SiNANO-NEREID Workshop:

Towards a new NanoElectronics Roadmap for Europe

Leuven, September 11th, 2017

WP2/Beyond CMOS

J. Ahopelto, VTT

C. M. Sotomayor Torres, ICN2

HORIZON 2020

Outline

1) CMOS vs Beyond CMOS
2) Methodology
3) Emerging technologies for Beyond CMOS
4) Alternative Computing Paradigms
5) Recommendations

Emerging Technologies for Beyond CMOS

CMOS technology

- •MOSFET
- •Complementarity (p- and n-type)
- •Digital (binary)
- •Boolean algebra, von Neumann architecture, generic
- •Well-established technology and design tools
- •Problem: Heat dissipation (clock frequency saturation, “dark silicon”, multicore)

Beyond CMOS (non-CMOS)

- •TRL 1-4, “in the lab”
- •Several potential technologies
- •Digital, multi-level, analog
- •Non-von Neumann architecture (e.g. memory and switch in the same node)
- •Case specific (e.g. optimised to perform a specific function, low power, speed…)
- •FOMs to be defined

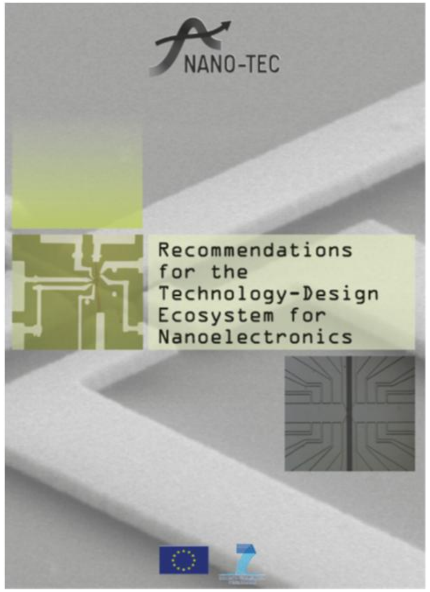
Outline

1) CMOS vs Beyond CMOS
2) Methodology
3) Emerging technologies for Beyond CMOS
4) Alternative Computing Paradigms
5) Recommendations

Methodology

Background

- NANO-TEC: Recommendations on Beyond CMOS Nanoelectronics (February 2013) (NANO-TEC, EU FP7 2010-2012, download at https://www.fp7-nanotec.eu/)
- Current and recent European projects and initiatives (FET, FET Proactive, Flagships…)


NANO-TEC

Recommendations for the Technology-Design Ecosystem for Nanoelectronics

The Beyond CMOS part of the NEREID Roadmap is based on output of two workshops arranged, and discussions during other NEREID meetings.

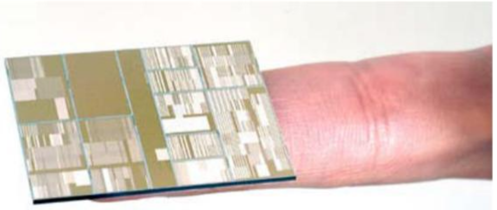
During the one-and-half day meetings invited experts gave talks on specific topics and dedicated Discussants and Rapporteurs helped finalising the summaries.

- Workshop 1: "Emerging technologies for Beyond CMOS“, May 2016 Helsinki
- Workshop 2: "Alternative Computing Paradigms“, May 2017 Barcelona

Outline

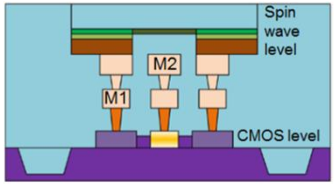
1) CMOS vs Beyond CMOS
2) Methodology
3) Emerging technologies for Beyond CMOS
4) Alternative Computing Paradigms
5) Recommendations

