Smart Diaspora 2023

SMART ENERGY SOLUTIONS FOR THE NEXT GENERATION INTERNET-OF-THINGS

Mircea Modreanu

Tyndall National Institute-University College Cork, Ireland

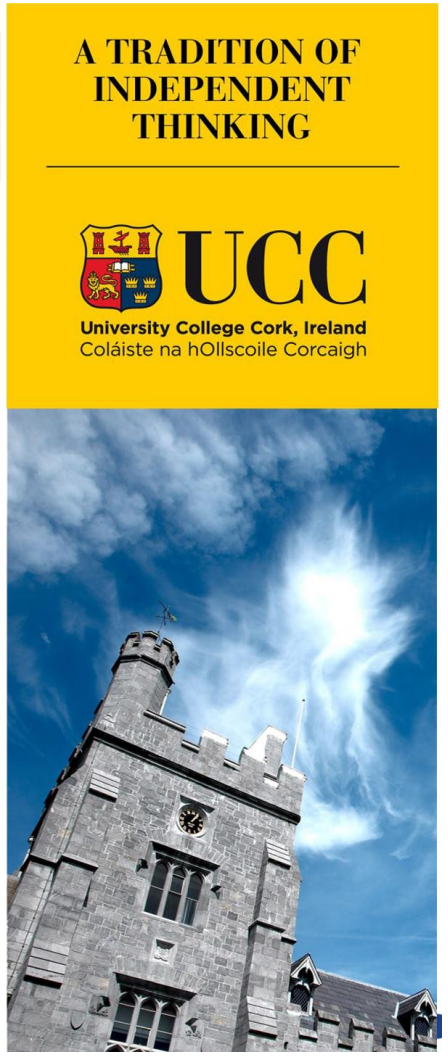
Outlook

- Introduction:
  - Tyndall National Institute and University College Cork
- Smart Cities
  - The 4th Industrial Revolution-*European Concept*
  - Society 5.0- *Japanese concept*
- Internet of Things *future and stringent needs*
- The need for material research as trigger for new device architecture
- Smart Materials platform developed within an European Innovation Council project, NANO-EH
  - Nanoscale hafnium zirconium oxide ferroelectric
- NANO-EH's multi-source EM energy harvesting/energy storage platform integrated on Si substrate
- Conclusions

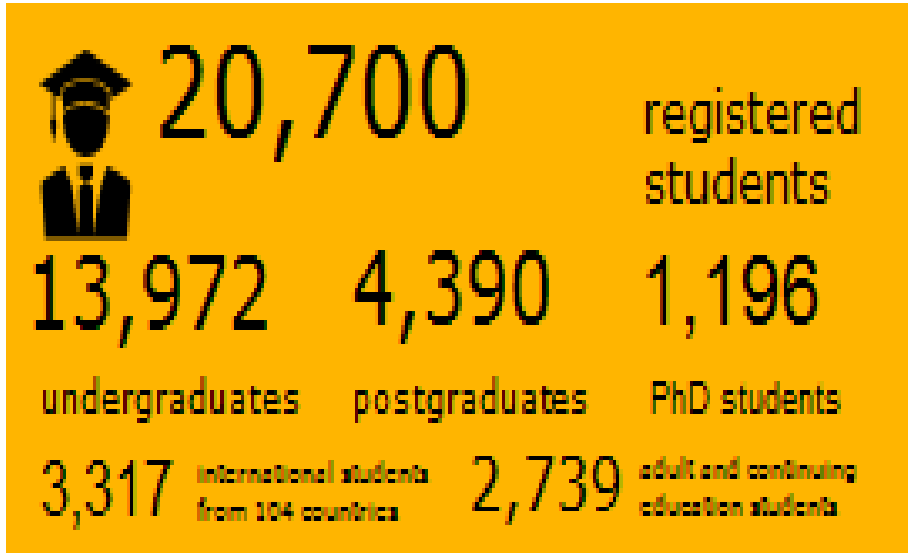
Tyndall National Institute and University College Cork

University College Cork – quick facts

- Comprehensive university – Est. 1845
- Ranked in the Top 2% of universities worldwide
- Wide range of internationally recognised degrees
- Ireland's first five star university (*QS Stars*)
- 13 subject areas ranked in world's top 300 (QS)
- Sunday Times University of The Year 2016 and 2017
- First university in the world awarded the international green flag for environmental friendliness
- 84% of higher degree and diploma graduates are in employment or further study



