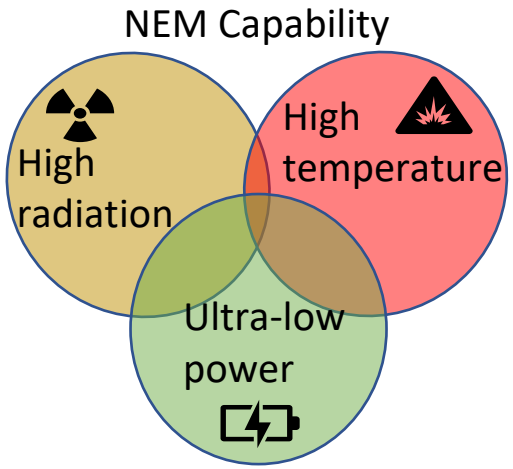
The ZeroAMP Project – Electronics for Extreme Environments

Dinesh Pamunuwa, University of Bristol
and Piers Tremlett, Microchip Inc.

What is the point of NEM switch technology?

- It enables electronics for impossible environments



Zero standby power at 300 °C and 1 Mrad

- NEM switch technology has applications in manufacturing and construction environments, industrial electronics, space, defence, nuclear, automotive, oil field
  - Many edge computing applications will require some combination of resilience to high temperatures and radiation - an example is the ZeroAMP project IIoT “Token”
  - Battery passport for automotive EV vehicles and electric aircraft
  - Rugged Memory for harsh environments in Space, drilling and industry

Outline of this presentation

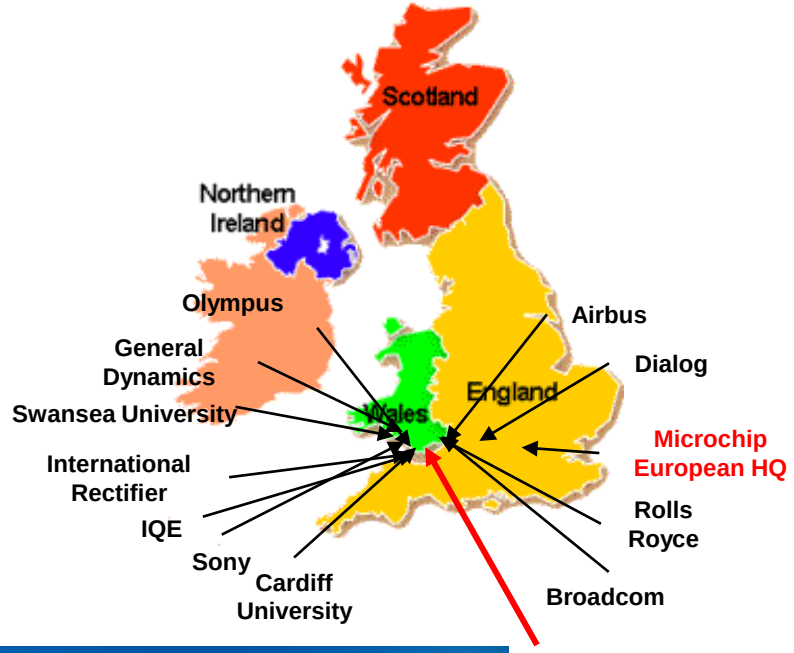
- Context: the genesis of our NEM switch technology
- NEM Technology
  - NEM Switches for logic and memory
  - How are the switches made
  - Integration strategy
  - Packaging
- Development roadmap
- Application space for NEM technology
  - Intelligent sensors and control system – The “Token”
  - Harsh-environment tracking and data collection – battery passport and ruggedised memory

Microchip Caldicot site background

- Microelectronics factory
  - Established in South Wales since 1983
  - ~130 employees, 30,000 square foot facility

- Design & Assembly Expertise:
  - SMT, CoB
  - Focused on solving complex problems
  - High reliability customers

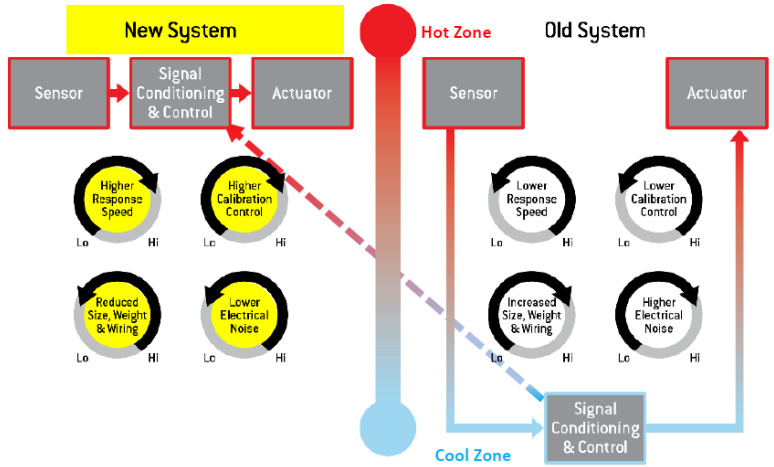
- Specialising in “**Miniaturisation**”
  - Expanding miniaturization into Harsh Environments



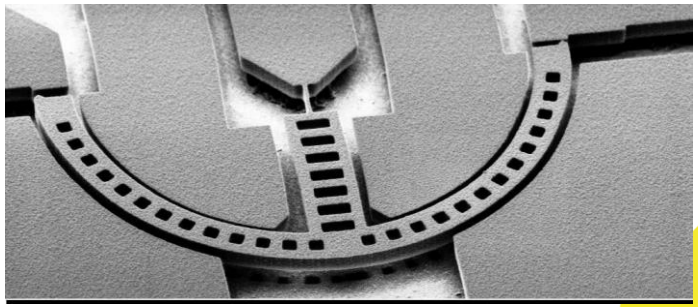
Microchip Advanced Packaging

The “genesis” of our NEM switch technology

- Microchip were developing high temperature control for sensor/actuator systems
  - To use the advantages of local control rather than remote control
  - Improved: EMC, response times, bandwidth, calibration control
  - But high temperature memory was missing

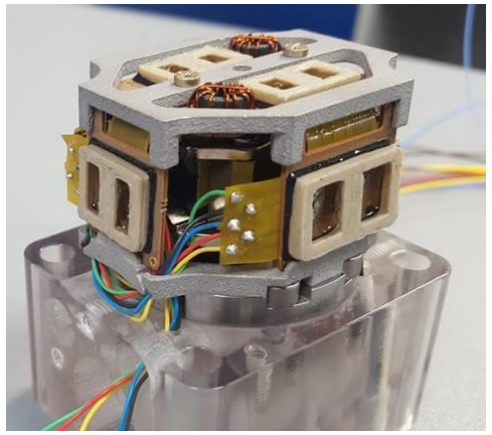


- Bristol University had been researching MEMS relay technology
  - This offered the memory that we were looking for



The NEMICA Project

- UK Innovate project to develop NEM technology
  - Leading to the ZeroAMP project
- Expected outcomes
  - 340 °C MEMS based non-volatile memory
  - Control system for 175C jet engine fuel valve actuator



Four partners:

MOOG

University of BRISTOL

MICROCHIP

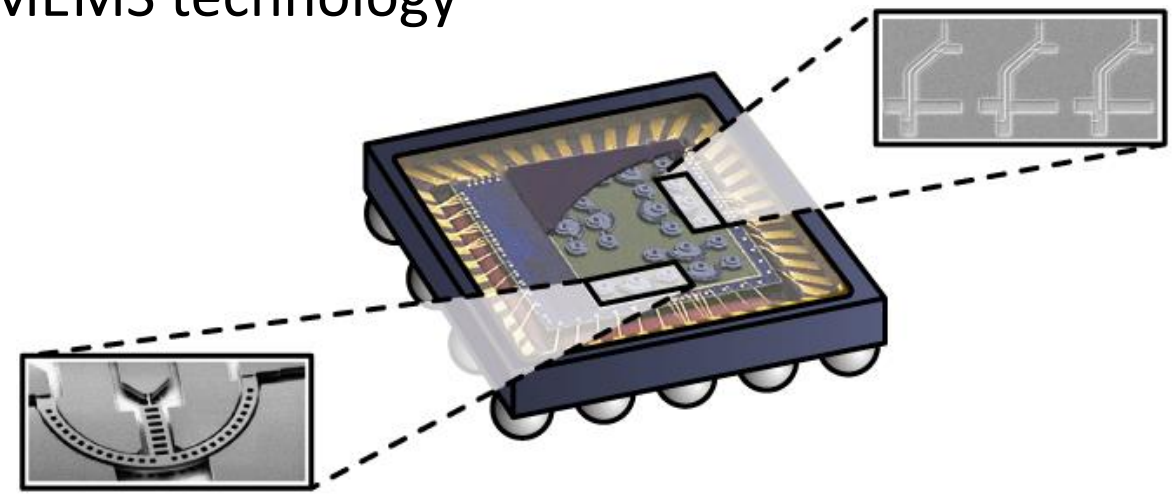
UNIVERSITY OF Southampton

Zero AMP

CONFIDENTIAL INFORMATION

The ZeroAMP Project

- ZeroAMP is a follow on project to NEMICA
- 7 partners
- 4 year H2020 project
- Started January 2020, finishes June 2024
- An Horizon 2020 funded by the EU
- To develop mechanical “transistors” using MEMS technology



