NANO-TEC

Identification-Benchmarking-SWOT Analysis-Recommendations
of

Beyond CMOS Technologies

Coordination Action in FP7 Contract no. 257694

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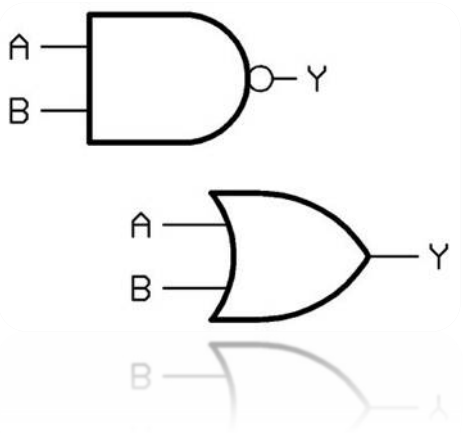
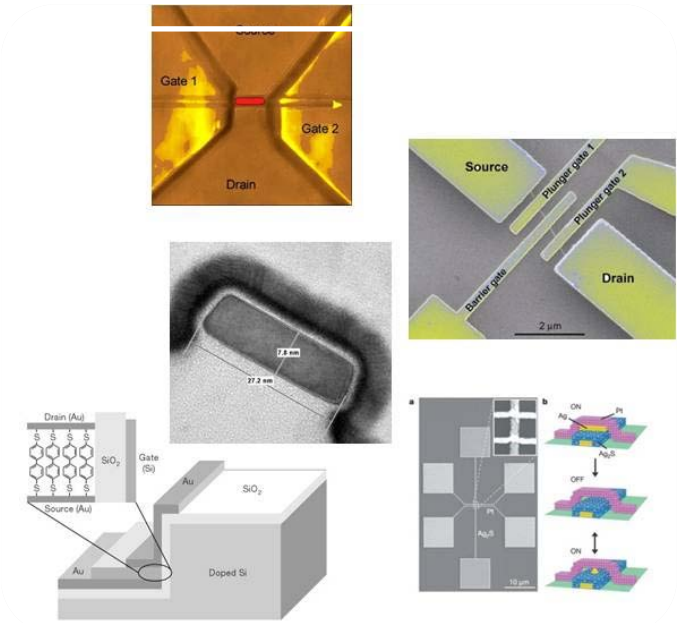
OUTLINE

- Motivation
- Methodology
  - International Cooperation
- Examples of outcome
- Summary

MOTIVATION

- CMOS era coming to its end? Probably not in coming tens of years
- Large number of emerging ”Beyond CMOS” device concepts
- Can those be used for data processing (computation/memory/interconnects…)?
- Device fabrication: Manufacturability? Variability? Reliability?
- Architectures, design tools, libraries?