UCC AT A GLANCE



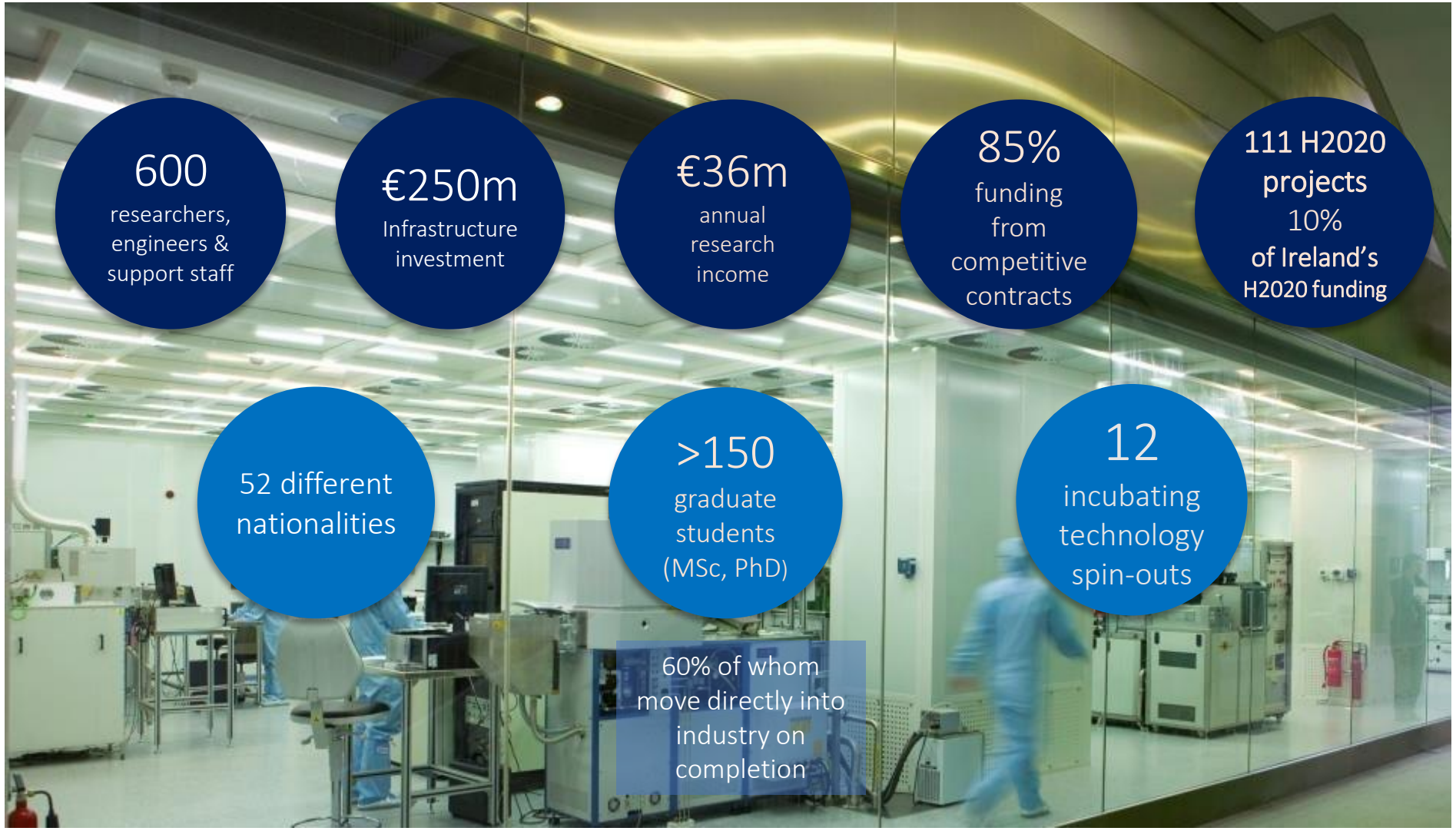
Tyndall National Institute in brief

- **Tyndall is Ireland's largest research institute. A leading European Research Centre in Integrated Information and Communications Technology hardware and systems**
- **Established in 2004, created from the National Microelectronics Research Centre (NMRC) – Est. 1982**

- **Host to:** iERC International Energy Research Centre; MCCI Microelectronic Circuits Centre Ireland; IPIC Bringing Photonics to Life; CONNECT Networks of the Future
- **Our Expertise:**

  - Smart Sensors & Systems
  - Optical Communication Systems
  - Mixed Signal & Analog Circuit Design
  - Microelectronic & Photonic Integration
  - Semiconductor Wafer Fabrication
  - Nano Materials & Device Processing

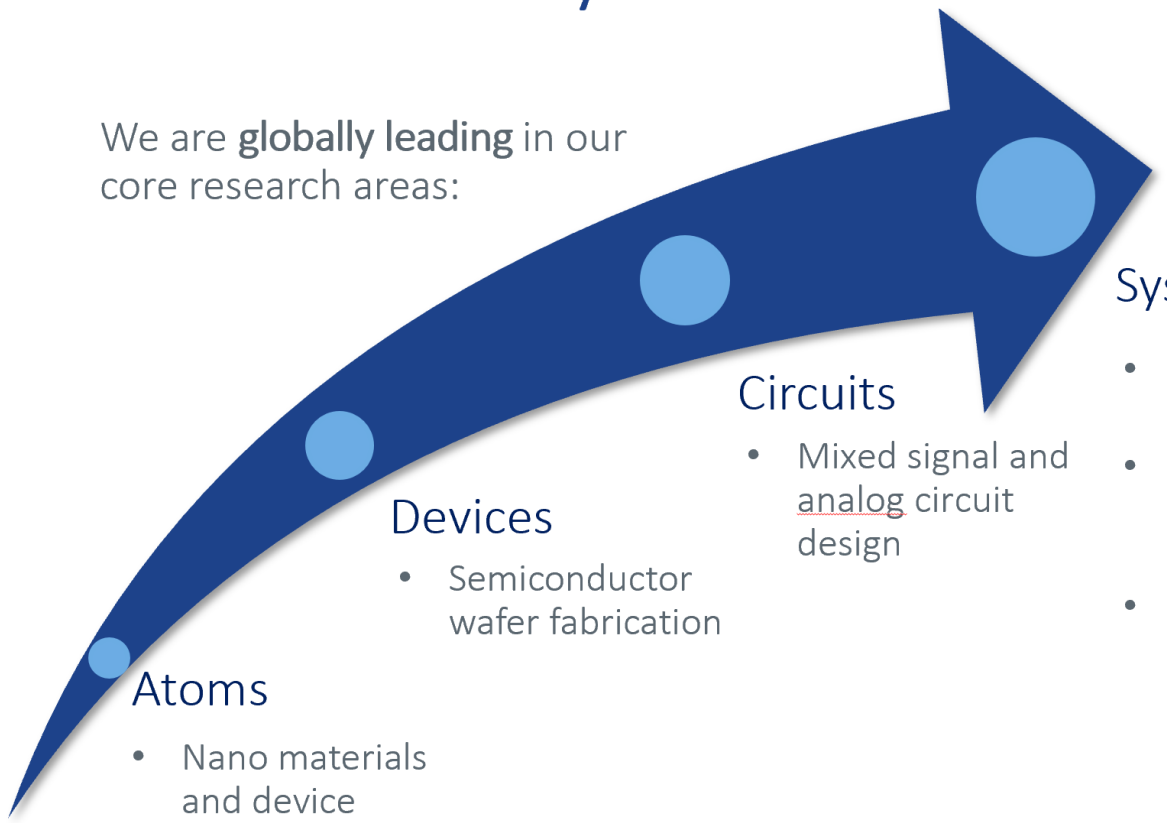
Tyndall National Institute at a glance
UCC and Ireland flagship Research Institute



Tyndall's *research philosophy*

From atoms to systems

We are **globally leading** in our core research areas:



Atoms

- Nano materials and device processing

Devices

- Semiconductor wafer fabrication

Circuits

- Mixed signal and analog circuit design

Systems

- Smart sensors and systems
- Optical communication systems
- Microelectronic and photonic integration

Tyndall National Institute at a glance
UCC and Ireland flagship Research Institute