Introduction to NEM Technology

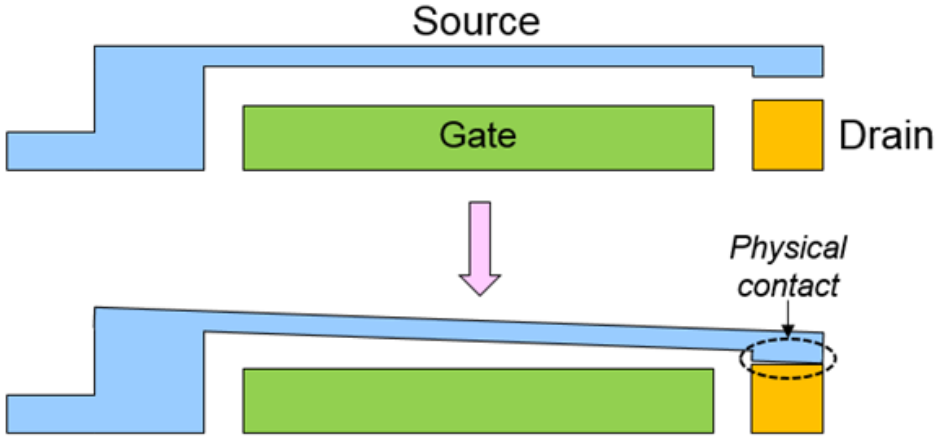
Dinesh Pamunuwa,

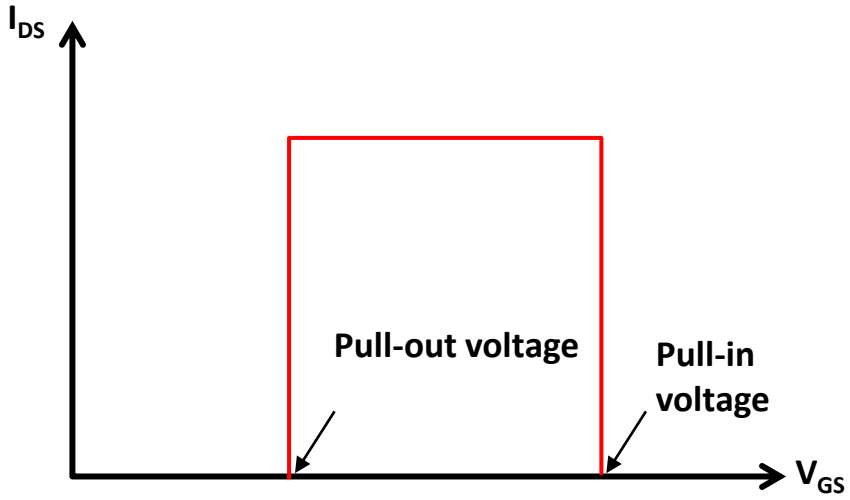
Bristol University

Zero-AMP NEM Switch Integration Platform

- Devices
  - “Volatile” switches that turn off when actuation is removed: used for logic
    - 3-T switches: straight replacement for transistors in complementary style logic
    - 4-T switches: allow for very efficient logic circuits with reduced device count
  - “Non-volatile” switches that stay switched when actuation / power is removed: used for on-chip NV memory
- Integration
  - Multi-layer interconnect wafer fabricated using standard foundry offering of X-FAB
  - NEM circuits realised as a BEOL process: wafer bonding at KTH, device structuring at Bristol, contact solution at AMO, final device suspension at KTH
  - Process that allows choice of substrates, flexibility in processing
- Packaging
  - High temperature / rugged packaging at Microchip and KTH
- Testing
  - Metrology and material characterisation: CSEM and AMO
  - Die-level and packaged testing: CSEM, Bristol, KTH

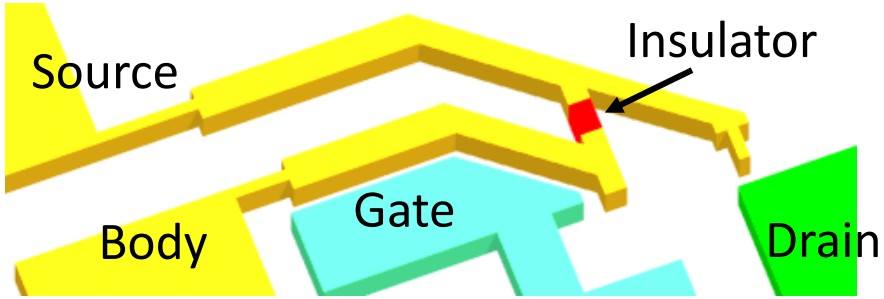
3-T Nanoelectromechanical (NEM) Relay

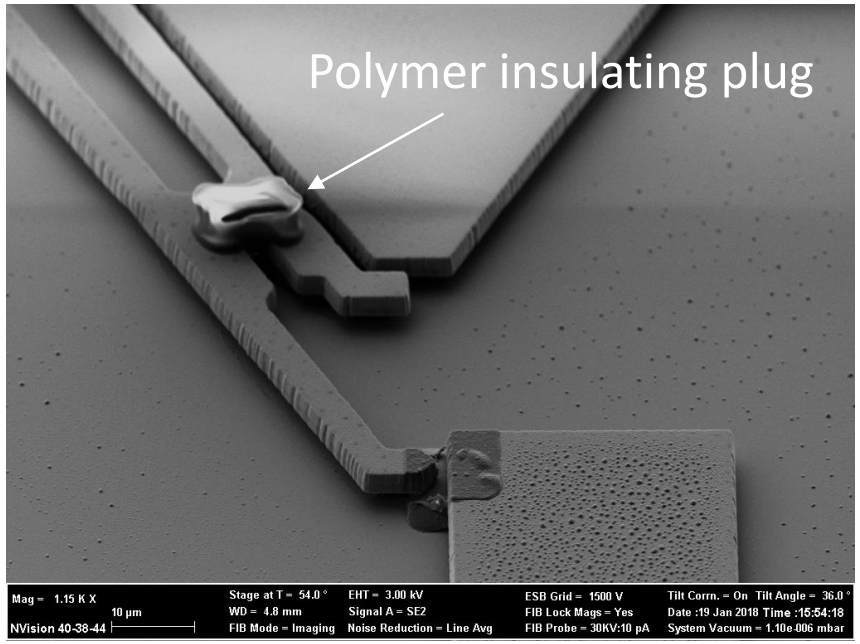




- Advantages
  - Zero off-state leakage and abrupt switching
  - High temperature operation
  - Radiation resistant

