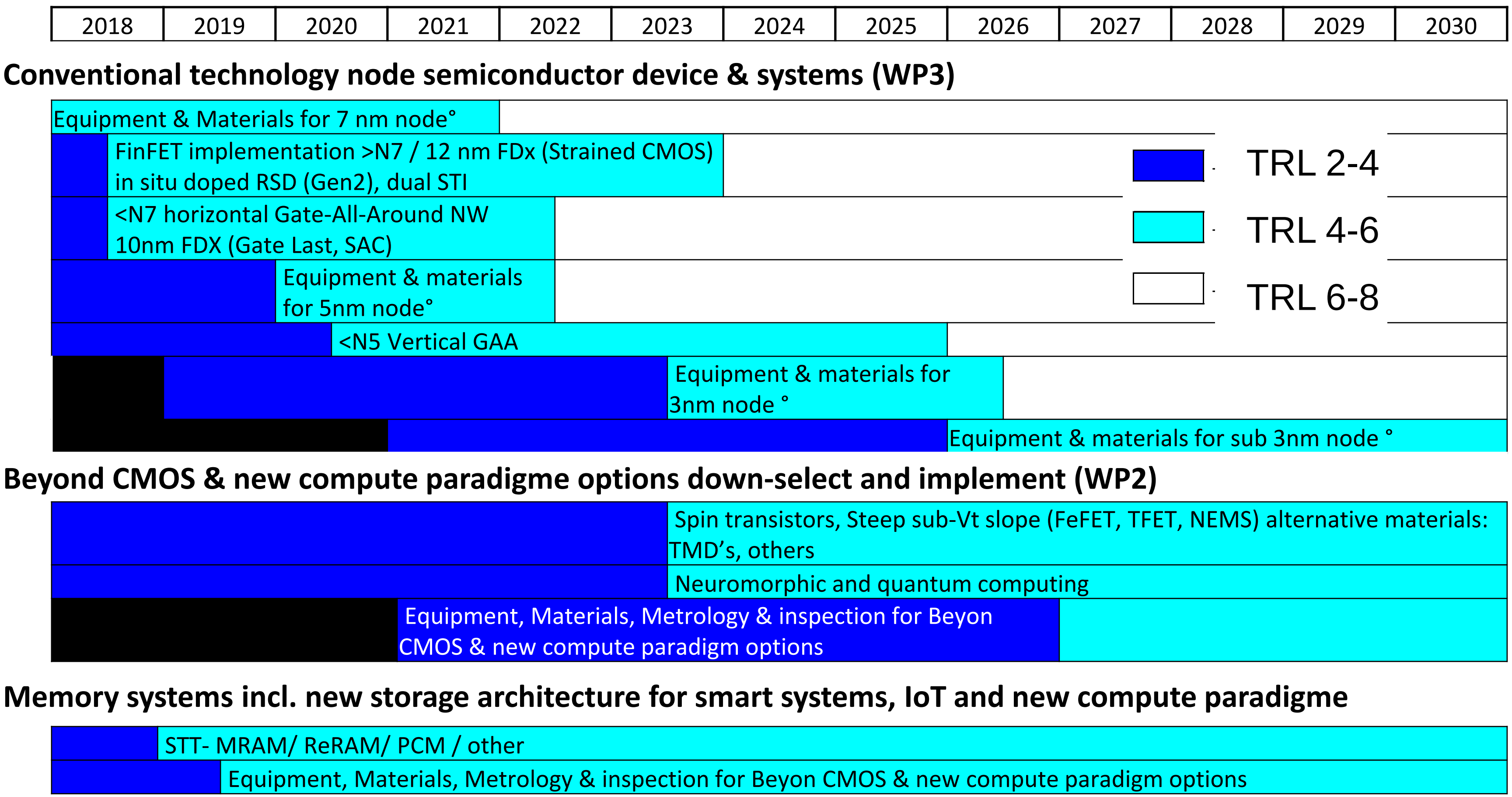
Highlights of System Design & Heterogeneous Integration

Europe has an excellent opportunity to drive the increase in System Knowledge bringing Europe to a leading position for System Level Applications