Agritech & Food Security

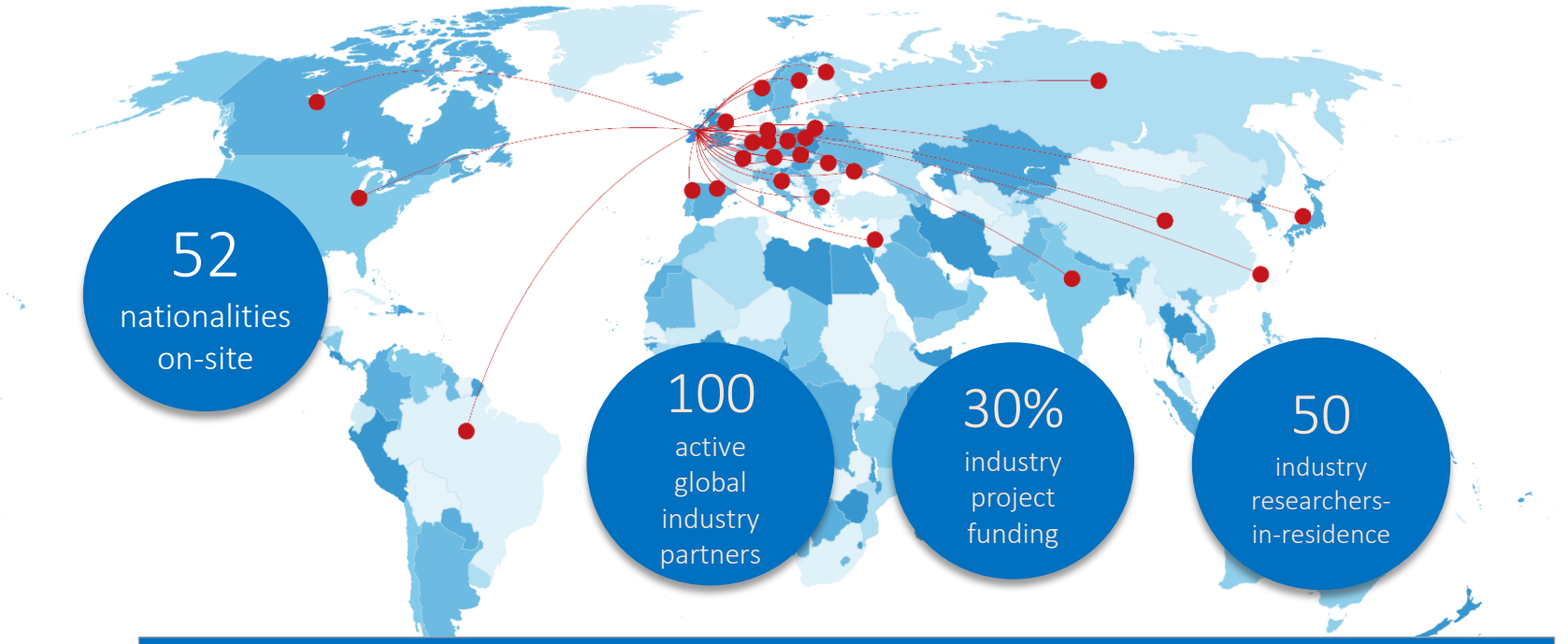
Health & Life Sciences

Deep technology research at the convergence of micro & nano-electronics, photonics and materials, involving chemists, physicists, engineers and manufacturing personnel

Micro & Macro Energy

Information & Communications

Tyndall Global industrial impact



Industrial partner recognition: 3 of 12 Intel *Global Outstanding Researcher Awards* have been awarded to Tyndall researchers

On-going-collaboration with Romanian's Academics@SMEs

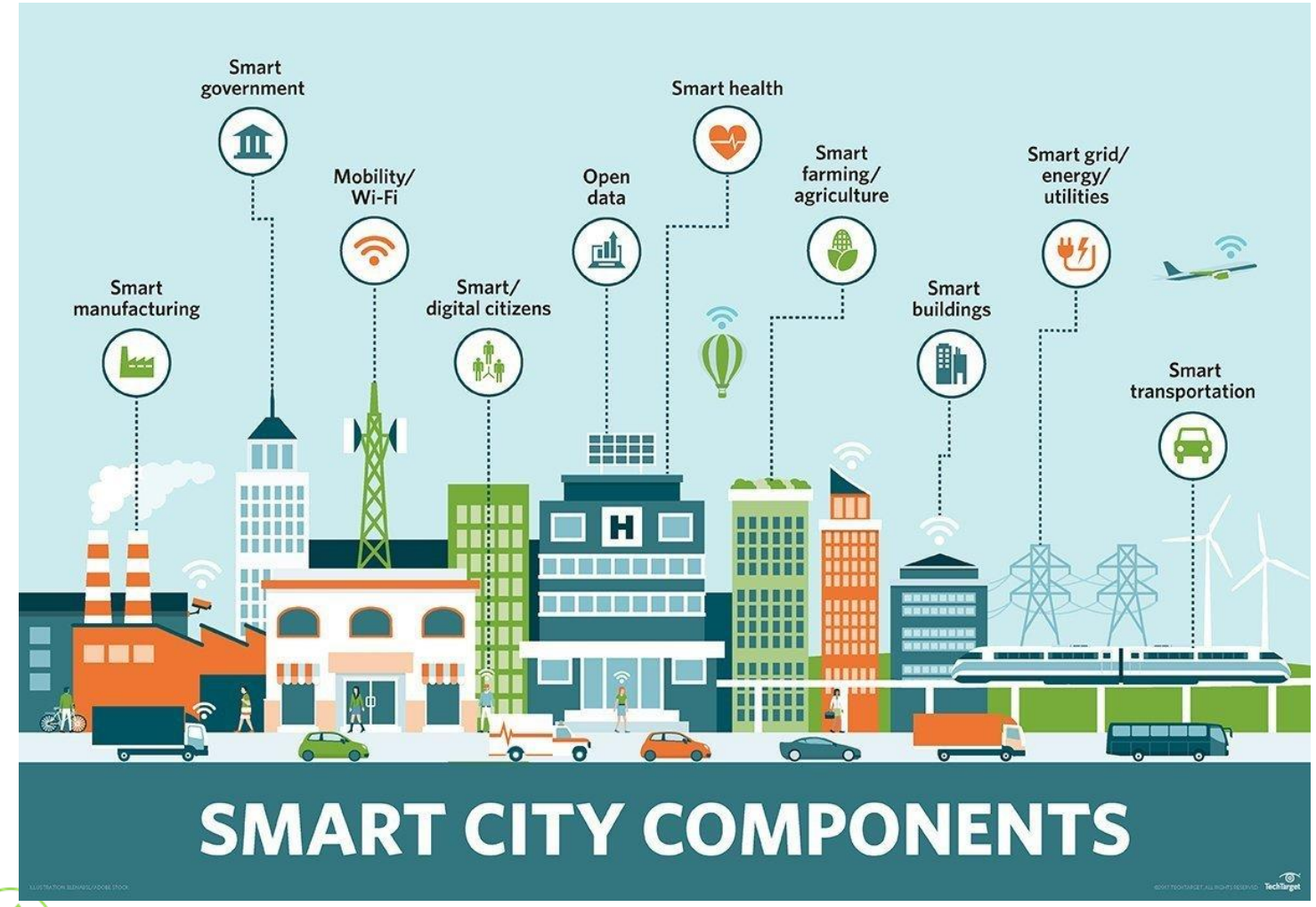
Currently 4 EU projects, one ICT, one EIC FETProactive, one EIC FETOpen and one Twinning action

NANO components for electronic SMART wireless systems	NANOMATERIALS ENABLING SMART ENERGY HARVESTING FOR NEXT-GENERATION INTERNET-OF-THINGS	ACTIVE OPTICAL PHASE-CHANGE PLASMONIC TRANSDIMENSIONAL SYSTEMS ENABLING FEMTOJOULE AND FEMTOSECOND EXTREME BROADBAND ADAPTIVE RECONFIGURABLE DEVICES	NETWORKING CENTER FOR EXCELLENCE IN NANOELECTRONIC DEVICES FOR AIR MONITORING

Some other EU projects under evaluation including here an ERC Synergy in a second stage…