4-Terminal NEM Relay

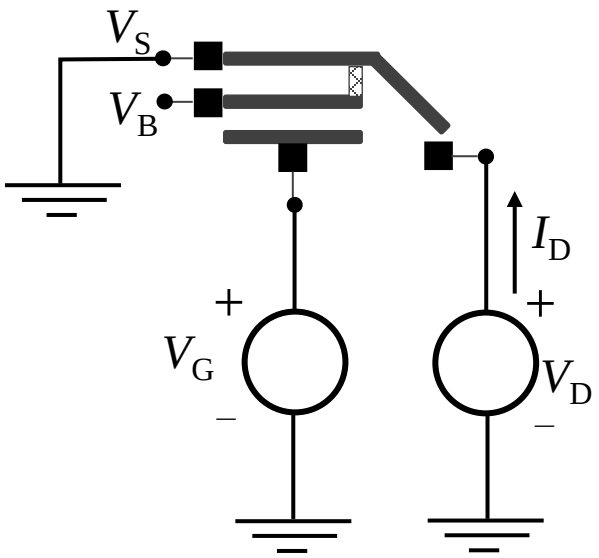


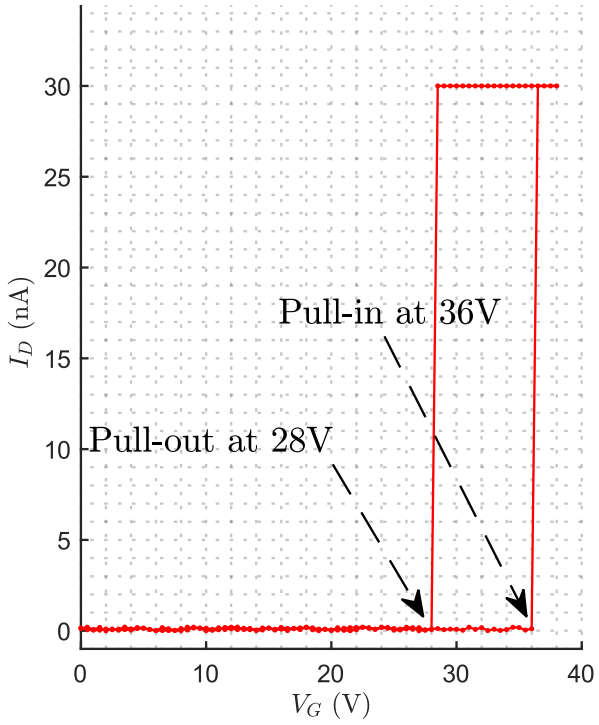


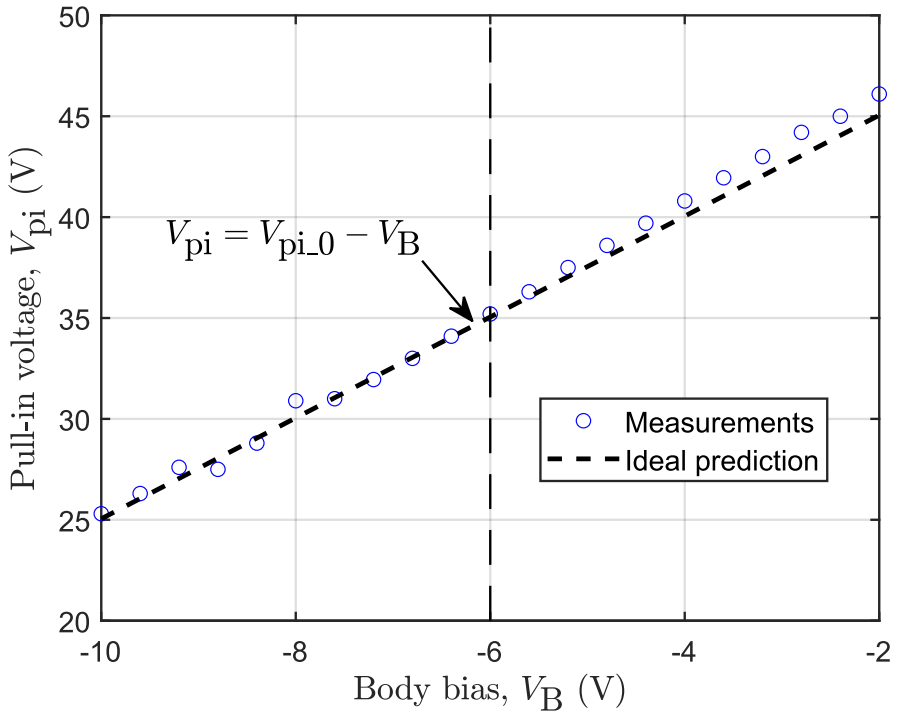
- Decouple the control signal from the data signal for much more efficient circuits than with 3-T
  - Eg: 2 devices instead of 12 for 2-to-1 MUX
- Body-biasing to reduce pull-in voltage
- Single-contact, in-plane architecture
  - Simple fabrication with only two masks
  - Robust against contact failure
- Common geometrical framework with 3-T relay makes design and layout more convenient

J. D. Reynolds, S. Rana, E. Worsey, Q. Tang, M. K. Kulsreshath, H. M. H. Chong, D. Pamunuwa, "Single-contact, four-terminal microelectromechanical relay for efficient digital logic," *Advanced Electronic Materials*, under review, 2022.

4-Terminal Relay Body Biasing







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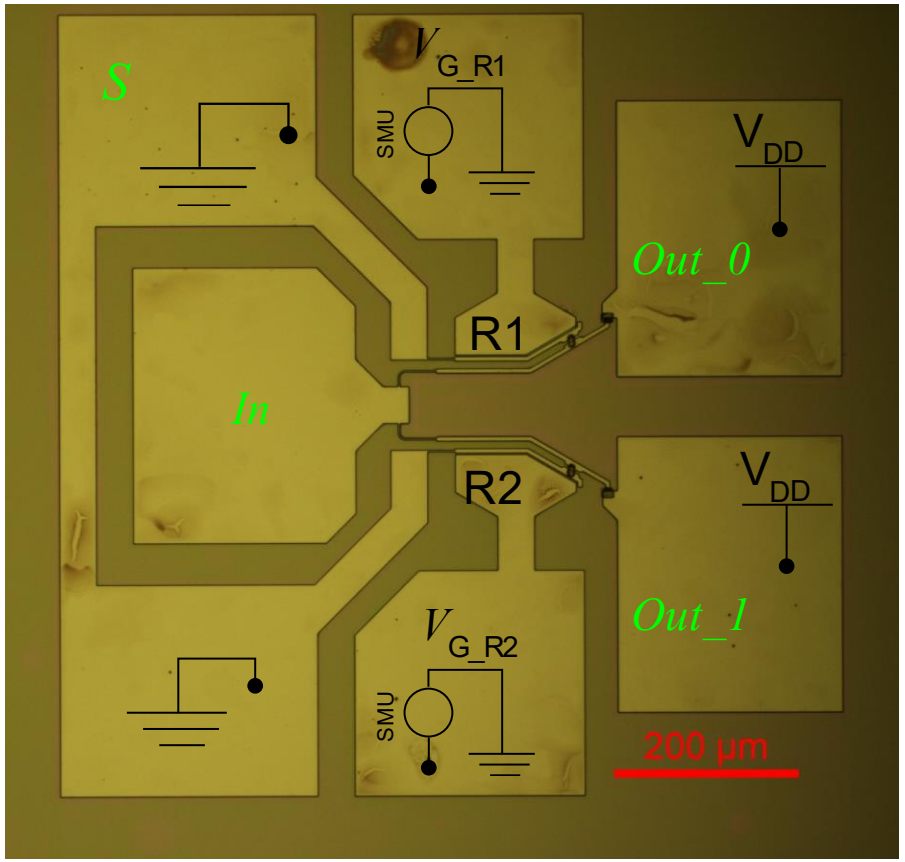
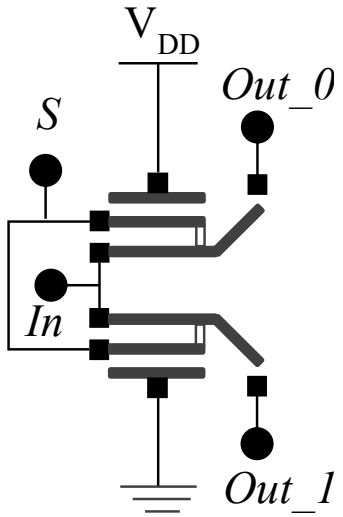
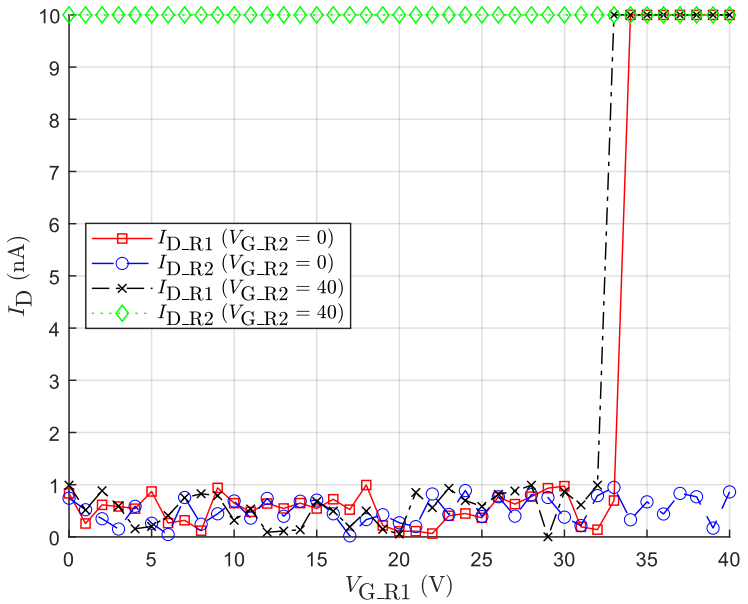
4-T Relay-Based 1-to-2 DEMUX Circuit

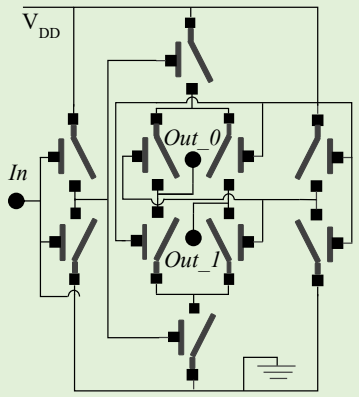




V_{G_R1}	V_{G_R2}	*Out_0*	*Out_1*
0	0	'Z'	'Z'
0	1	'Z'	*In*
1	0	*In*	'Z'
1	1	*In*	*In*