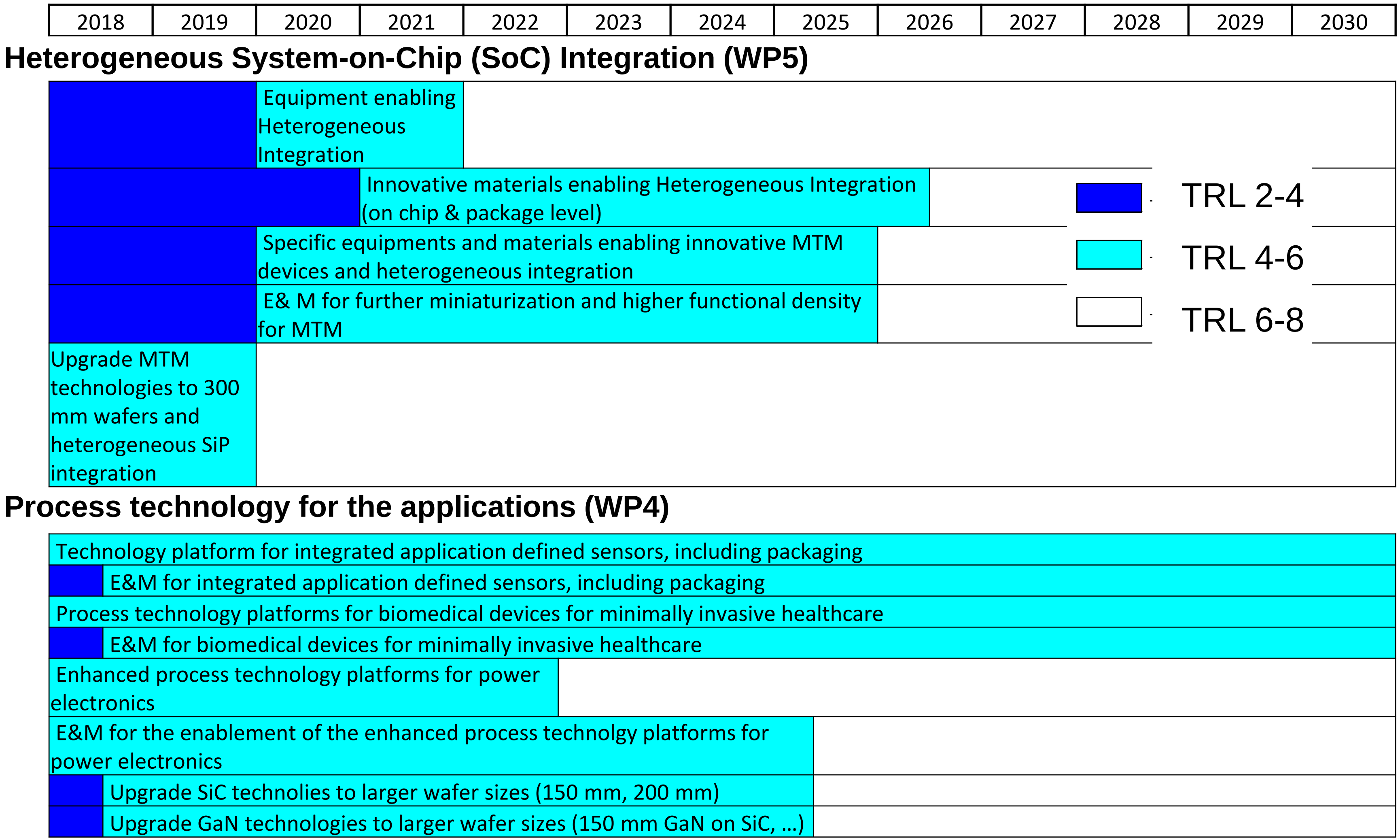
- The future is to move **from Embedded Computing to Embedded Intelligence** towards **Smart Adaptive Systems**
- **From Connected Devices to Distributed Embedded Intelligence** (System of Systems)
- The **working environment is part of the System** and needs to be taken into account
- **Energy Autonomy**
  - Push limits of **energy harvesters** to their fundamental optimum
  - **Integrate miniaturised storage** with high-energy density and high-power capability
  - **Power management**; holistic approach integrating hybrid energy harvesting and aiming at reducing consumption for each layer and as a whole (consumption when is necessary only)
- Definition of **Standards** for Interoperability. Openness of standard cannot prevent monetisation.
- **Re-Usability / Reconfigurability; also "zero maintenance"**