Emerging Technologies for Beyond CMOS - WS1

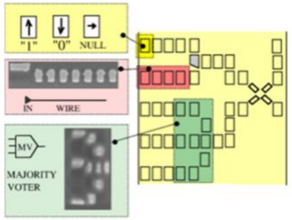


H. Riel: Future of computing

Keynote talks

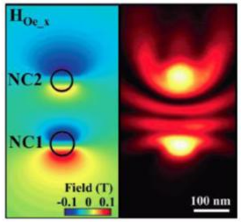


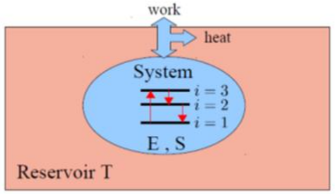
M. Heyns: Next generation CMOS technologies



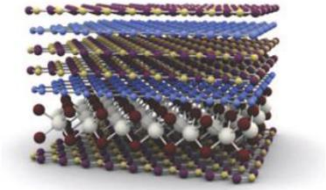
M. Graziano: Design aspects

J. Åkerman: Spintronics meets Magnonics

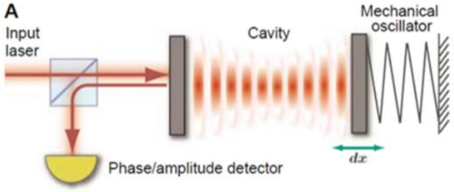




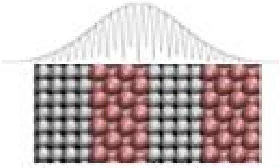
M. Esposito: Information thermodynamics



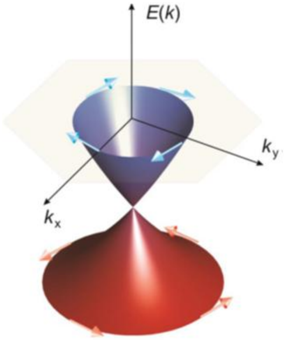
R. Enrstorfer: Dynamics in TMDCs



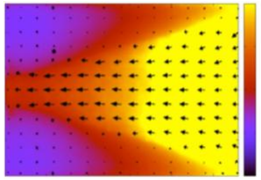
A. Martinez: Nano-optomechanics



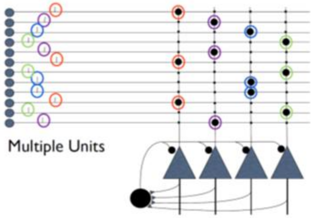
S. Volz: Heat transport at nanoscale



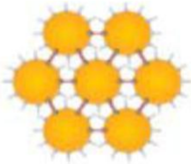
M. Costache: Topological insulators and Magnons



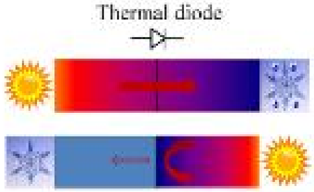
L. Colombo: Thermal transport in 2D materials



S. Thorpe: Neuromorphic computing with spikes



M. Calame: Molecular electronics



B. Li: Phononic computing

Outline

1) CMOS vs Beyond CMOS
2) Methodology
3) Emerging technologies for Beyond CMOS
4) Alternative Computing Paradigms
5) Recommendations

From WS1 to WS2

Main considerations for workshop 2 topic selection:

- ❖ Research area maturity level
- ❖ Continuous progress from concept towards a computing technology.
- ❖ Examples:

- Magnonics is emerging and Spintronics is at a higher TRL.

- 2D materials & Valleytronics are at TRL 1 level – not covered in WS2

- Optomechanics is emerging and Si quantum photonics is at a high TRL.

From WS1 to WS2

In WS 2 attention turned to:

- State variables different form charge and or new FET concepts radically different from those in More Moore
- Architectures replacing or complementing von Neumann computing architecture
- Matching alternative computing paradigms to applications they could be particularly suited for.