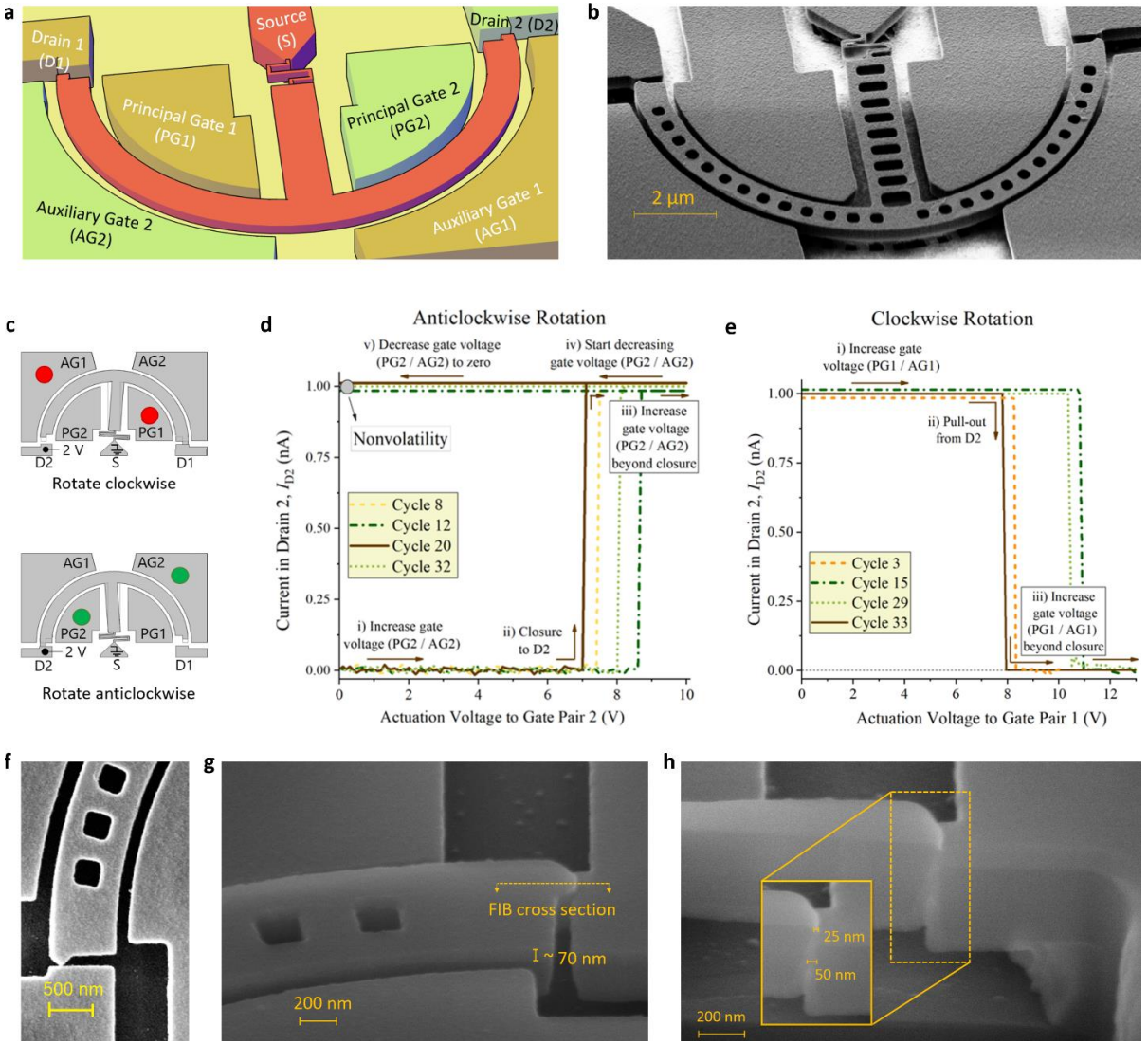
3-T relay implementation would have 10 devices!



J. D. Reynolds, S. Rana, E. Worsey, Q. Tang, M. K. Kulsreshath, H. M. H. Chong, D. Pamunuwa, "Single-contact, four-terminal microelectromechanical relay for efficient digital logic," *Advanced Electronic Materials*, under review, 2022.

7-Terminal Relay

- Relay with semi-circular beam that eliminates electromechanical pull-in instability
  - Finer electrostatic control than with a conventional straight beam architecture
  - Relay stays switched through stiction
  - Reprogrammed electrostatically
- Non-volatile memory alongside logic

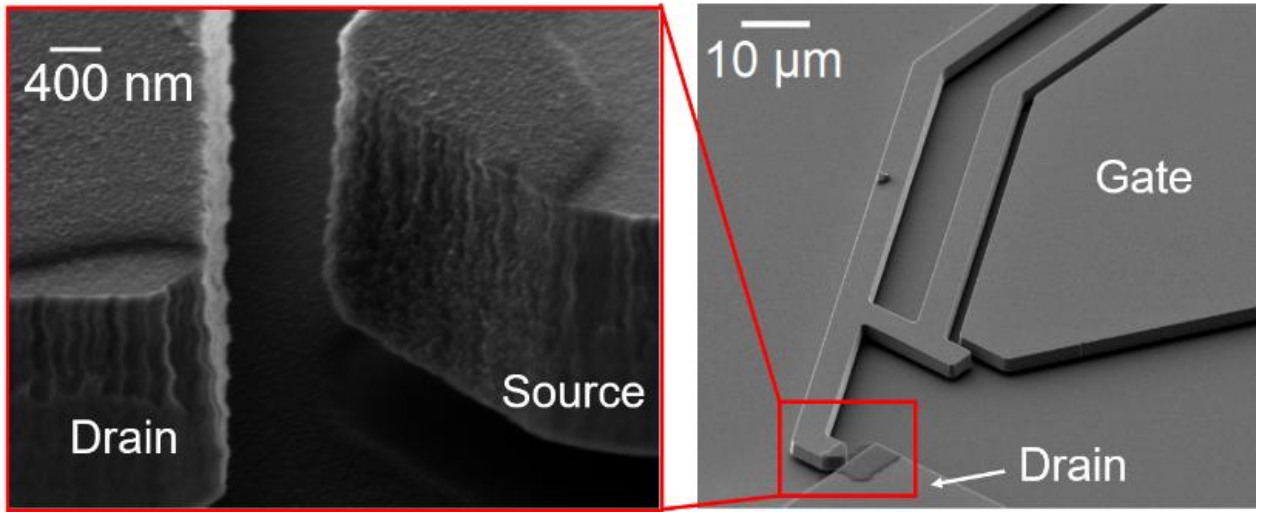


S. Rana, J. Mouro, S. J. Bleiker, J. D. Reynolds, H. M. Chong, F. Niklaus, and D. Pamunuwa, "Nanoelectromechanical relay without pull-in instability for high-temperature non-volatile memory," *Nature Communications*, vol. 11, no. 1, pp. 1-10, 2020.

Dinesh Pamunuwa, Elliott Worsey, Jamie D. Reynolds, Derek Seward, Harold M. H. Chong, and Sunil Rana, "Theory, design and characterisation of nanoelectromechanical relays for stiction-based non-volatile memory", *IEEE J. Microelectromechanical Systems*, vol. 31, no. 2, pp. 283-291, April 2022.

Reliability

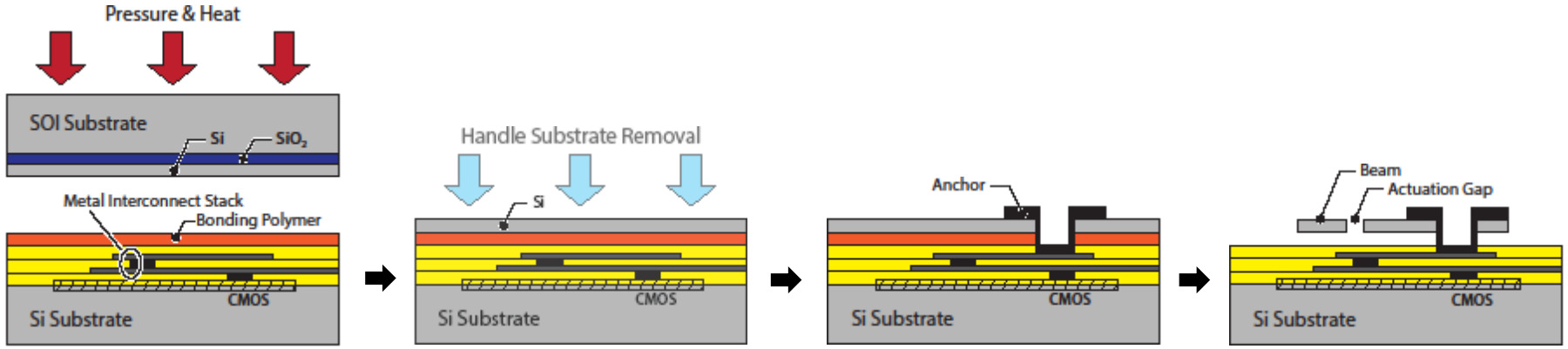
- Contact degradation is the main failure mode for NEM / MEM relays
- Carbon coated contacts show best reliability
  - Amorphous carbon trialled by IBM[1] in a previous EU project, NEMIAC
  - We have developed nanocrystalline graphite coated contacts in prior projects with Southampton University[2], which is being further optimised by AMO in ZeroAMP



[1] *Grogg et al., IEEE MEMS, 2014*
[2] S. Rana et al. and [D. Pamunuwa], "Nano-crystalline graphite for reliability improvement in MEM relay contacts," *Carbon*, vol. 133, pp. 193-199, 2018.