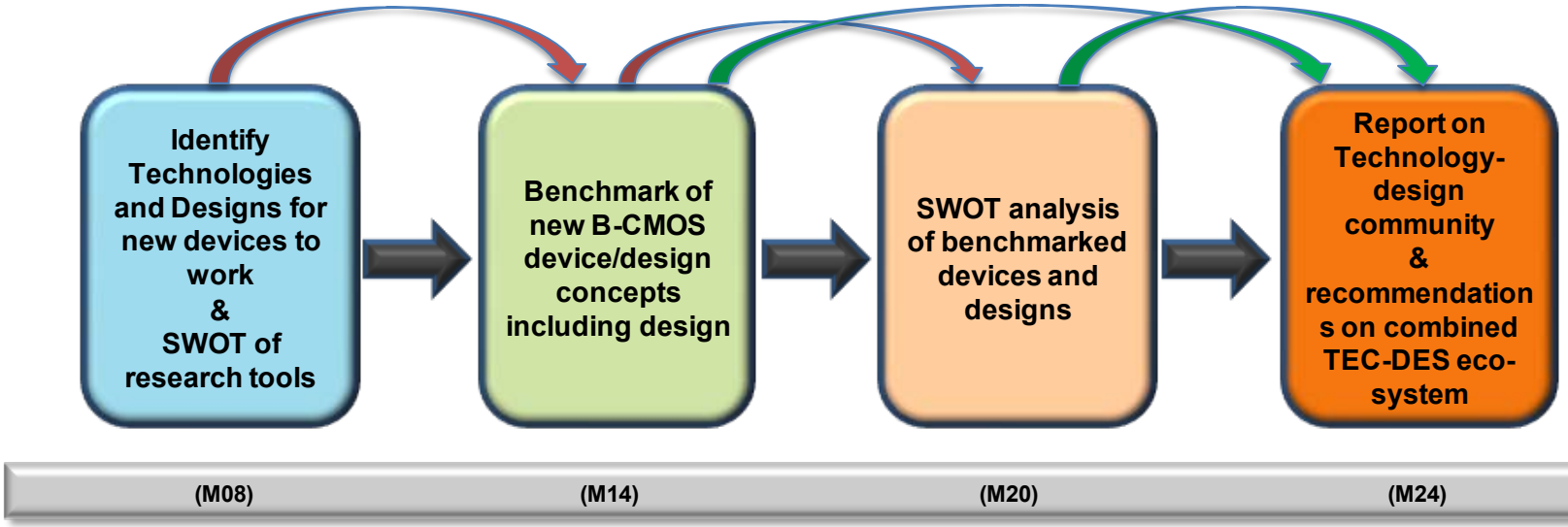
PROJECT CONCEPT

Aim is to:

- Identify, benchmark and SWOT analyse the emerging device concepts and technologies
- Bridge the gap between the emerging technologies and design
- Provide recommendations for future actions in this field in Europe

METHODOLOGY

Series of Workshops was arranged to carry out the mission



Input from broad range of experts was collected

- Academia; EU projects on nanoelectronics, literature, conferences, position papers
- Research organisations; LETI, IMEC, SRC (ITRS)
- Industry; IBM, HP, Micron
- NANO-TEC consortium

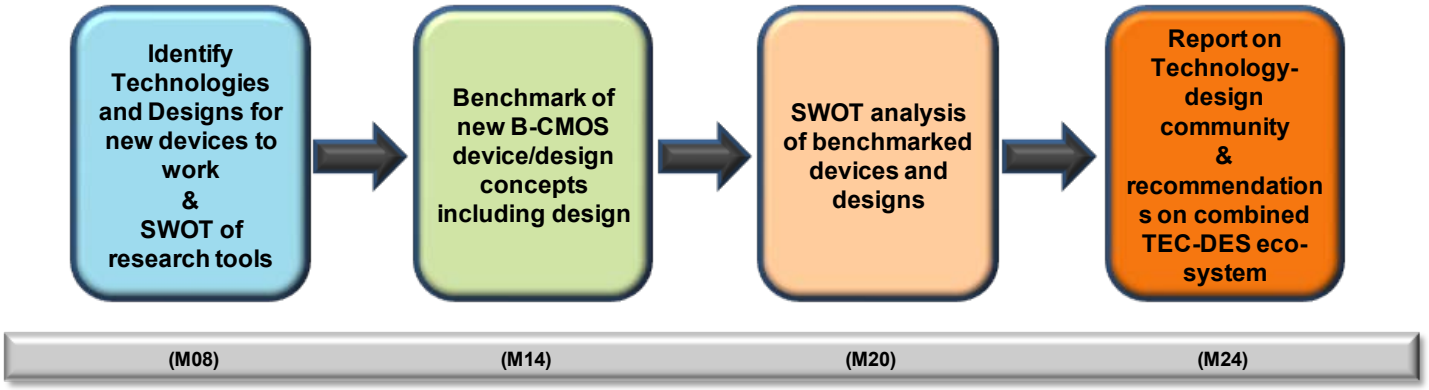
→ **Recommendations**

METHODOLOGY

In the Workshops:

- Invited talks on various fields
  - Speakers from Europe, US and Asia
  - Discussants
  - Rapporteurs
  - Working groups
  - Panels
- Advisory Board

First excercise to Identify/Benchmark/SWOT Beyond CMOS devices in Europe



NANO-TEC Advisory Board

Michel Brillouet (CEA-LETI)

Livio Baldi (Micron)

Roger de Keersmaecker (IMEC)

Danilo Demarchi (Polytechnic Univ Torino)

Very engaged board members!

NANO-TEC WORKSHOP SERIES

WS1: Identify Technologies & Designs for new devices to work

Granada, 20-21 January 2011

NANO-TEC WORKSHOP SERIES: WS1

Speakers

Nanotechnology trends for the next decade
J Welser, SRC

Compound semiconductor-based electronics
W Stanchina, Pittsburg

Carbon-based electronics
J.-Sun Moon, HP

Bridge to Design
P Lugli, TU München

Silicon-based electronics
M Brillouet, CEA LETI

Analogue-Mixed signal design
H Graeb, TU München

Spintronics
S Valenzuela, ICN

Molecular Electronics/ Quantum Computers
G Wendin, Chalmers

NANO-TEC WORKSHOP SERIES

NANO-TEC WORKSHOP SERIES: WS2

Speakers

Molecular Electronics
D Vuillaume, CNRS

MEMS
Lina Sarro, TU Delft

Solid State Quantum Computing
Jaw-Shen Tsai
NEC &The Riken Institute

Spintronics
J Åkerman,
Gothenburg U & NanoSC

Nanowires
Heike Riel, IBM Zurich

Memristors
J Grollier, CNRS-Thales

Graphene
J Kinaret, Chalmers University of Technology

NANO-TEC WORKSHOP SERIES: WS2

Panel discussion on how new device concepts could meet the needs set by the design community and vice versa