European Portfolio on Emerging Computing Paradigms

EC has invested 0.7 bn euros in 511 R&D project on alternative computing paradigms in FP7 and H2020. Current topics:

Category	Coverage
Quantum computing	Technologies to build qubits and transport information between them, including algorithmic and architecture
Molecular electronics	Solid-state information processing functions built on organic molecules including biomolecules; molecular spintronics
Spintronics	Spin-based electronics and related materials
2D materials	Carbon-based and transition metal dichalcogenides, as well as electronic and spintronic functions based on these
Extended & beyond CMOS	Non mainstream semiconductor transistors, including III-V materials, steep-slope devices, single electron transistors, etc.
Neuromorphic computing	Hardware implementation of neural networks, analogue and digital, architectures and applications

From: E Fribourg-Blanc, WS2

Introduction: Examples of European initiatives

- HUMAN BRAIN FLAGSHIP
- QUANTUM TECHNOLOGIES Flagship to be (CSA proposals in 2017).
- NEUROMORPHIC CSA (2018)
- SPINTRONICS FACTORY Network
- Several recent/running projects on alternative computation – contributed to WS2, e.g.:
  - MOSQUITO
  - NeuRAM3
  - RAMP
  - MOSAIC

From IRDS 2016 BCMOS - ERD white paper

Example of “Difficult Challenge” 2020-2030

“Continue functional scaling of information processing technology substantially beyond that attainable by ultimately scaled CMOS. Enable new computing paradigms by device technology breakthrough.”

Example of “Summary of Issues and Opportunities”

“Invent and reduce to practice a new information processing technology eventually to replace CMOS as the performance driver.

Ensure that a new information processing technology has compatible memory technologies and interconnect solutions.

A new information processing technology must be compatible with a system architecture that can fully utilize the new device. Non-binary data representation, non-Boolean logic, or non von Neumann architectures may be required to employ a new device for information processing, which will drive the need for new system architectures.”

Unchanged from ITRS 2.0

From IRDS 2016 BCMOS - ERD white paper

Example of
“Potential
solutions”

> “… superconducting electronics (SCE), e.g., SFQ (Single Flux Quantum) and AQFP (Adiabatic Quantum Flux Parametrons), are suitable for applications where advantages such as speed, power, or energy efficiency outweigh disadvantages such as cryogenic temperature operation, low maturity, and lower density.”

Unchanged from ITRS 2.0

Concept: Quantum nanomechanics

Key research questions or issues

- How big must the thermal driving field (driven fluctuations) be compared to the signal level?
- How to define an operational temperature in the nano-scale?
- How does entropy change with varying distance between nanogaps and how important is it?
- Potential to reach THz in NEMs-based computing with low power operation.
- Potentially ultra-sensitive NEMs-based sensors.

Potential for application or Application needs and Impact for Europe

- Harvest fluctuations instead of fighting them for computing (entropy-based computing?)
- NEMs-based concepts could deliver cooling solutions by enhancing efficiency via driving the TE generator.
- Integration with spintronics.

Concept: Quantum nanomechanics

Technology and design challenges

- What are the tolerances of thermal energy and fluctuation-based components and circuits?
- Other schemes to apply the concepts of NEMs-generated thermoelectricity?
- How to reach the ground state to move to quantum computation?
- Scalability?
- Need for ultra-clean devices.
- Control of nano scale motion.
- Do we have a better chance with hybrid computation using one or more of these approaches and or with other state variables?

Definition of FoMs (quantitive or qualitative))

- Switching times
- Energy as information (magnitude, frequency, …)

Concept: Quantum Photonics

Key research questions or issues

- Photons do not suffer from decoherence so highly suitable for computing. Single photon detectors for Si quantum photonics, currently rely on hybrid III-V/Si detectors & superconducting nanowires.
- Some photonic schemes require low temperature operation (2 K). In phase change photonic circuits for computation, encoding information in the signal transmitted power allows brain function emulation.

Potential for application or Application needs and Impact for Europe

- Quantum Computation, neuromorphic computing and their applications (see Concept on Neuromorphic Computing).
- Si-based quantum photonics can use linear circuits, e.g., 8-qubit processor demonstrated

Concept: Quantum Photonics

Technology and design challenges

- More theory is needed to develop alternative architectures.
- Two-photon absorption losses in detectors need speed vs loss compromise in optical switching.
- Full integration of all components on a chip for quantum computing and phase change materials for opto-neuromorphic computing.
- Long-term stability of photonic schemes must be improved, especially phase change materials, which require high peak temperatures.
- Development needed on the cooling system technology.
- Footprint and scaling challenges for phase change photonic computation.