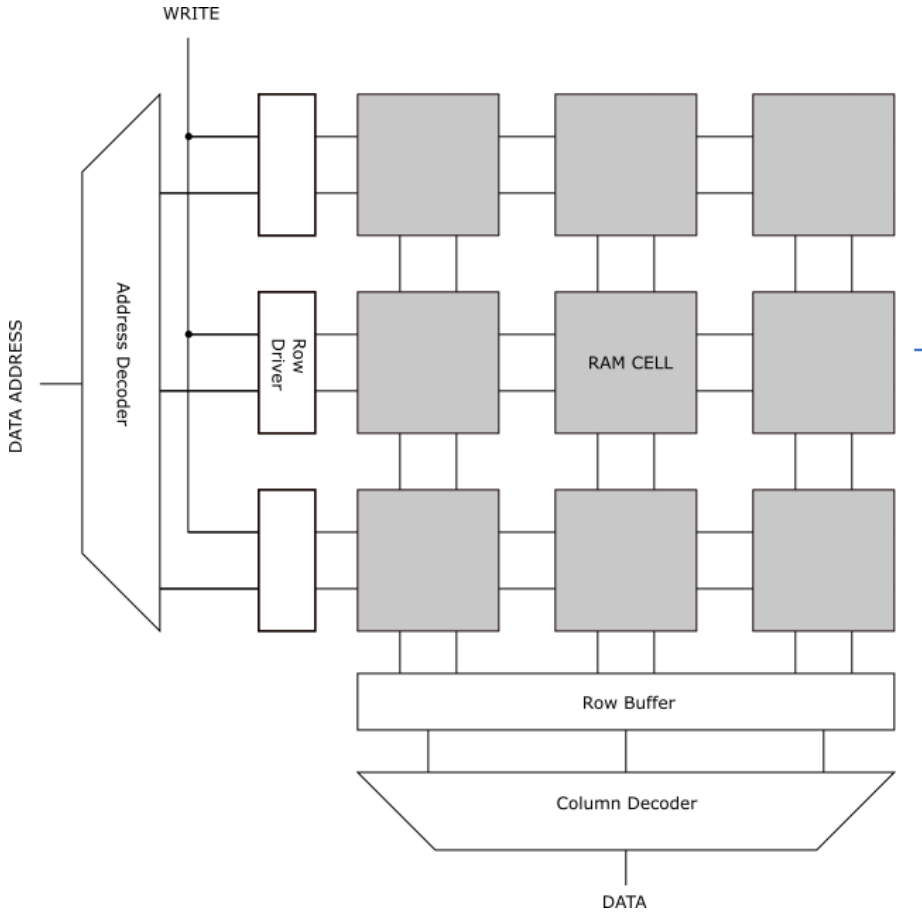
Heterogeneous 3-D Integration

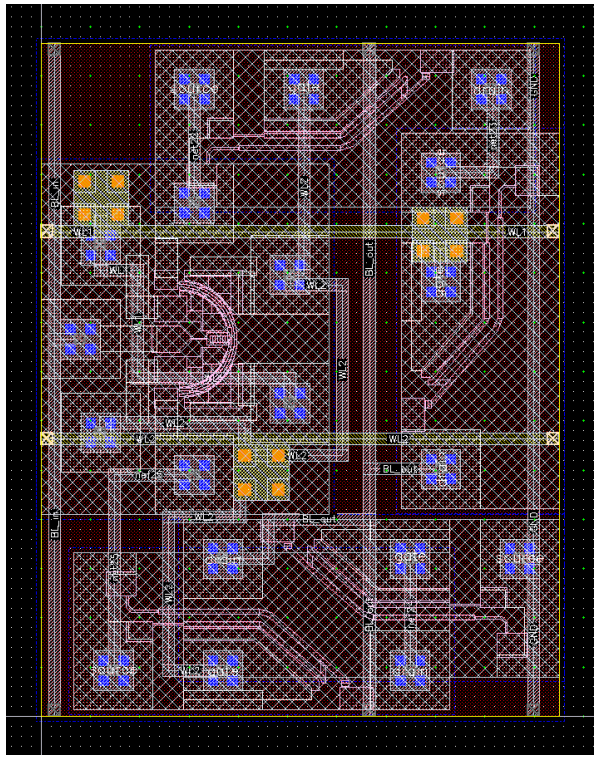
- Fabricate CMOS foundry wafer with interconnect stack
- Bond interconnect wafer to SOI / carrier wafer
- Structure NEM switches on SOI device layer
- Deposit contact layer and perform release etch



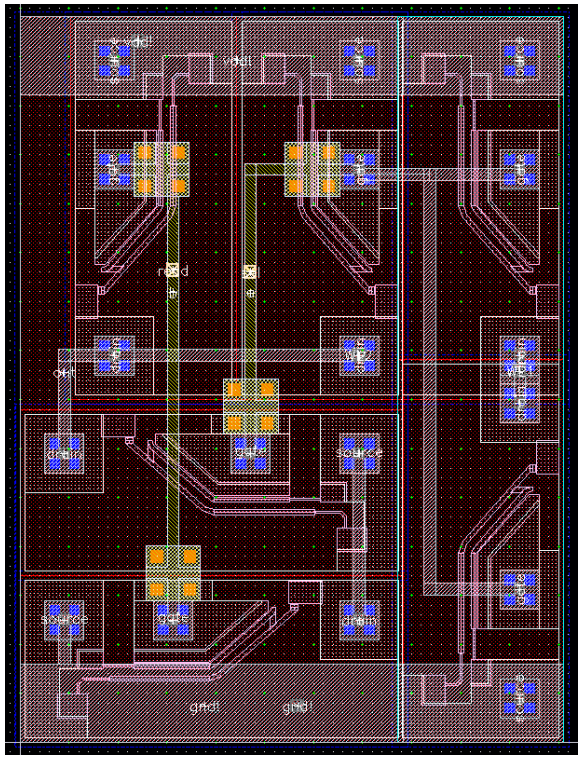
T. Qin, S. J. Bleiker, S. Rana, F. Niklaus, and D. Pamunuwa, "Performance analysis of nanoelectromechanical relay-based field-programmable gate arrays," *IEEE Access*, vol. 6, pp. 15997-16009, 2018.