Smart City of the future builds on *Internet of Things concept*

The 4th Industrial Revolution-European Concept

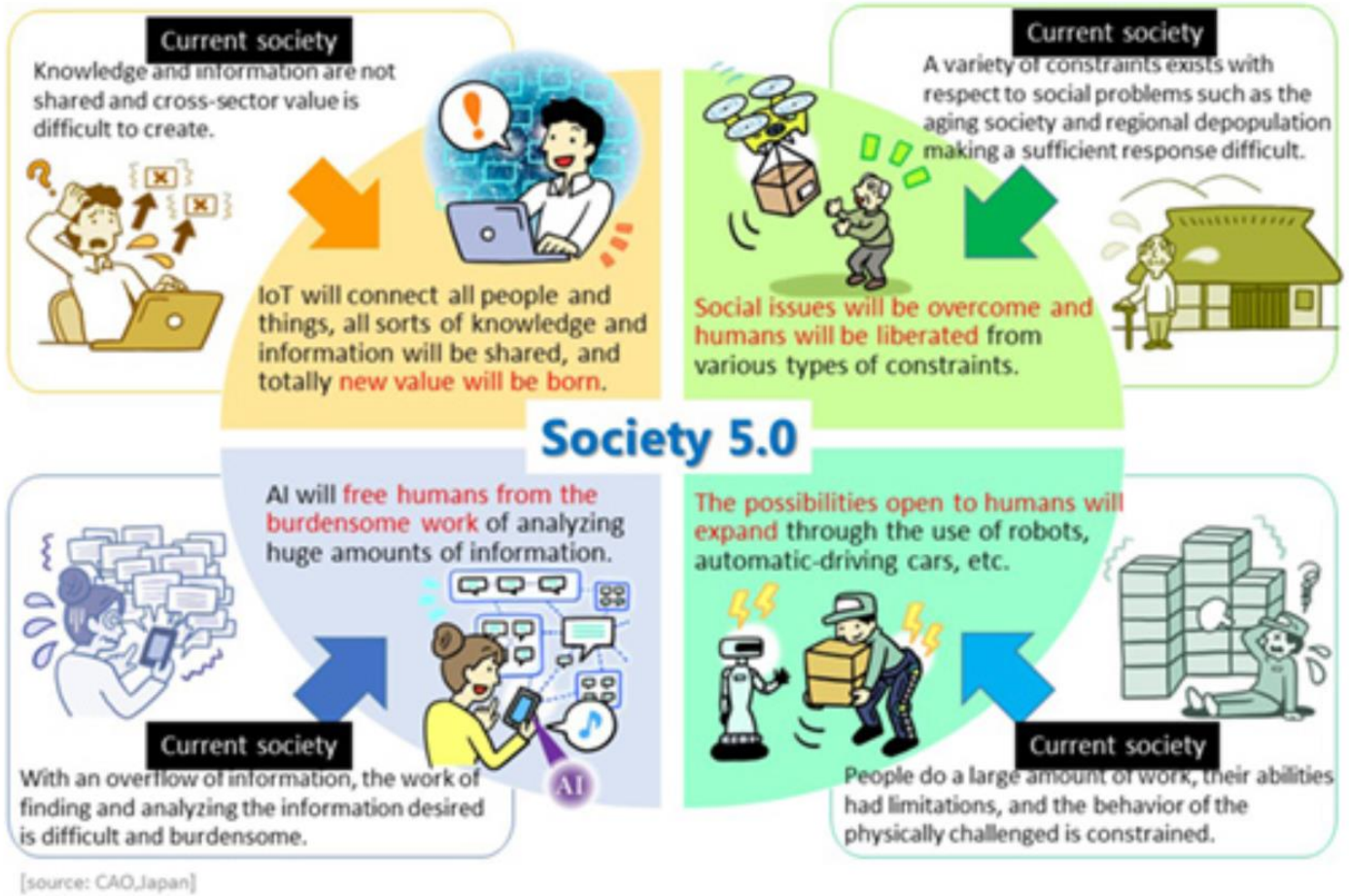


IoT describes the network of physical objects embedded with sensors, software, and other technologies for the purpose of connecting and exchanging data with other devices and systems over the internet

30 billions IoT devices by 2030

Smart City of the future builds on *Internet of Things concept*

Society 5.0- Japanese concept



[source: CAO,Japan]

Internet of Things future and stringent needs

The 4th Industrial Revolution

Next Gen Mobile Comm.
Emerging Connected-Health
Smart Farming
Smart Cities
builds on the

Internet-of-Things (IoT) paradigm

- **Scenario (2030) of having billions of interconnected autonomous mobile devices, with unprecedented processing power, storage capacity and access to knowledge**

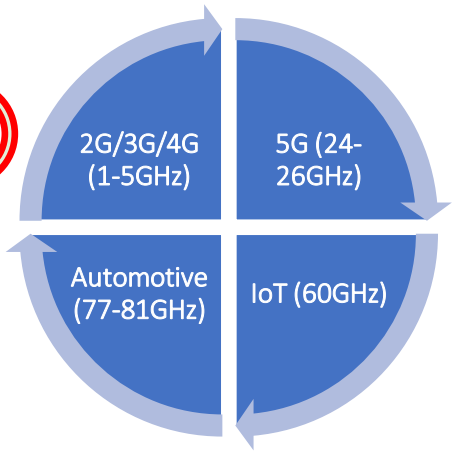
Billions interconnected of IoTs in networks need to be remotely deployed

- **IoTs maintenance may be either inconvenient or impossible(e.g. in 4IR)**

Key to successful deployment of future IoTs networks

IoT nodes operates maintenance-free over their whole predicted lifetime

The *broadening of the wireless communication spectrum* in Europe makes the Radio frequency (RF) energy scavenging a highly desirable way forward for clean powering of the next-generation IoT.



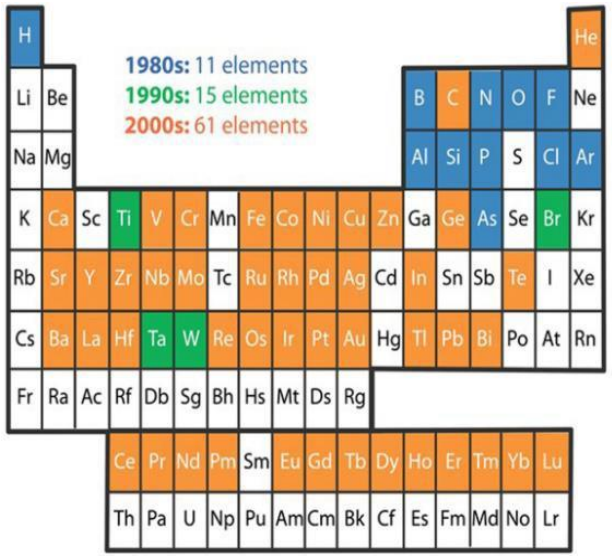
NANO-EH consortium aims to use RF energy scavenging a clean energy source for powering IoT