Sandip Tiwari

Lars Hedrich

Paolo Lugli

Chair
Dan Herr

Diederik Verkest

NANO-TEC WORKSHOP SERIES

WS3: SWOT analysis of benchmarked devices and designs

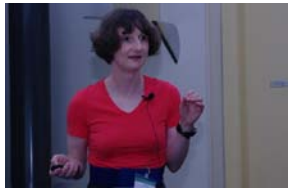
Lausanne, 30-31 May 2012

NANO-TEC WORKSHOP SERIES: WS3

Speakers

Solid-state Quantum Computing *Goran Wendin, Chalmers, Gothenburg*

Molecular Electronics *Prof. Dr. Sense Jan van der Molen, Leiden Univ.*



Nanowires *Dr. Heike Riel, IBM*

Spintronics *Prof. Dr. Charles Gould, University of Wuerzburg*

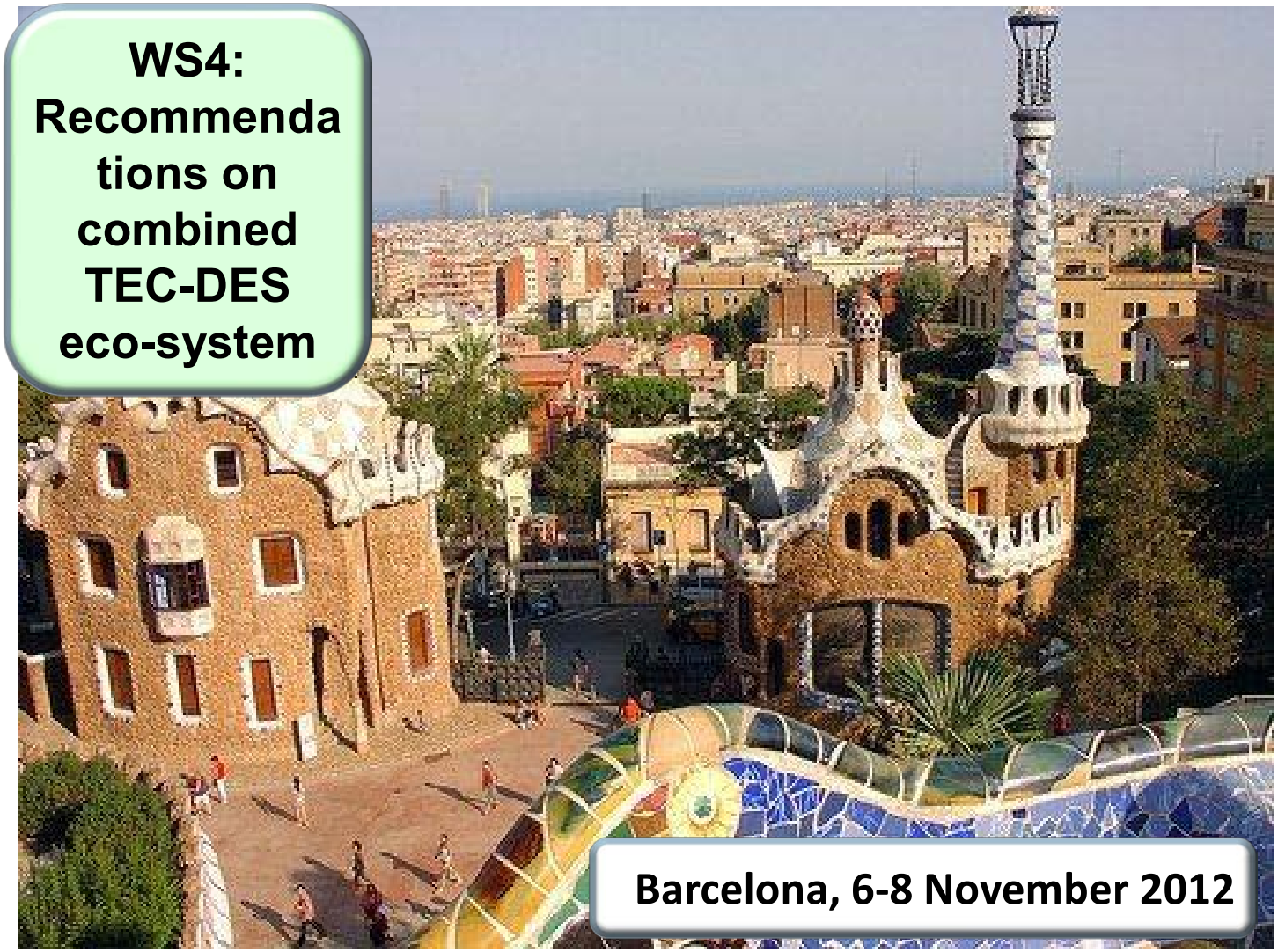
Graphene *Prof. Dr. Max Lemme, KTH, Stockholm*