Definition of FoMs (quantitive or qualitative)

- Sources: brightness, jitter and indistinguishability.
- Circuits: Losses in circuit and connections. Chip homogeneity else balancing e.g. beam splitters, will cause loss of efficiency. State fidelity when processing.
- Detectors: efficiency, speed, dark count rate, jitter.

Concept: Quantum Photonics

Other issues and challenges, and interaction with other Tasks/WPs

- Similar to those faced by solid-state quantum computation.
- Need novel architectures and more algorithms that harness the possibilities of quantum computing.
- WP5 Manufacturing & Equipment: photonics-related manufacturing lags behind that of nanoelectronics. Needs research infrastructure or access to modern nanofabs.

Preliminary Recommendations

- Covered by the Quantum Technology flagship
- Europe has a leading position in Si-based quantum photonics and SoA research in phase-change nanophotonics.

Concept: Spintronics

Key research questions or issues:

- STT-MRAM almost ready for volume production and
- Expect huge reduction of the power consumption.
- How is this technology better than CMOS?
- Lowering critical current for writing.

Potential for application or Application needs and Impact for Europe

- Expected full replacement of e-FLASH by STT-MRAM technology in the next few years.
- MRAM usual applications: non-volatile operations, memories, memristor, sensors, bioaplications and energy harvesting.

Technology and design challenges

- No logic gate available

Concept: Spintronics

Technology and design challenges

- No logic gate available

Definition of FoMs

- CMOS compatible
- Fast operation (~ 5ns)
- Large lifetime memory ~ 1020 cycles at 0.6V
- Insulating nature with control damping

Preliminary Recommendations

- Stronger industry-academia interactions are needed to identify jointly solutions to challenges.

Concept: Spin waves - Magnonics

Key research questions or issues:

- ❖ Wavelength down to nm and frequency up to THz, 300 K operation and long propagation length (~ cm).
- ❖ Compatibility with waveguide concept.
- ❖ Efficient non-linear effect.
- ❖ No Joule heat involved.
- ❖ Not yet compatible with CMOS.
- ❖ Enhancement of existing detecting techniques.

Potential for application or Application needs and Impact for Europe

- ❖ Computation operation, energy harvesting (Spin Seebeck effect), memories among many others.
- ❖ Size reduction

Concept: Spin waves - Magnonics

Technology and design challenges

- Reduce the temperature dependence of magnetic anisotropy for high T operation.
- Reduce the size, time of operation and power.
- Fabrication processes size and reliability
- Slow group velocity (c/100)
- Expensive material and difficult to grown (YIG)
- New insulators with control damping.
- High attenuation (six order of magnitude higher than for photons in a standard optical fibre)

Technology: Entropy as information

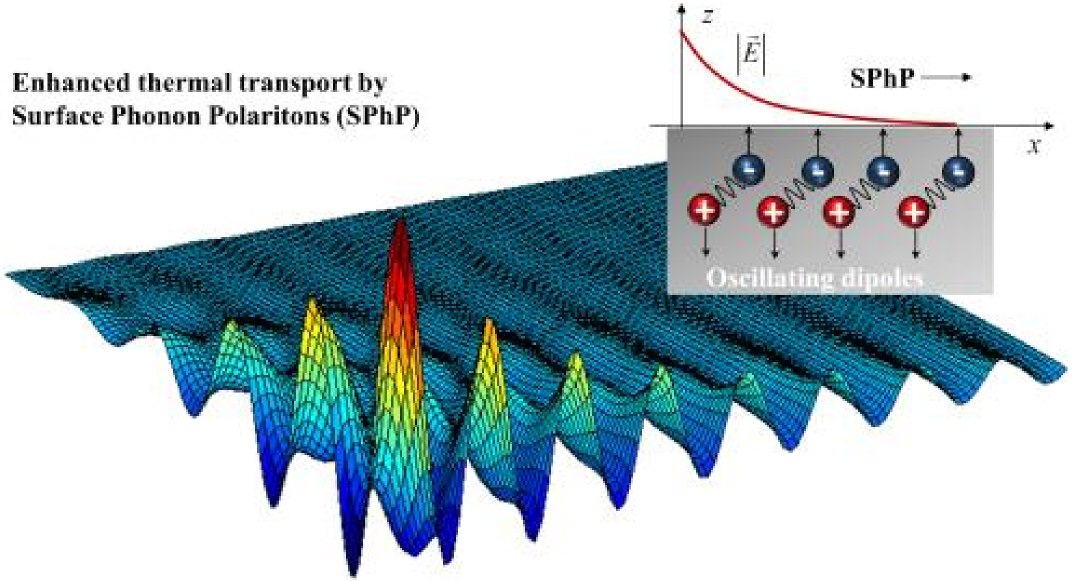
Thermal energy in the Nano scale plays a crucial role in nanoelectronics because:

- Understanding thermal process and heat transport can address (solve) thermal management in current (opto)electronics (generate less heat, transport it more efficiently to heat sinks, etc.
- Engineering nano-scale thermal transport can potentially lead to an increase in frequency beyond 5 GHz.
- Understanding phonon physics may lead to a breakthrough in technologies of Phase Change Materials (non-volatile memories, multi state for switching, …).
- In the medium term, it will enable exploitation of properties affected by interaction with phonons (RT operation). For example nanomechanics and opto-mechanics.
- In the long term the knowledge gained can advance Brownian computing and open the door to a larger range of entropy-based computation.

Concept: Thermal computing

Key research questions or issues

- Potential for energy conversion in the nano-scale near-field radiative heat not yet tested, except in realisations of surface-phonon polaritons and not in sufficiently wide range of technological-relevant materials.
- Surface-phonon polaritons have been demonstrated to transmit thermal energy over 100 um's on the surface.
- How to apply the concept of surface-phonon polaritons to interfaces?



SPPs: Near-field heat propagation over 100s um.

- Boundaries and their implications between the picture of signals performing a random search a way out in a maze of a circuit determined by topology and the disordered-induce Anderson localisation?

Concept: Thermal computing

Potential for applications

- Surface-phonon polaritons could be applied to enhance efficiency of thermal photovoltaics, magnetic switching and phase changes.
- Design of future computers and neural networks.
- Potential to lower power consumption by harvesting fluctuations.

Technology and design challenges

- Can we attempt evanescent wave engineering?
- What are the tolerances of thermal energy and fluctuation-based components and circuits?

Definition of FoMs (quantitive or qualitative)

- Energy as information (magnitude, frequency, …)

Preliminary Recommendations

- Industry needs to be convinced of the value that this community can bring, especially in low power in the near future and in sub $k_B T$ information processes in the long term.

Concept: Brownian computing

Key research questions or issues

- Brownian computing demonstrated use of fluctuations in circuits based on SETs, through a random search mechanism, also counting, testing of conditional statement, memory and arbitration of shared resources.

Potential for application

- Design of future computers and neural networks.
- Potential to lower power consumption by harvesting fluctuations.
- Brownian motion is used in less complicated device and to obtain universality.

Technology and design challenges

- What are the tolerances of thermal energy and fluctuation-based components and circuits?