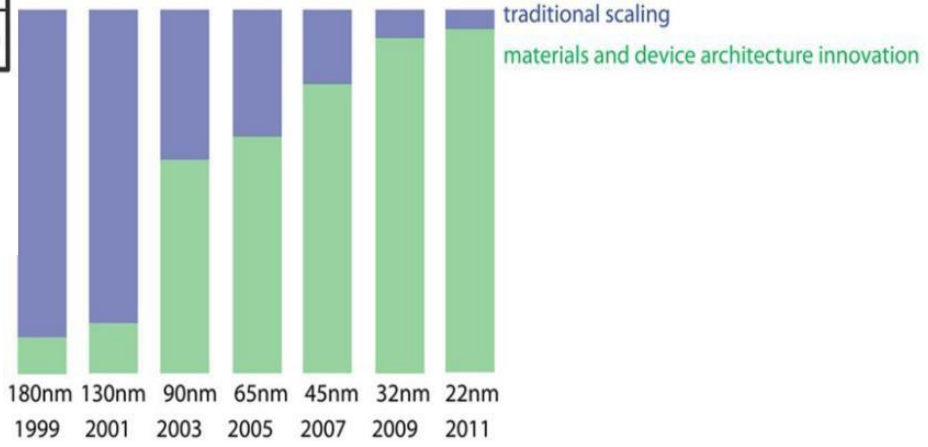
Emerging materials triggers device architecture innovation

The end of Moore's Law could be the best thing that has happened in computing since the beginning of Moore's Law," R. Stanley Williams, research scientist for HP Labs.

"Confronting the end of an epoch should enable a new era of creativity."

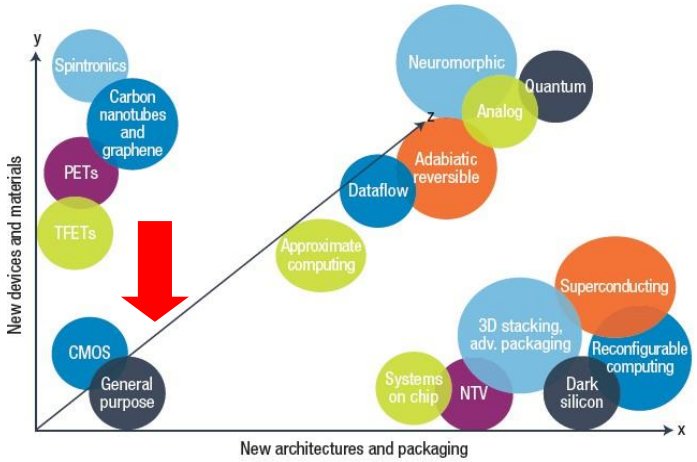
(Computing in Science & Engineering. IEEE CS and AIP – March/April 2017)

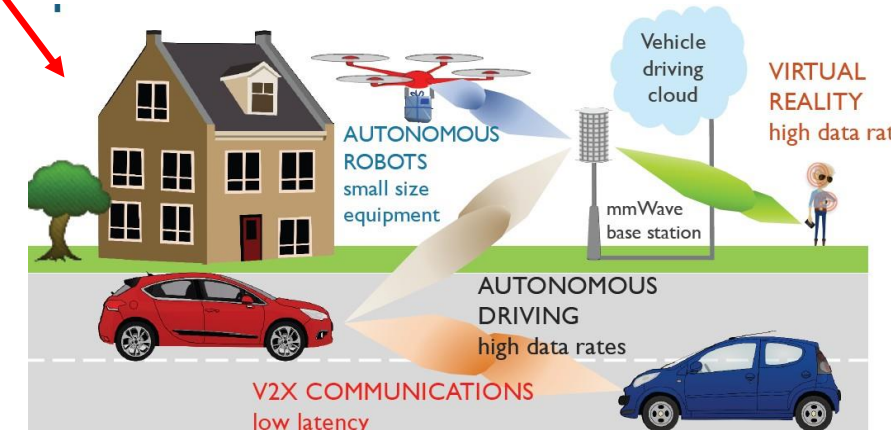




Applied Physics Reviews 4, 011105 (2017)

Materials and devices architecture innovation





Circuits reconfigurability and tunability for reconfigurable computing and communications such as 5G, 6G

NANOMATERIALS ENABLING SMART ENERGY HARVESTING FOR NEXT-GENERATION INTERNET-OF-THINGS

- **EU FUNDED UNDER EUROPEAN INNOVATION COUNCIL (EIC)**

- FET Proactive project : *emerging paradigms and communities call* (FETPROACT-EIC-05-2019) in the subtopic “Breakthrough zero-emissions energy generation for full decarbonisation”.

- **WWW.NANO-EH.EU**

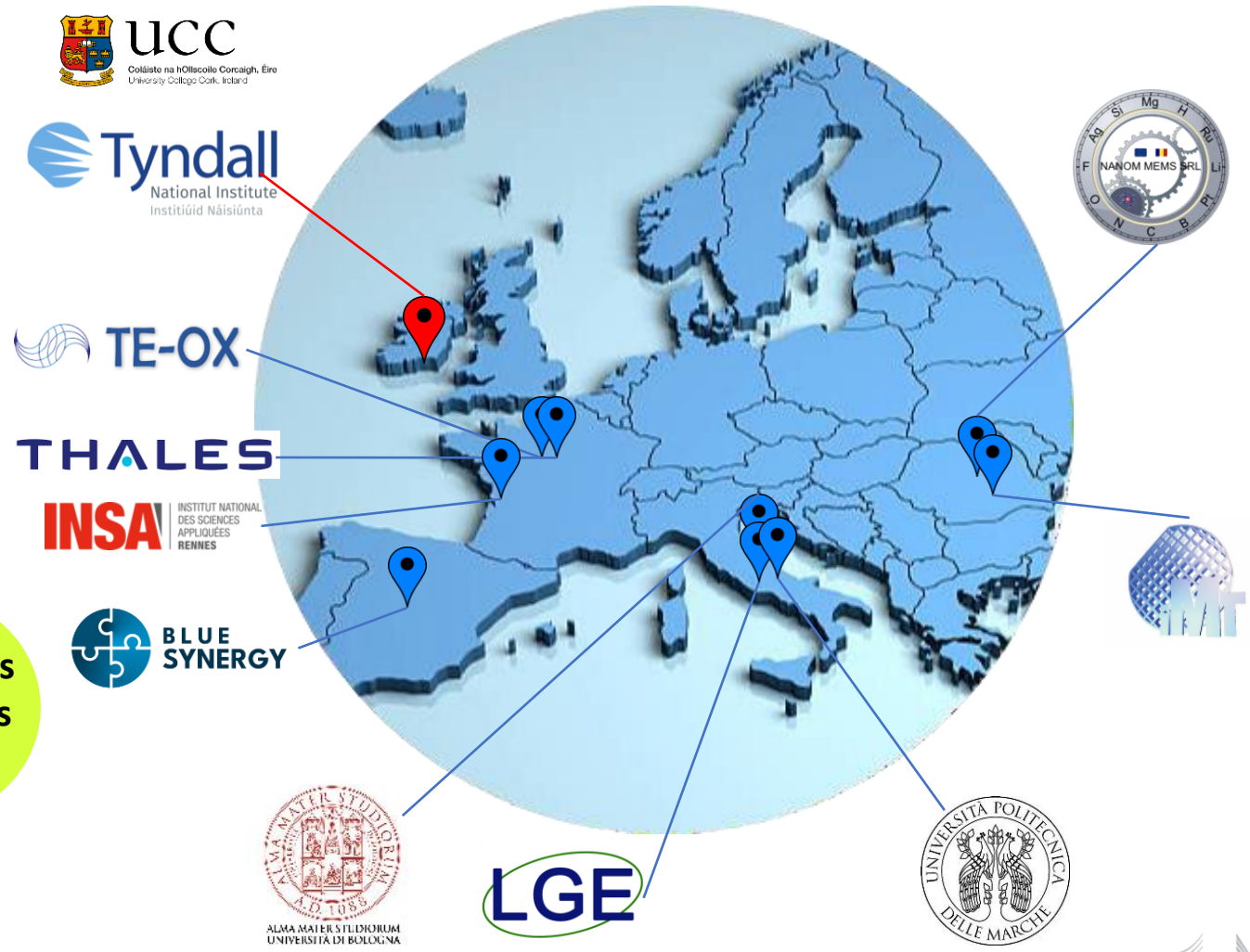
NANOMATERIALS ENABLING SMART ENERGY HARVESTING FOR NEXT-GENERATION INTERNET-OF-THINGS :NANO-EH