NEM Relay-Based Non-Volatile Memory





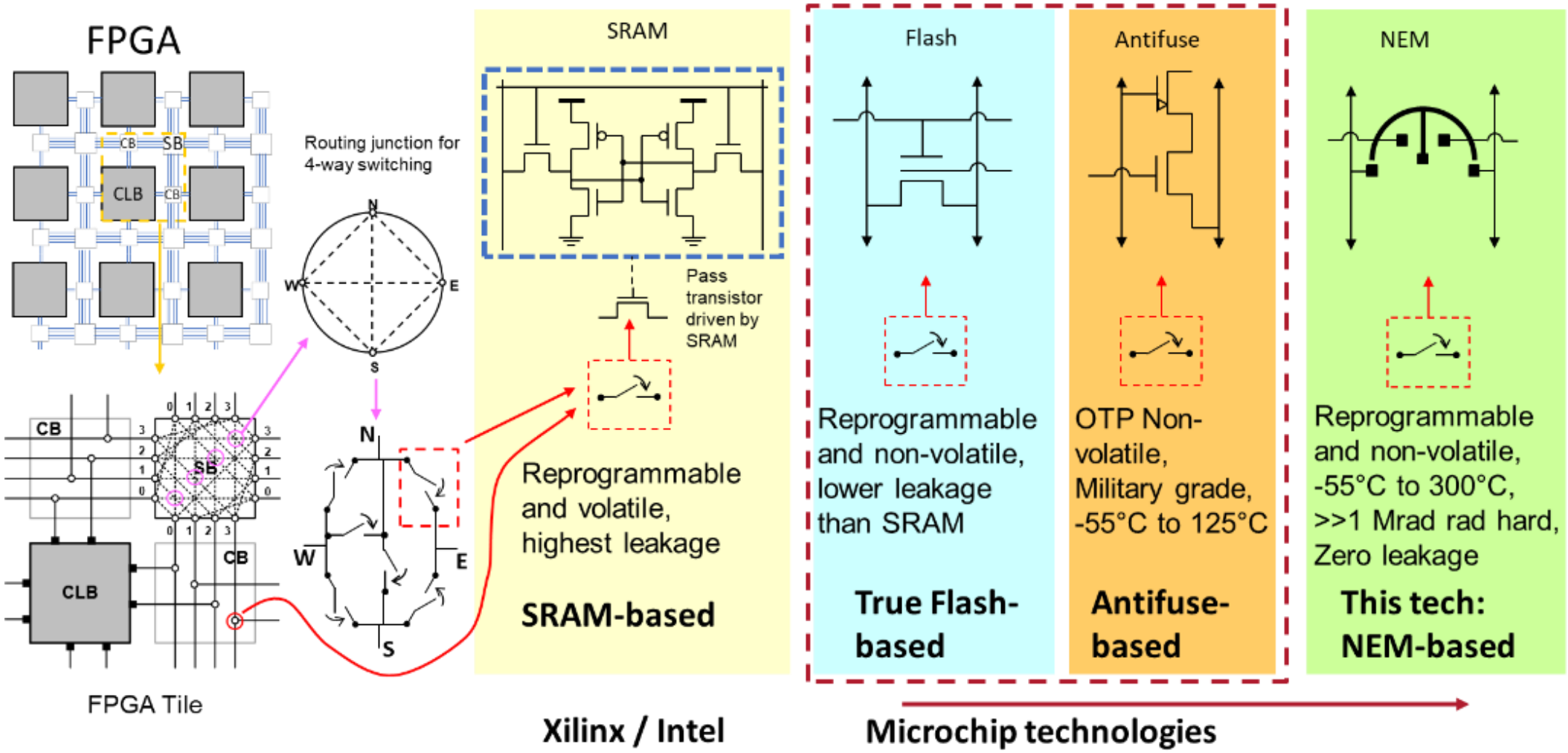
Core RAM Cell



Wordline driver

All circuits are built from relays using 3-layer interconnect stack in X-FAB XI10 process

NEM Relay-Based FPGA

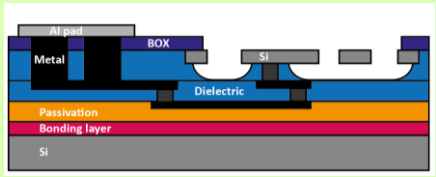


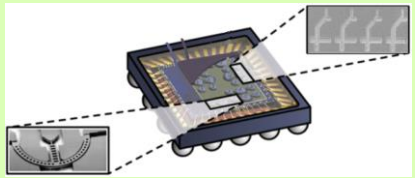
SRAM vs NEM technology: 38 fewer on-chip devices and eliminates off-chip non-volatile memory!

Design and Tooling

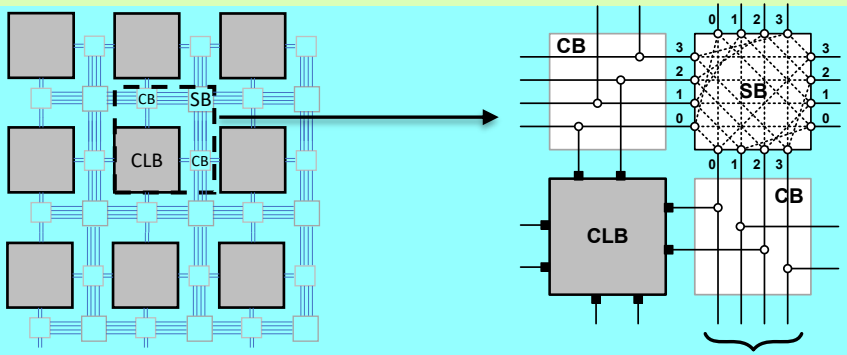
Firmware and software

Integration and packaging

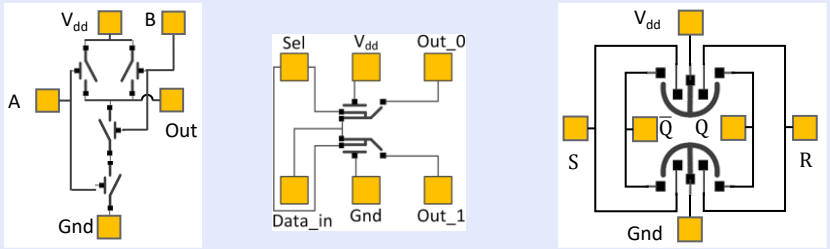




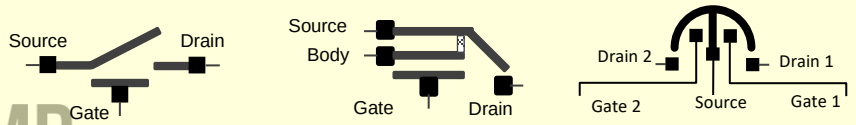
Reconfigurable systems



Circuits



Devices



RTL programming and synthesis on to FPGA

VTR Suite

NEM / CMOS codesign

Cadence

X-FAB PDK

Custom NEM PDK

Micro architecture and on-chip communication network

VTR Suite

Circuit simulation

Cadence

Model order reduction

FEM (Ansys)

Analytical Model + Parametric layout

MATLAB

Design and Simulation Framework

ZeroAMP Design Entry and PDK Demonstration

Elliot Worsey,

Bristol University

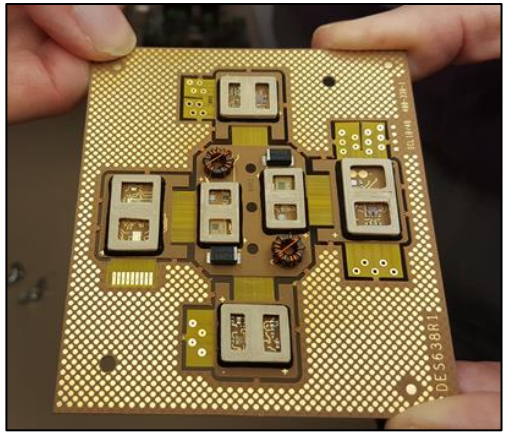
Packaging, Roadmap and Applications

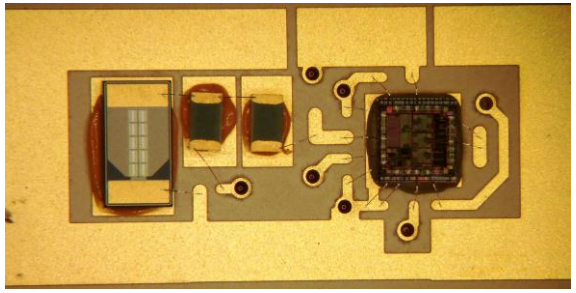
Piers Tremlett,

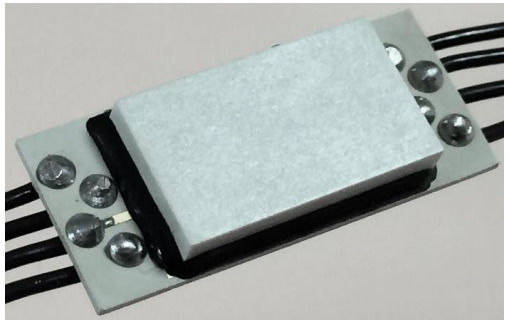
Microchip Technology Inc.