Concept: Brownian computing

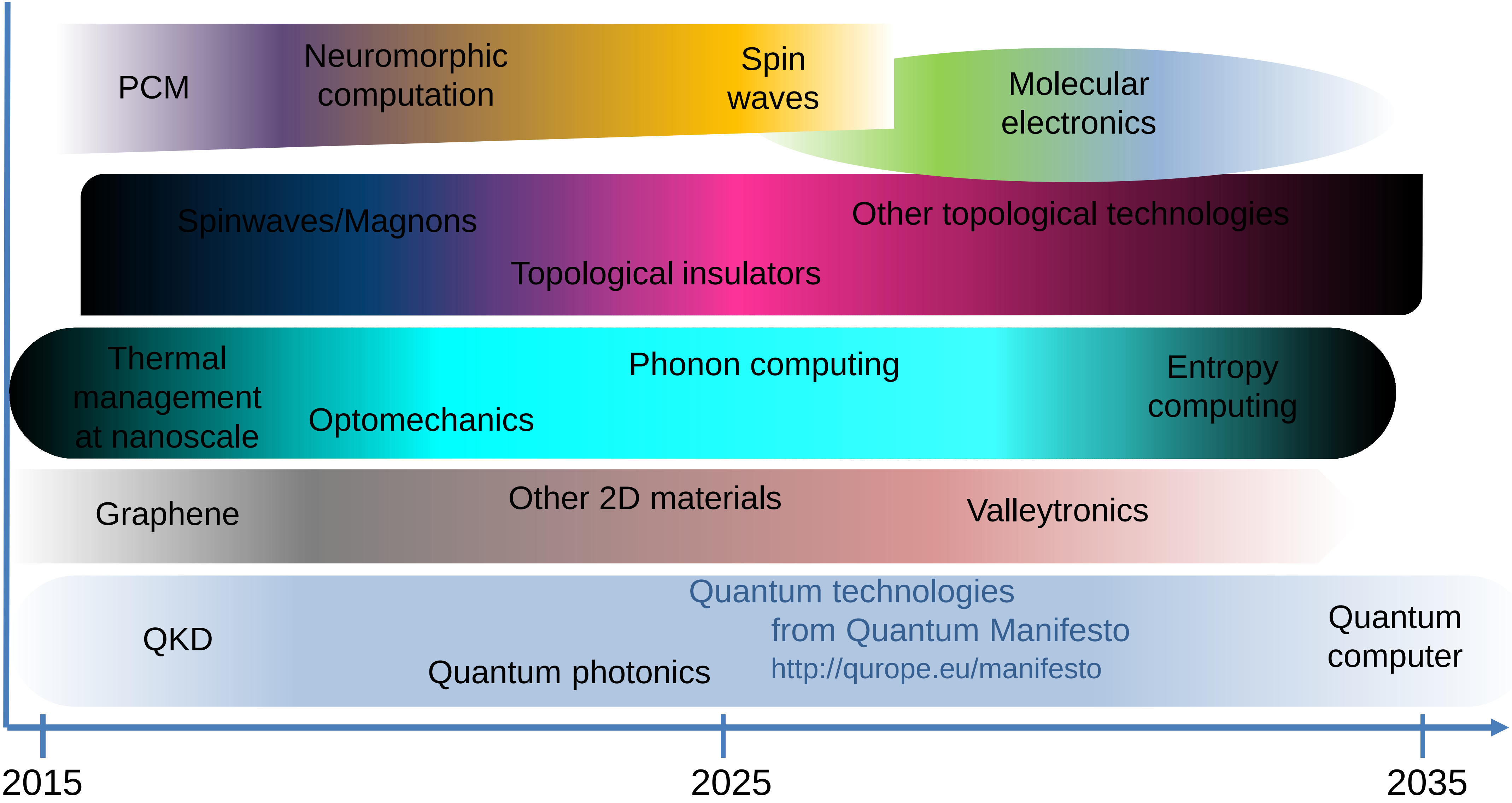
Definition of FoMs

- Orders of magnitude demonstration in power consumption.
- Switching times
- Orders of magnitude demonstration in power consumption.
- Switching times

Outline

1) CMOS vs Beyond CMOS
2) Methodology
3) Emerging technologies for Beyond CMOS
4) Alternative Computing Paradigms
5) Recommendations

Mapping of the possibilities of Beyond CMOS technologies



PCM

Neuromorphic computation

Spin waves

Molecular electronics

Spinwaves/Magnons

Other topological technologies

Topological insulators

Thermal management at nanoscale

Phonon computing

Entropy computing

Optomechanics

Graphene

Other 2D materials

Valleytronics

QKD

Quantum technologies from Quantum Manifesto
http://qurope.eu/manifesto

Quantum photonics

Quantum computer

2015

2025

2035

Recommendations

- A shift of paradigm in thermal management research is of paramount importance to: (i) overcome “heat death” of current nanoelectronics, and (ii) in long term lay foundations for entropy-based information processing.
- Development of dedicated hardware for neuromorphic functionalities is important for, e.g., IoT.
- Strengthen efforts in 2D materials (for TFETs, optoelectronics, valleytronics and topological structures, requires manufacturing and tooling).
- Magnonics has potential to low power and compact information processing systems.
- Stimulate industrial interest