Duration:	42 months
Call identifier	H2020-EIC-FETPROACT-2019
Total Cost	3 929 360.00 €
Coordinator	Mircea Modreanu, UCC-TNI
Project website	www.nano-eh.eu

- Tyndall National Institute, Ireland
- University of Bologna, Italy
- University Polytechnical delle Marche
- INSA Rennes, France
- IMT-Bucharest, Romania
- Thales, France
- TE-OX, France
- NANOM, Romania
- Luna Geber, Italy
- Blue Synergy, Spain

2 RDTs
2 University
1 Large Industry
4 SME

10 partners
5 countries



NANO-EH: OBJECTIVES

Hybrid integration of multi-source harvesters (RF, piezoelectric, heath, ambient light) on the same platform.

1. On-chip energy storage capabilities integration via high-performace supercapacitors.
2. On-demand energy harvesting: the appropriate source of energy harvesting selected according to the ambient availability, or a combination of the various sources.
3. Low cost, reliable, efficient and high-volume CMOS-compatible manufacturing processes on silicon.
5. Green technology approach: exploitation of non-toxic, easy materials recovery and recyclable materials for environment-friendly battery-less energy supply sub-systems/modules for IoT and WSNs

- **NANO-EH address the fragmentation in the energy supply module for IoT market by proposing a platform compatible with Si planar technologies**
- Key Benefits : lower cost, able to deliver large volume, easily deployable and widely accepted technological platform

NANO-EH: SMART MATERIALS PLATFORM

NANO-EH's exploits three classes of ***smart nanomaterials*** that are *non-toxic, lead- and rare earth-free :*

- One new class of energy harvesting/storage oxide nanomaterials: *Hafnium Zirconium Oxides* ($HfZrO_f$ *and* $HfZrO_d$)
- One new class of energy harvesting of *Two-Dimensional (2D)* nanomaterials: *2D* MoS_2
- One class of renewable bio-based piezoelectric nanomaterials, namely the *functionalised nanocellulose*
- Energy storage functionality will be built in via *high performance supercapacitors (* $HfZrO$ *and* $VO_2(B)$ *oxides)*

NANO-EH's has the ambition of covering the whole technological value chain:

Materials development → design and modelling of devices → devices fabrication and testing →integration of devices in demonstrators

1st Challenge
- Nanomaterials development at wafer scale

2nd Challenge
- Design with electromagnetic modelling tools of new energy harvesting and energy storage device architectures

3rd Challenge
- Fabrication, testing and benchmarking at both device and submodule level

Emerging nanoscale wide bandgap HfO_2 ferroelectrics

Nanoscale HfO_2 ferroelectrics: first report of orthorhombic polar (o-III) phase

- The discovery of ferroelectricity in few nm HfO_2/HfZrO was a Big Surprise
- Traditional thinking (*20 years ago…)* →HfO_2 (HfZrO) is a dielectric irrespective crystalline polymorphs (***m***, ***o***, ***t*** or ***c***)

Orthorhombic polar (o-III) Raman fingerprint around 322cm^{-1}

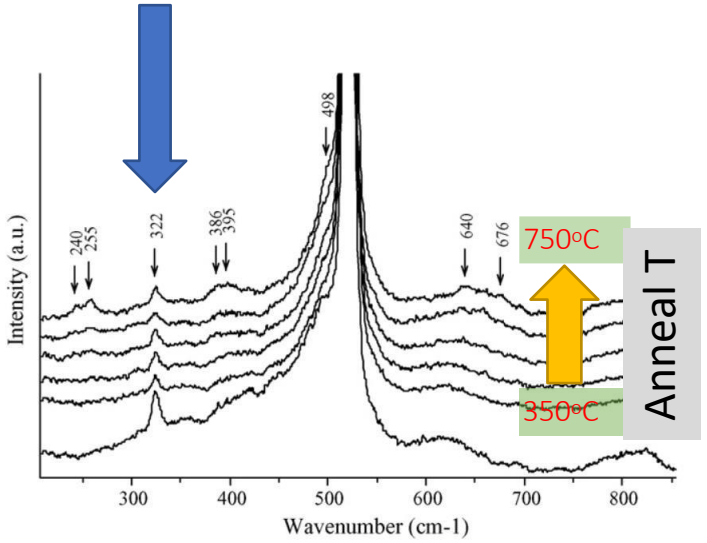


Fig. 4. Raman spectra recorded in 600 s at 325 nm on samples Hc1 (bottom) to Hc6 (top). The peak of Silicon is located at ~520 cm^{-1}. The peak at 322 cm^{-1} cannot be assigned to any known HfO_2 crystalline phase.

First report of HfO_2 Orthorhombic polar (o-III) : 2006

M. Modreanu et al./Applied Surface Science 253 (2006) 328–334

First reported at EMRS Spring Meeting 2005 !