MEMS *Dr. Michael Gaitan, NIST, Gaithensburg, MD, U.S.A.*

Neuromorphic Computing *Dr. Julie Grollier, CNRS-Thales, Palaiseau*

NANO-TEC WORKSHOP SERIES

WS4: Recommendations on combined TEC-DES eco-system



Barcelona, 6-8 November 2012

NANO-TEC WORKSHOP SERIES: WS4

Speakers

Nanoelectronics in EU Horizon 2020, Dirk Beernaert, EC

SRC views on nanoelectronics, Victor Zhirnov, SRC

Neuromorphic computing as a new computing paradigm Prof. Dr Simon Thorpe, CNRS

Topological insulators Prof. Dr. Laurens Molenkamp, Univ. Wuerzburg

Panel Discussion: "Design Tools for Beyond CMOS technologies" Mustafa Badaroglu, IMEC

Wolfgang Rosenstiel, edacentrum GmbH

Paolo Lugli, Technical University of Munich

Sandip Tiwari, Cornell University

Chair Livio Baldi

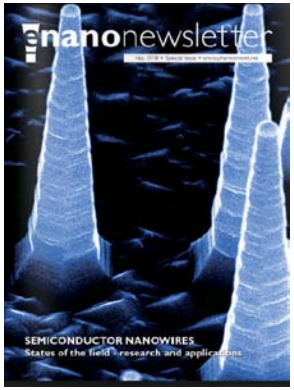
Position Papers by

2008 CNTs

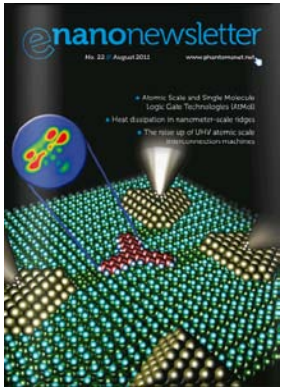
2008 NEMs

2009 Modelling

Position papers can be downloaded from www.phantomsnet.net/nanoICT/

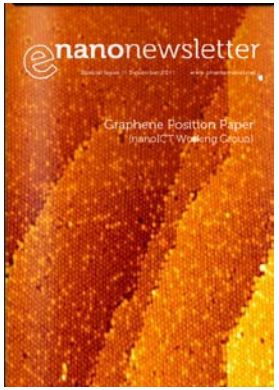


2010 Nanowires



2011 Single molecule technology

2011 Nanophotonics-Nanophononics



2011 Graphene

Identifying the Beyond CMOS Technologies

WS1: Identify Technologies & Designs for new devices to work

In the discussions after the Workshop 1 the following technologies were selected

- **Molecular Electronics**
- **MEMS**
- **Solid-State Quantum Computing**
- **Spintronics**
- **Nanowires**
- **Memristors**
- **Graphene**

Benchmarking exercise in US

Circuits used to Benchmark Device

- Inverter with a fanout of 4
- 2-input NAND with a fanout of 1
- 32b adder

Bernstein et al., Device and Architecture Outlook for Beyond CMOS Switches, Proc. IEEE 98 (2010) 2169.

BENCHMARKING

WS2: Benchmark of new Beyond-CMOS device and design concepts

All the speakes filled the Table in advance

NANO-TEC

Benchmarking Beyond CMOS Devices

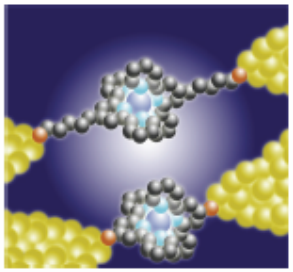
Technology	[Wires, graphene, MEMS etc… please insert name]
Gain Signal/Noise ratio Non-linearity	
Speed Power consumption	
Architecture/Integrability (Inputs/outputs, digital, multilevel, analog, size etc.)	
Other specific properties	
Manufacturability (Fabrication processes needed, tolerances etc.)	
Timeline (When exploitable or when foreseen in production)	

Aim to a broader scope:

- No direct comparison with CMOS
- Allow for other concepts in addition to digital switches
- Challenge the design community

Example: Molecular Electronics

single molecule electronics

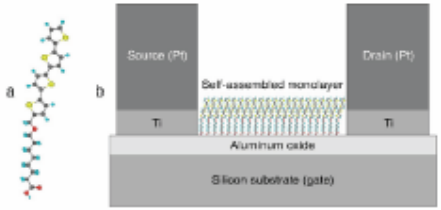


L < a few nm
t < a few nm

basic science
knowledge development

no foreseen applications
in a reasonable time-scale

self-assembled molecular electronics



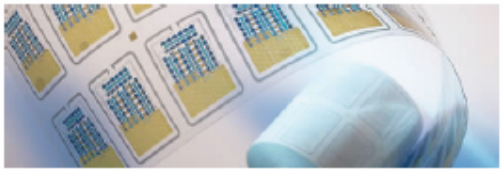
L ~ tens nm - µm
t < a few nm

basic science
knowledge development

possible applications
foreseen

SAMFET

thin-film molecular electronics



L > µm
t > few 10 nm

plastic electronics
(OLED, OFET, OPV)

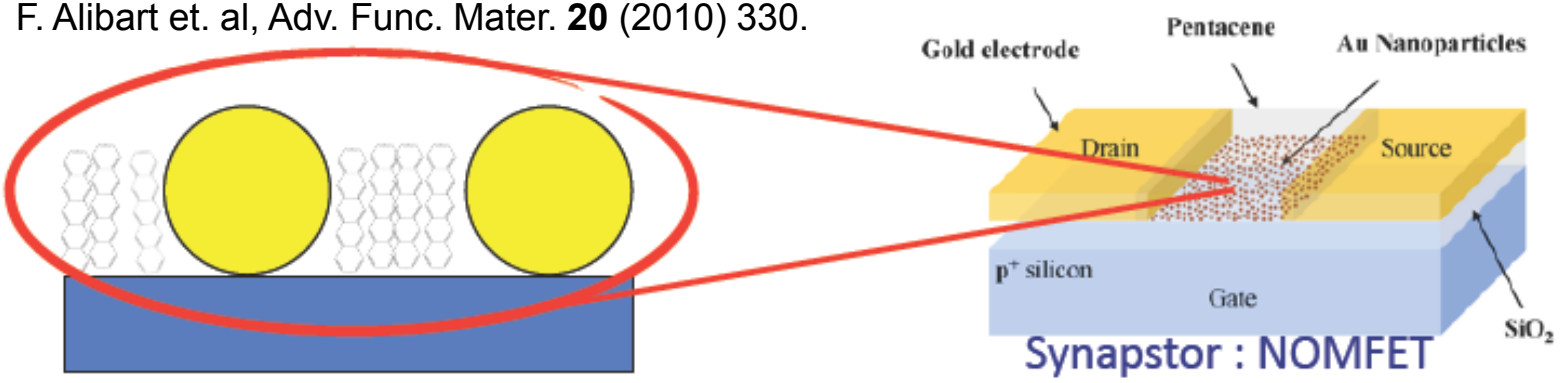
some products already
commercialized

Example: Molecular Electronics

Benchmarking Beyond CMOS Devices

Technology	Molecular Electronics D. Vuillaume, CNRS & University of Lille
Gain **Signal/Noise ratio**	Ok with SAMFET (to be optimized), 2-terminal junction: low current Noise not yet studied (a few publications)

F. Alibart et. al, Adv. Func. Mater. **20** (2010) 330.



(Fabrication processes needed, tolerances etc.)	Defect control? Large variability (but not a problem if we envision artificial neural networks)
Timeline **(When exploitable or when foreseen in production)**	> 5 – 10 years (if ever?)

SWOT Analysis

WS3: SWOT analysis of benchmarked devices and designs

Tables were compiled in the Working Groups during the Workshop 3

Molecular electronics

Strengths	Weaknesses
• Making use of quantum effects at room temperature • Natural nanometer scale • Programmable functionalities (vs. light, E-field, temperature)	• Low stability at room temperature • Low conductance per molecule • Electrodes define true dimensions • Low performance compared to Si MOSFET
Opportunities	**Threats**
• Multimolecular devices (by self-assembly: SAMs, networks) • Sensors and specific functionalities connected to CMOS • Control of quantum interference	• Mostly basic research yet • A niche technology at most • Low interaction with design communities

Neuromorphic Computing

Strengths	Weaknesses
• Low power • Speed • Non-volatility	• Need to improve OFF/ON ratio • Memristors physics
Opportunities	**Threats**
• Possibility of 3T devices (ex atomic switch) • New reconfigurable architectures • Logic in memory	• Not sufficient endurance