Equipment, Materials and Manufacturing Science

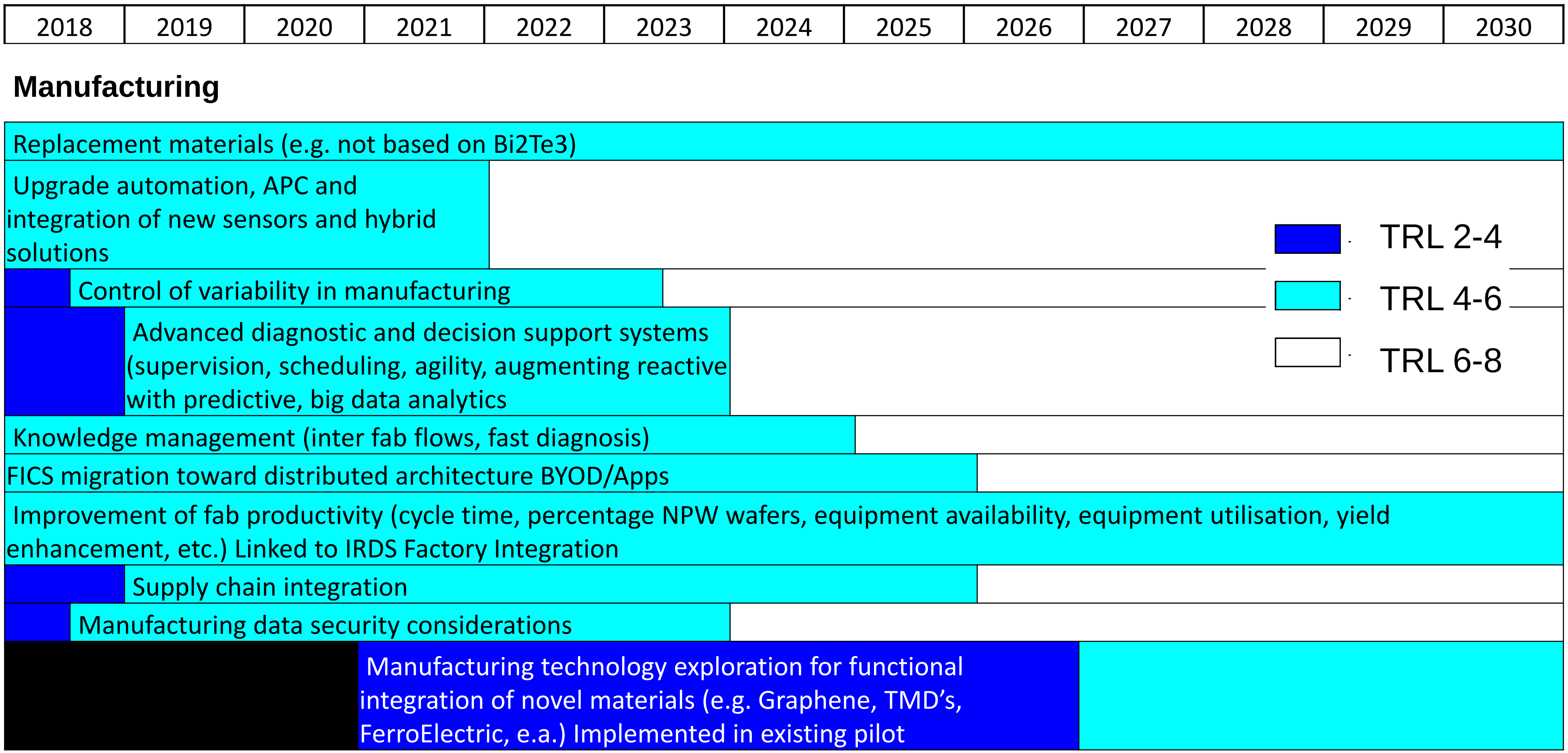
More Moore: Materials, Processes and Equipment