However, in 2006 HfO_2 Orthorhombic polar was not known

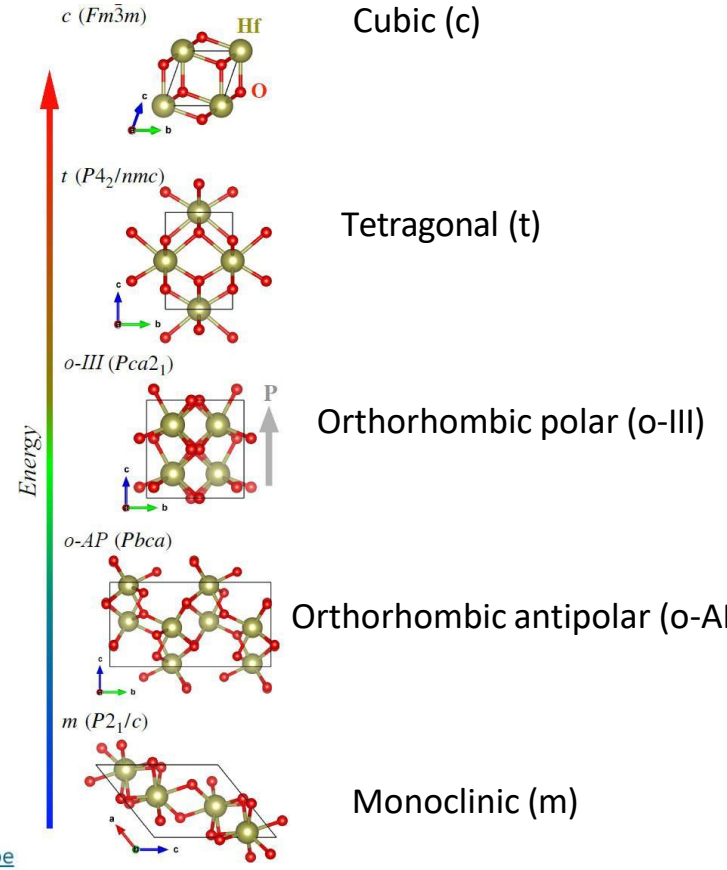
Raman phonon modes for Orthorhombic polar (o-III) : 2022

nature › npj quantum materials › articles › article

Article | Open Access | Published: 18 March 2022

Vibrational fingerprints of ferroelectric HfO_2

Shiyu Fan, Sobhit Singh, Xianghan Xu, Kiman Park, Yubo Qi, S. W. Cheong, David Vanderbilt, Karin M. Rabe



Why researching nanoscale HfO_2 (and others) ferroelectrics ?

Traditional ferroelectric (e.g. $BaTiO_3$ or PZT) cannot

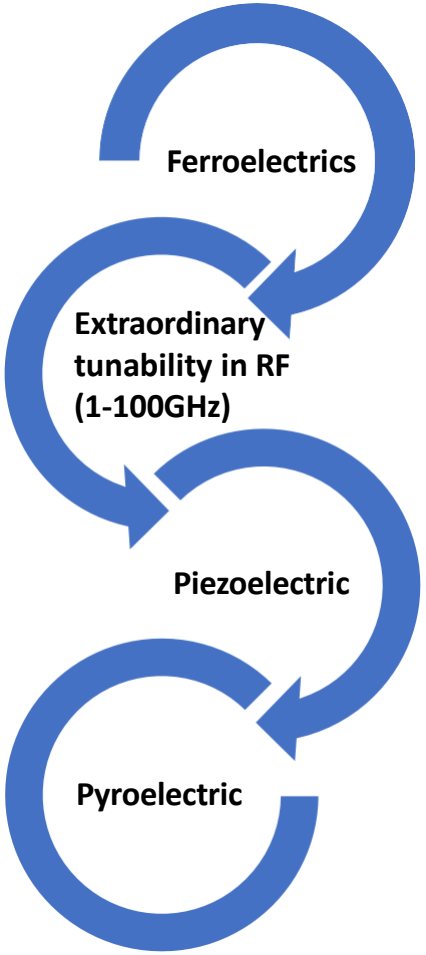
- Be downscaled to a few nm
- Requires high operation voltages
- Not CMOS compatible

Emerging Hafnium oxides ferroelectrics

- Can be downscaled to 1-2nm
- Low operation voltages 1-3V
- CMOS compatible

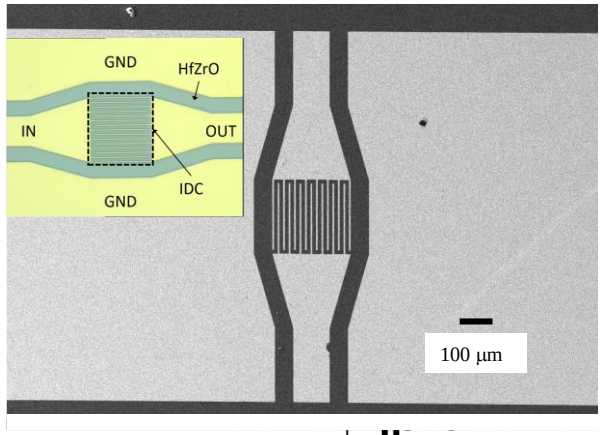
The rise of ferroelectrity at nanoscale

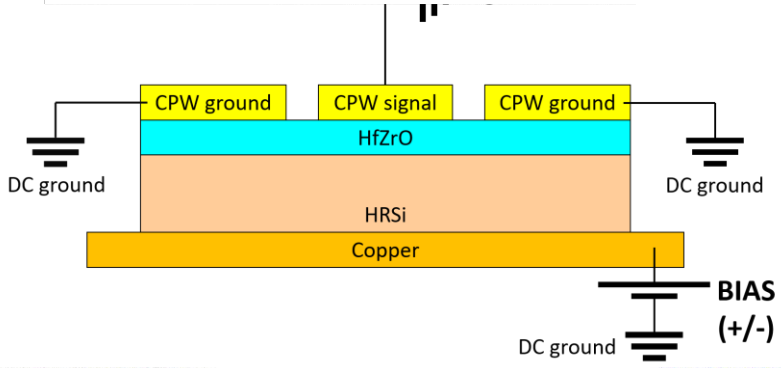
- New devices architectures for CMOS
  FeFET, FERam
- New devices architectures for high frequency devices (5G&6G)
  RF and Pyroelectric Harvesters and energy storages devices



Direct growth of HfO_2 ferroelectrics on High Resistivity Si opened the way for high-frequency application

HfZrO ferroelectrics: RF applications-*Phase shifters*





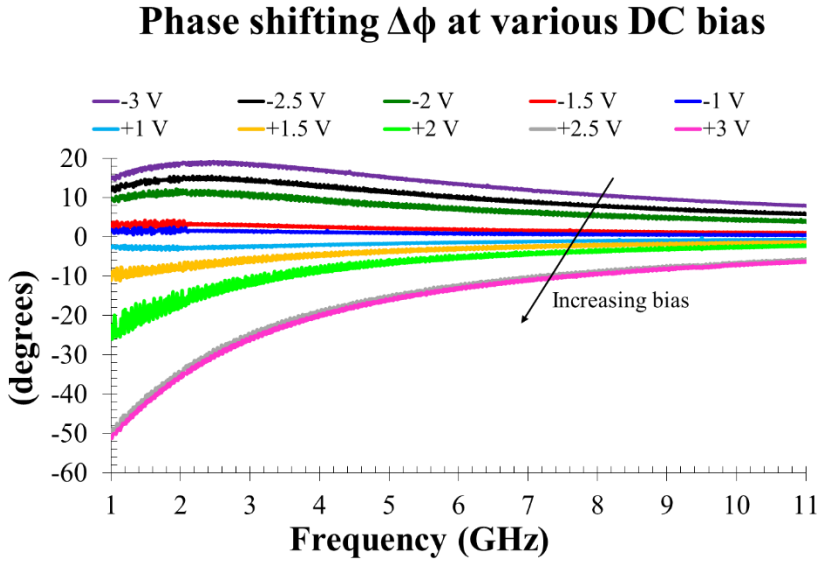
Nanotechnology 28 (2017) 38LT04 (5pp) https://doi.org/10.1088/1361-6528/aa8425