RECOMMENDATIONS

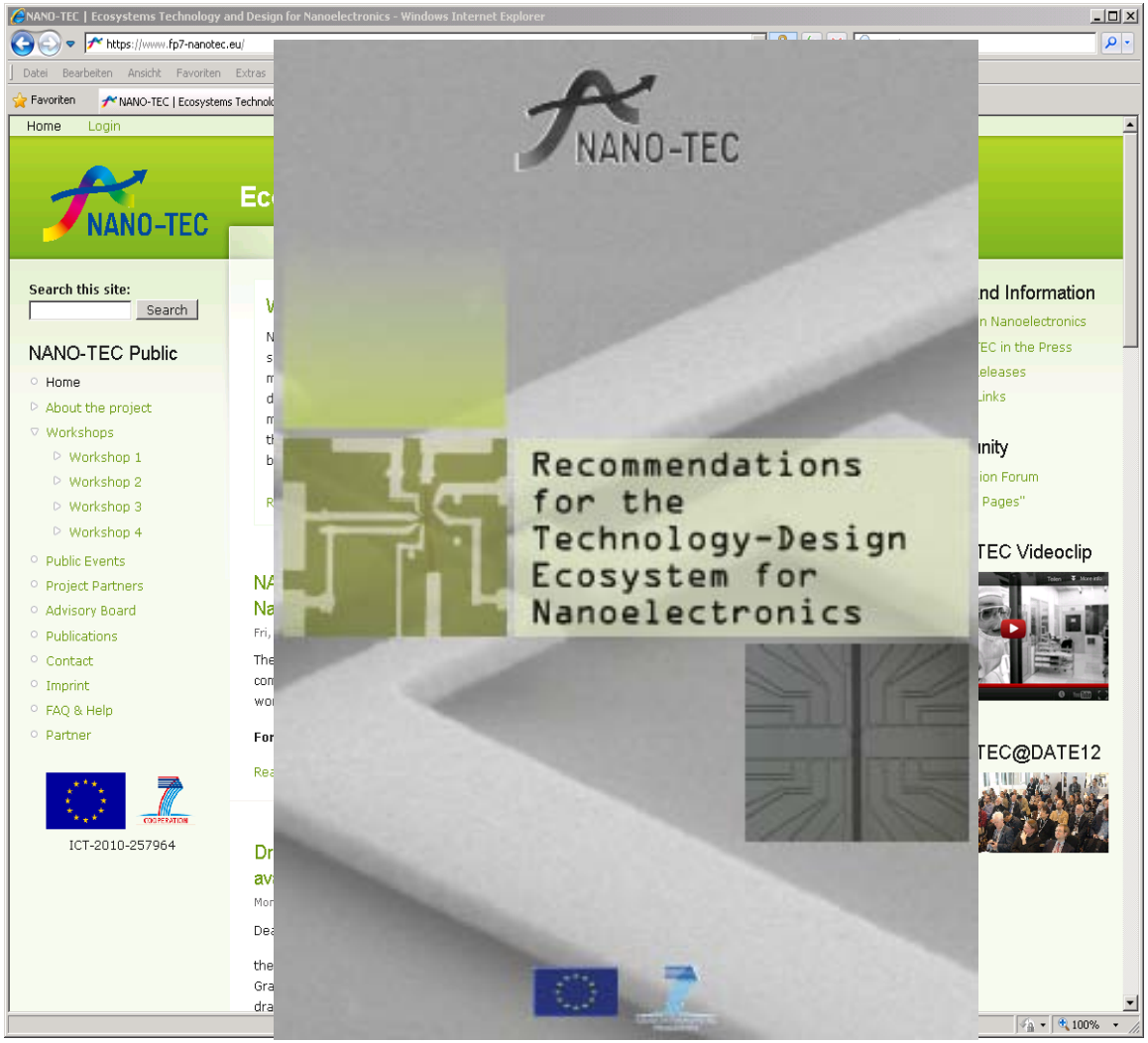
WS4: Recommendations on combined TEC-DES eco-system

The Recommendations were drafted in the Working Groups during the Workshop 4 and finalised by the Rapporteurs

Recommendations for:

- **Technology and design for information processing in Beyond CMOS**
- **Charge-based state variable technologies**
- **Non charge-based state variable technologies**
- **Technology and Design of new computing paradigms**
- **The ecosystem technology in Beyond CMOS in Europe**

Download Recommendations From the Web Site



www.fp7-nanotec.eu

- **Workshop presentations**
- **”Yellow Pages”**
- **Discussion Forum**
- **Recommendations**
- **Etc.**