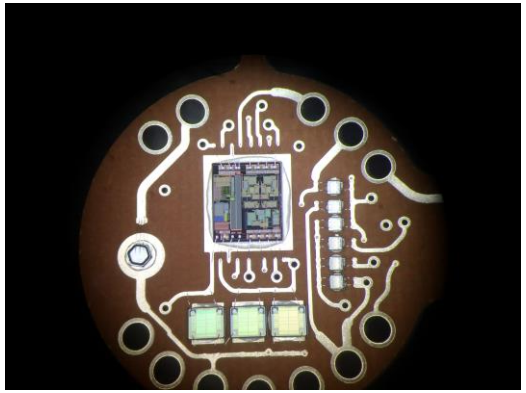
High temperature packaging

- Organic packaging from NEMICA for > 250 °C

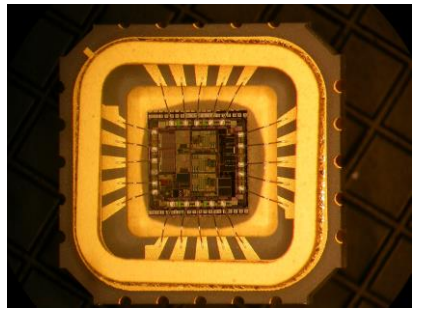


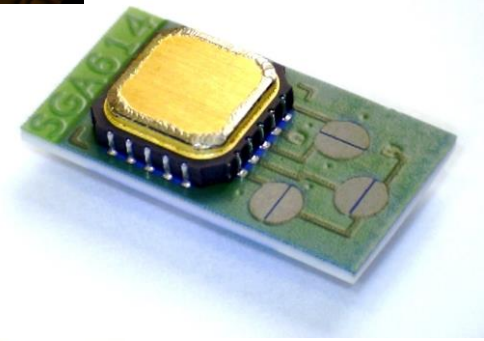


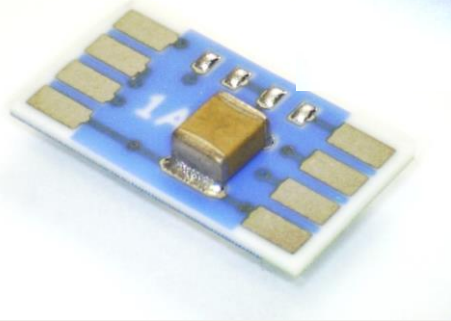




- Ceramic packaging examples
- development ongoing to reach 340 °C

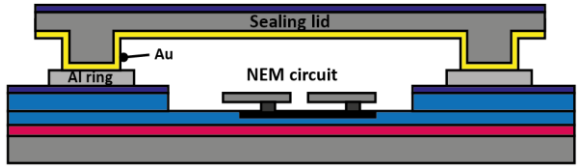


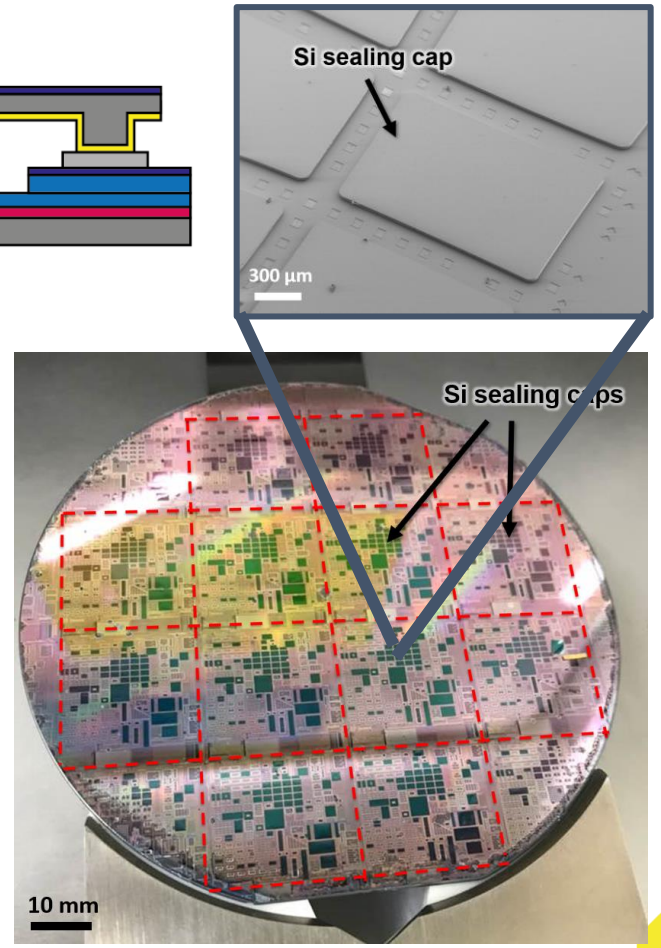




Wafer scale packaging developed in ZeroAMP

- Wafer-level sealing by Au-Al bonding enables a hermetically sealed die cavity
  - Cavity is vacuum or filled with inert gas
- Sealed cavity protects switches
  - Excludes O_2 for a longer life
  - Easier to handle the die
- Successful demonstration of wafer-level vacuum sealing.

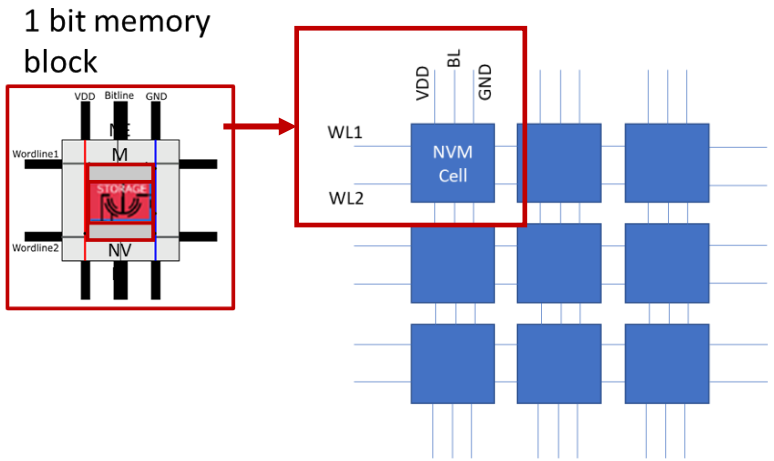


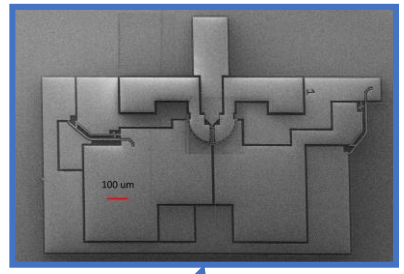


Jo, G., Edinger, P., Bleiker, S. J., Wang, X., Takabayashi, A. Y., Sattari, H., Quack, N., Jezzini, M., Lee, J. S., Verheyen, P., Zand, I., Khan, U., Bogaerts, W., Stemme, G., Gylfason, K. B. & Niklaus, F. "Wafer-level hermetically sealed silicon photonic MEMS," ***Photonics Research*** **10, A14 (2022).**

Prototyping Strategy – using SiP to test chip integration

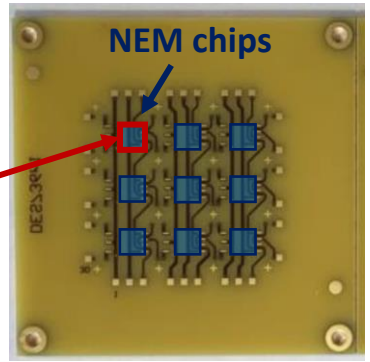
- Eg: single 1 bit memory is designed to be “tileable” in a WL / BL architecture
- 1st SiP, 1 bit chips: 3 x 3= 9 bits…… 2nd SiP, 9 bit chips: 3 x 3 (x 9)= 81 bits…etc etc
- End of project: fully integrated devices using X-FAB wafers