More-than-Moore: Materials, Processes and Equipment



Manufacturing



Highlights of Equipment, Materials & Manufacturing Science

- Execution of 2 Workshops and interaction with some leading equipment suppliers
  - More Moore and More-than-Moore considered from equipment, processes and materials perspective
    - Leading European equipment manufacturers need to follow- global roadmap for mainstream technologies (More Moore)
    - In other domains Europe is leading with specific process expectations, e.g. automotive, sensor, power, etc. (More-than-Moore)
  - Manufacturing science is incorporated as well

- Close interaction with all other NEREID technical areas (WP2-WP5)

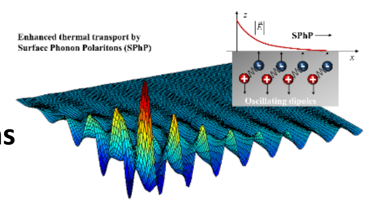
- ECSEL MASRIA used as basis for WP6 roadmap
  - Integration of outcome of all other NEREID work packages
  - Extension of time horizon until 2030

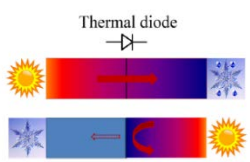
Beyond CMOS

Opportunities and Highlights in Beyond CMOS topics

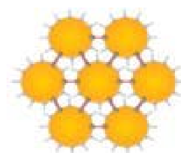
- New **state/hybrid state variables**: spin, magnon, phonon, photon, electron-phonon, photon-superconducting qubit, photon-magnon, etc…
- States can be digital, multilevel, analog, entangled…
- **Low power**: Spintronics, magnons, even entropy-based computing
- **High speed**: 2D systems, valleytronics (~100 fs relaxation times)
- Applications in information processing: **best suitable variables can be combined for efficient operation** (e.g. optomechanics for light to mm-wave conversion, neuromorphics for various pattern recognition tasks)
- Current TRLs: 1-3