Letter

Very large phase shift of microwave signals in a 6nm $Hf_xZr_{1-x}O_2$ ferroelectric at ±3V

Mircea Dragoman[1], Mircea Modreanu[2], Ian M Povey[2], Sergiu Iordanescu[1], Martino Aldrigo[1], Cosmin Romanitan[1,3], Dan Vasilache[1], Adrian Dinescu[1] and Daniela Dragoman[3,4]

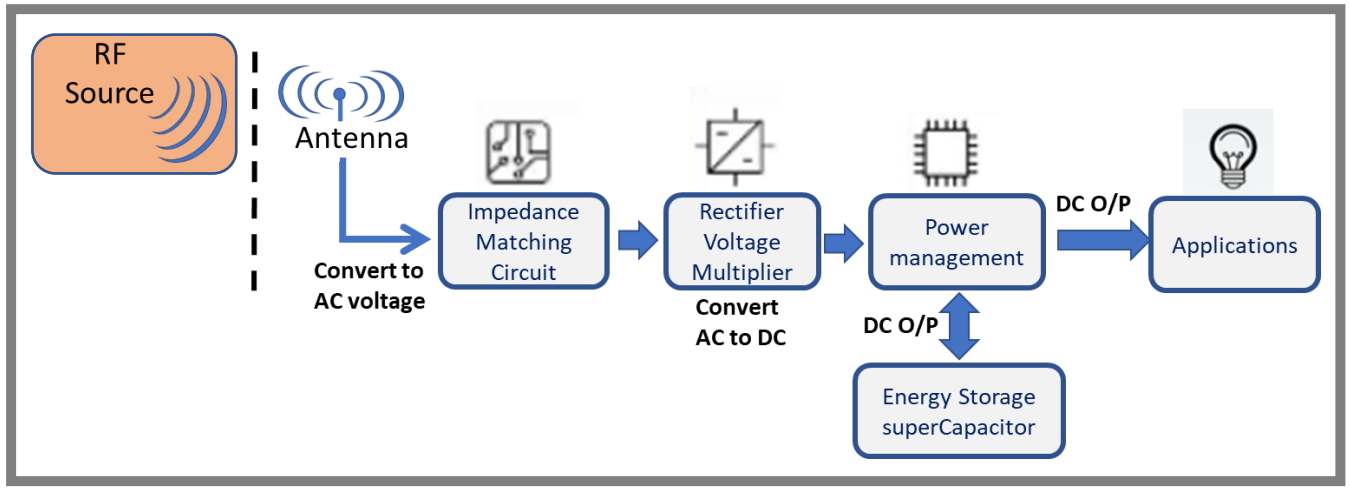
2017

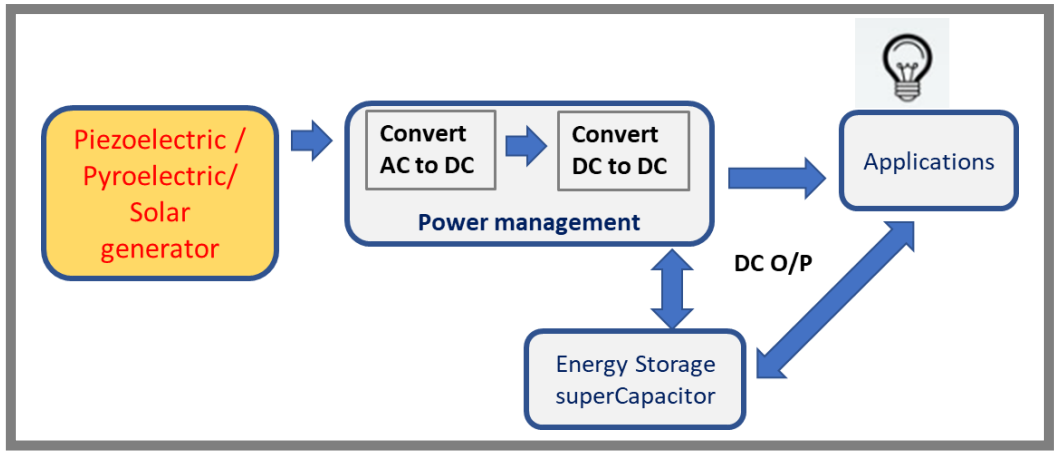


Frequency (GHz)	$\Delta\varphi_{-3V}$	$\Delta\varphi_{+3V}$	$\Delta\varphi_t$
1	14.99°	-51.24°	66.23°
2.45	18.92°	-30.87°	49.79°
5.5	14.20°	-14.56°	28.76°
10	8.78°	-6.86°	15.62°

Multi-source Energy Harvesting

- RF harvester
  - Antenna
    - 2.45 GHz → 2G/3G/4G
    - 24-26 GHz → 5G
    - 60 GHz → IoT
  - MIM or SS diodes
  - DC circuitry
  - Power divider
  - Phase shifter
- Piezoelectric harvester
- Pyroelectric harvester
- Solar/light harvester
- Energy storage devices
  - Supercapacitors





Conclusions

- Internet of Things *future and stringent needs they need to be energy autonomous*
- *Need to address* the fragmentation in the energy supply module for IoT market (30 bilions/2030)
- European Innovation Council's NANO-EH proposes a low cost, reliable, efficient and high-volume CMOS-compatible manufacturing processes on silicon
- NANO-EH envisages a Green technology approach: exploitation of non-toxic, easy materials recovery and recyclable materials for environment-friendly battery-less energy supply sub-systems/modules for IoT and WSNs

- Please follow our progress on www.nano-eh.eu as well on LinkedIn and Twitter

Acknowledgements

- **Mircea Modreanu, NANO-EH's Project Coordinator** thanks to many researchers from the NANO-EH Consortium

- **IMT BUCHAREST- MIRCEA DRAGOMAN, MARTINO ALDRIGO**
- **UNIVPM– LUCA PIERANTONI, DAVIDE MENCARELLI, EMILIANO LAUDADIO, PAOLA RUSSO, PIERLUIGI STIPA**
- **UNIBO- ALESSANDRA CONSTANZO, DIEGO MASSOTI, SIMONE TROVARELLO**
- **INSA RENNES- OLIVIER DURAND, BIENLO ZERBO, JACKY EVEN**
- **THALES- AFSHIN ZIAEI, ANA BOYA-BORTON**
- **TE-OX- GUY GARRY, OLGA ISHCHENKO, RIHEM NOUMI**
- **NANOM- MARIN GHEORGHE, CORNEL COBIANU**
- **LUNA GEBER-LUCA ROSELLI, FABIO GELATI**
- **BLUE SYNERGY- GERMAN CAVERO, PAOLA CASTRILLO**

- NANO-EH has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 951761
- The NANO-EH project was chosen in the FET Proactive: emerging paradigms and communities call (FETPROACT-EIC-05-2019) in the subtopic "Breakthrough zero-emissions energy generation for full decarbonisation".

www.nano-eh.eu

Thank you very much for your attention !

UCC Main Campus