RECOMMENDATIONS

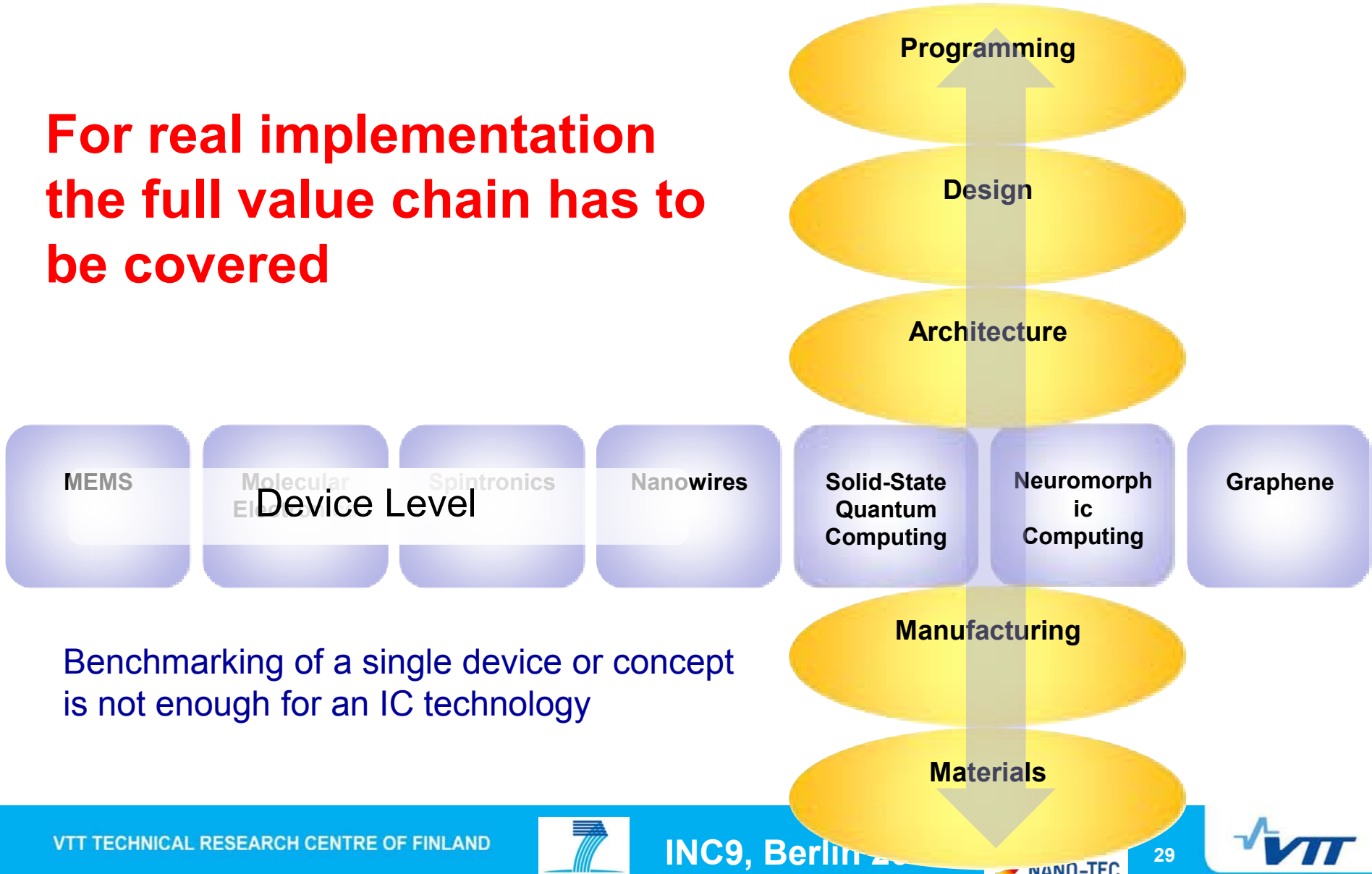
For *all state variables*, be these charge-based or not, it is recommended that research towards a better theoretical understanding of the underlying physics and material science of nano-scale devices is supported towards potential breakthroughs.

It is recommended to continue the exploration of *novel computation approaches in general*. In particular, a *comparative and dynamic analysis of the interaction between design and the emerging computation technologies* as an integral part of the R&D efforts would provide Europe with a valuable and probably decisive advantage.

The consortium finds that strong motivation and support are needed in order to facilitate *communication and cooperation between design and technology actors* from academia and industry. The consortium recommends that a couple of pilot projects are launched addressing explicitly not only the technical aspects but, above all, methodological aspects of this interactions with one or two well defined examples of novel state variables and a specific application each.