Surface phonon polaritons



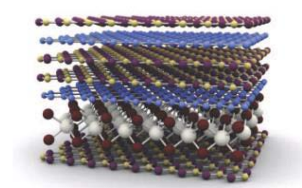


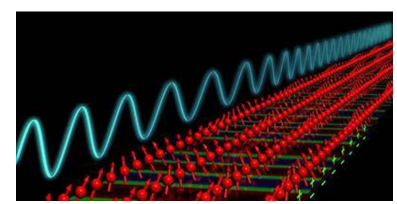
Thermal computing



Molecular electronics

2D materials



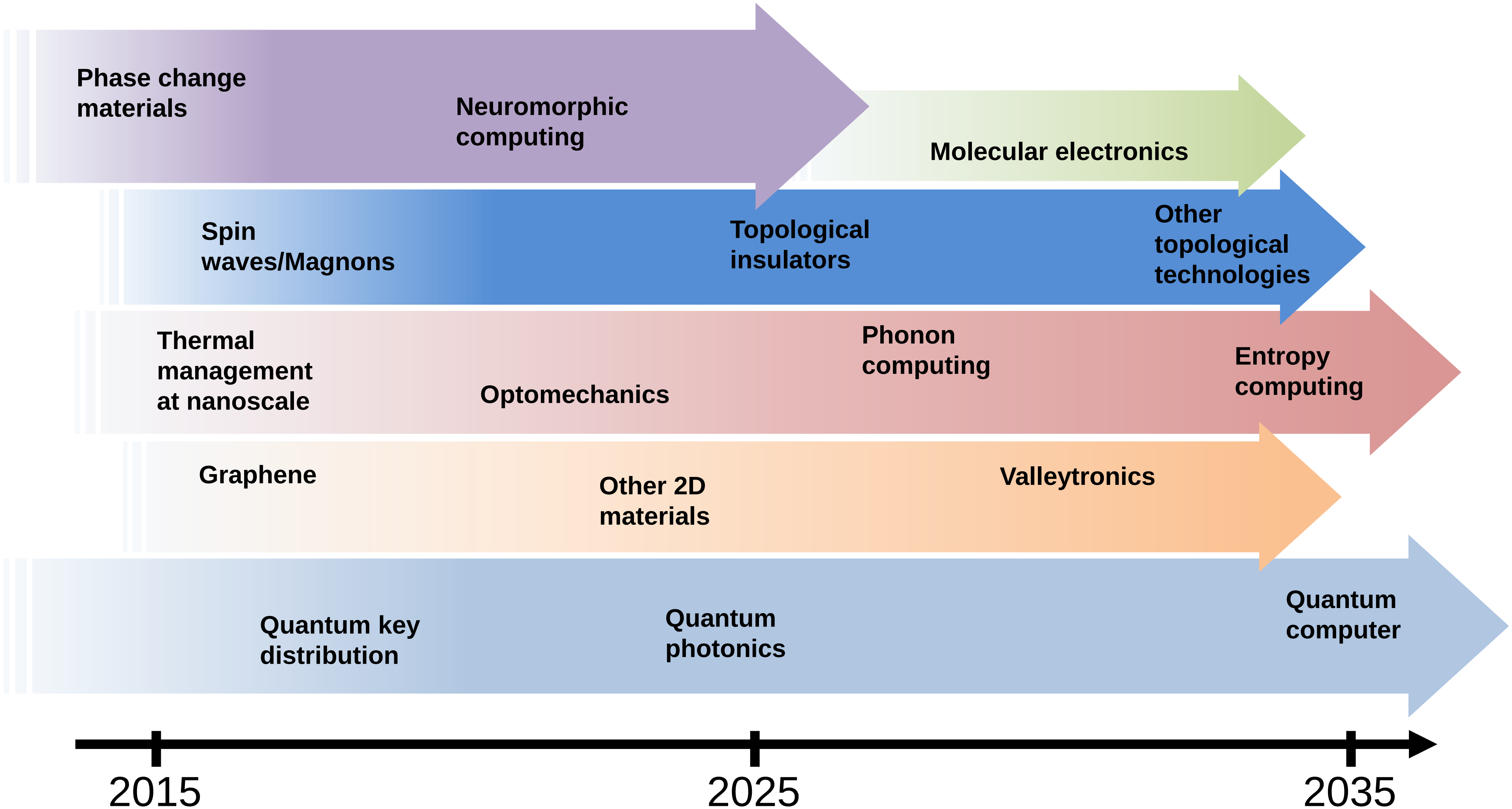


Magnons

Bottlenecks in Beyond CMOS Research

- **Manufacturability** (non-standard processes, bottom-up approach in many cases, tolerances, lab-scale)
- Operation conditions (temperature, magnetic field…)
- **Architectures** (interconnects, variability, amplification, various functions for logic operations, memory, programming)
- **Figure of Merits difficult to define before standardization** (different operation principles for each area/technology)
- Cultural and communication barriers between academic and ROs researchers, and stake holders: **community is very dispersed** and individual researchers can be “averse to application/TRL-speak”. **Projects in Beyond CMOS mainly ERC-funded** (individuals not consortium → Know-how transfer to industry probably less likely)

Beyond CMOS Roadmap



Recommendations for Beyond CMOS research

- Funding schemes needed in Europe that create an **ecosystem of small and medium size consortium-based projects** (FET open-, FET Proactive-like projects).
- **Foster synergies among these consortia-based projects** and establish links to the individuals holding ERC grants (common thematic workshops and working groups sharing one of more of materials, techniques, physics, potential applications), CSA's and project clusters with critical mass and win-win outcomes built in.
- **Identify common technological and design challenges** to most emerging Beyond CMOS approaches as first step to overcome them and advance to higher TRLs.
- **Identify industrial actors open to Beyond CMOS themes** and foster joint projects to submit to LEIT ICT or FP9 version of it.
- **Link up with potential flagships in ICT** (e.g., QuTec, Robotics, Big Data/AI, Health, Neuromorphic, Nanoengineering, etc.) and contribute to the next wave of innovations in those topics.
- Explore ways to break the cultural and communication barriers with industry, e.g., study the USA Semiconductor Research Council approach to academia and Beyond CMOS topics.

Next Steps

- Mid-term Roadmap available on: https://www.nereid-h2020.eu/roadmap

=> *Don't hesitate to contact us with any question or comment*

- Organization of next (and last) Domain/Cross-Domain/General Workshops in all Tasks/WPs

- Strengthening of the interaction with IRDS

- M36 (Nov. 2018): Final Roadmap

A fruitful European and International collaboration has been established and will be strengthened in the second part of NEREID targeting a very important long term Roadmap for the EU

Thank you !

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