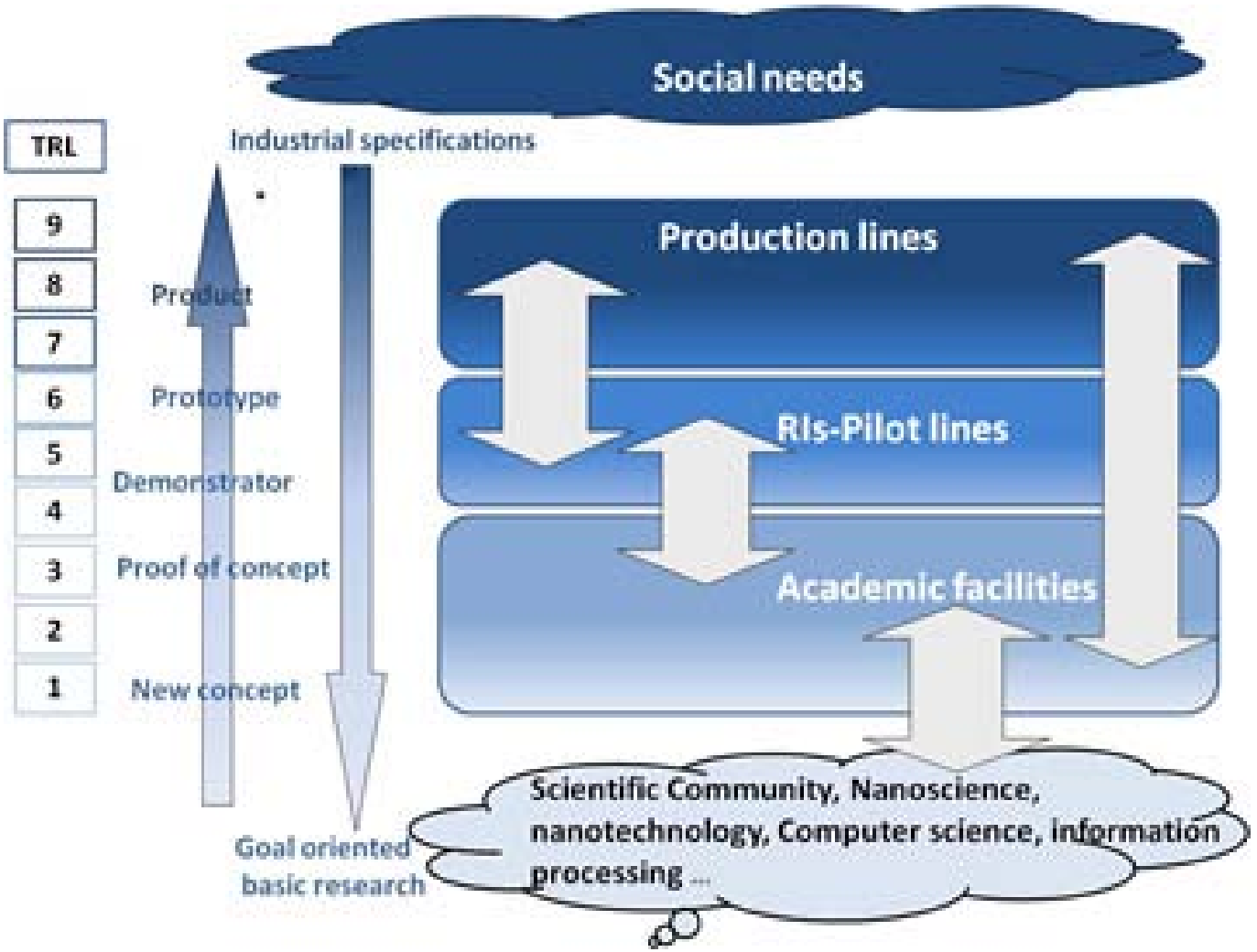
Vertical Value Chain

For real implementation the full value chain has to be covered



Benchmarking of a single device or concept is not enough for an IC technology

Ecosystem Technology



RESEARCH INFRASTRUCTURES

Establish an European Research Infrastructure Network for Beyond CMOS technologies

- Research Institutes
- Academic facilities
  - Flexible processes
  - Relaxed specs

SUMMARY

- First excersise in Europe on Beyond CMOS devices
- Broadband international cooperation
- Very open and positive spirit
- Recommendations
- NANO-TEC was a start…

Acknowledgements

- Speakers, Colleagues in the Panels and Advisory Committee
- All the participants
- NANO-TEC Consortium
- The European Commission (Contract no. 257694)