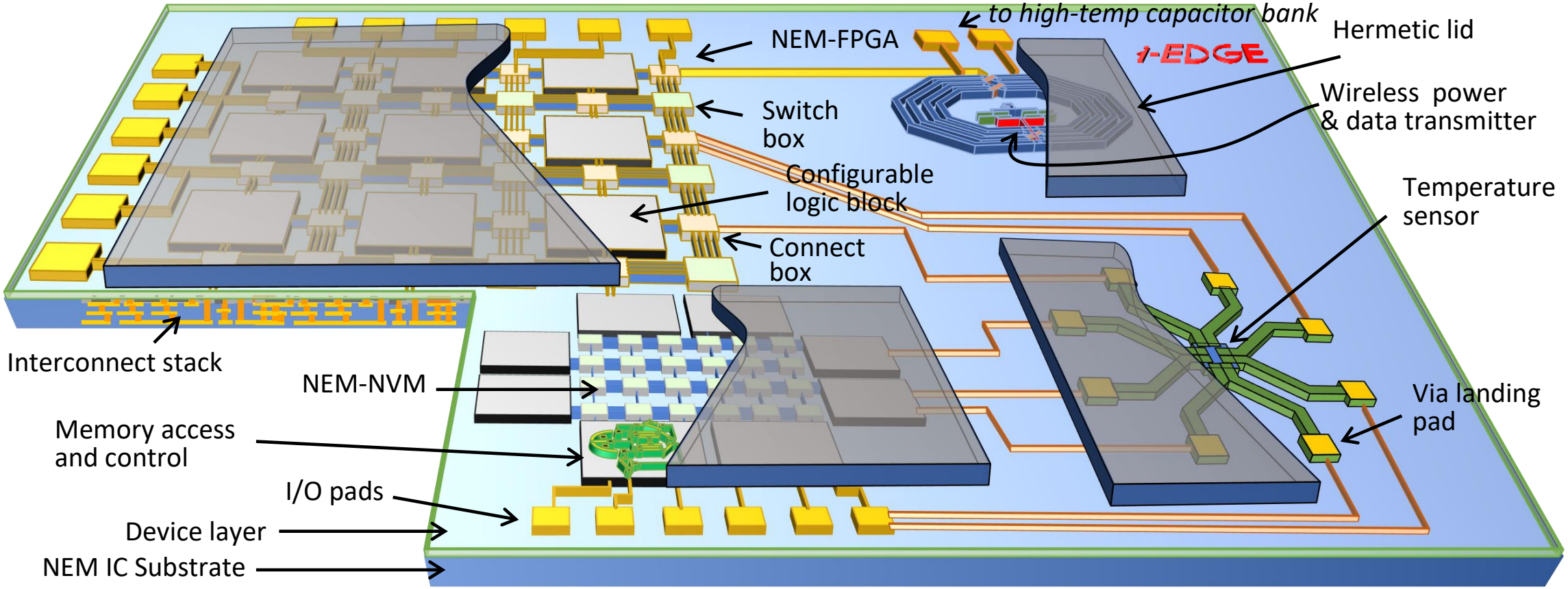


1 bit memory chip

3 x 3 bit memory chip SiP

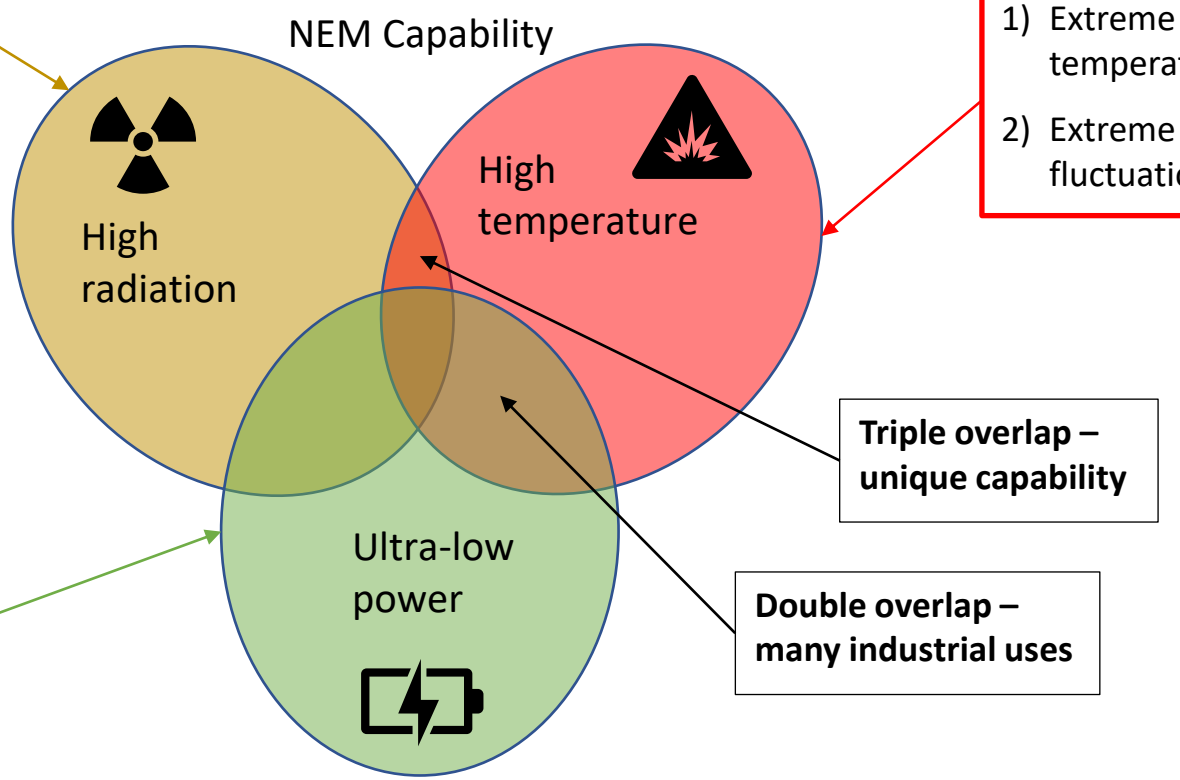


Road mapping - from System in a Package to System on a Chip



Field of Applications for NEM Switch Memory and Logic

1) Cosmic radiation
2) High radiation environments – gamma and heavy ion



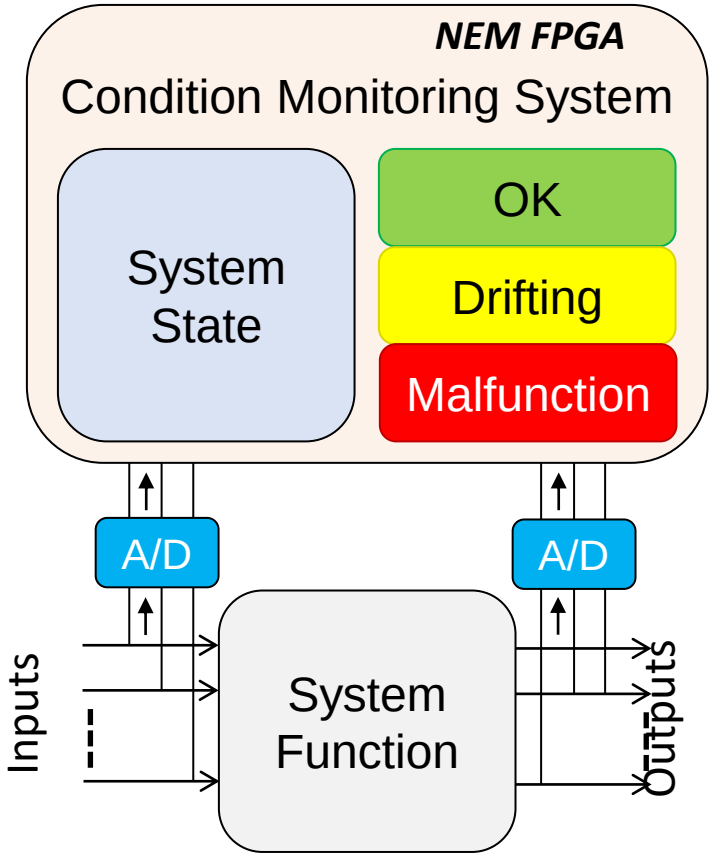
1) Extreme ambient temperature
2) Extreme temperature fluctuations

Triple overlap – unique capability

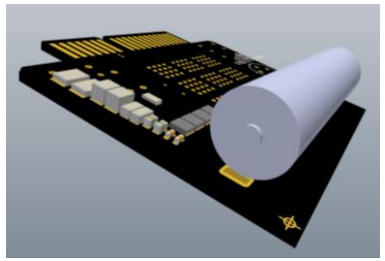
Double overlap – many industrial uses

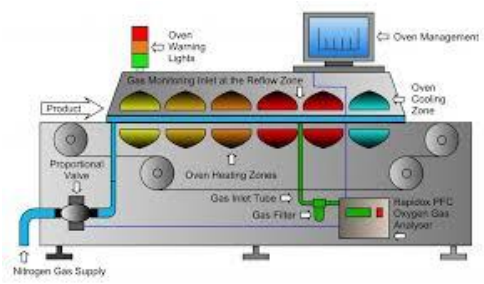
1) Areas difficult or expensive to access
2) Few or poor power sources - batteries for 150C to 340C
3) Weight or space of power sources is challenging and expensive

IoT Applications



Source: Axel Jantsch, TU Vienna





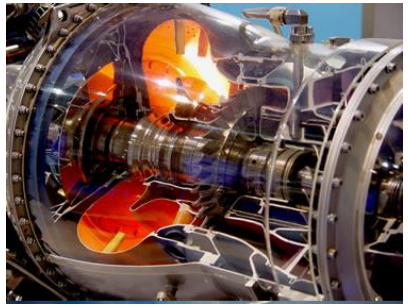
Reflow oven token: harsh environment data logging with NVM: developed in ZeroAMP

~100 devices / chip

Source: medicaldesignandoutsourcing.com

Sensor calibration: low complexity computation

~1K devices / chip

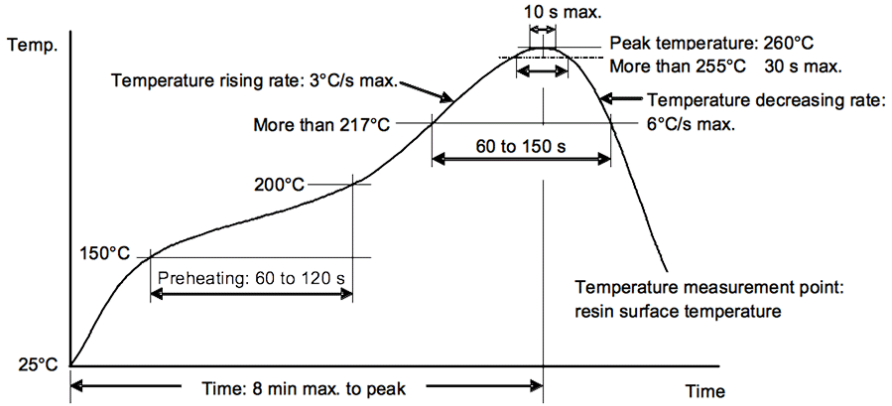


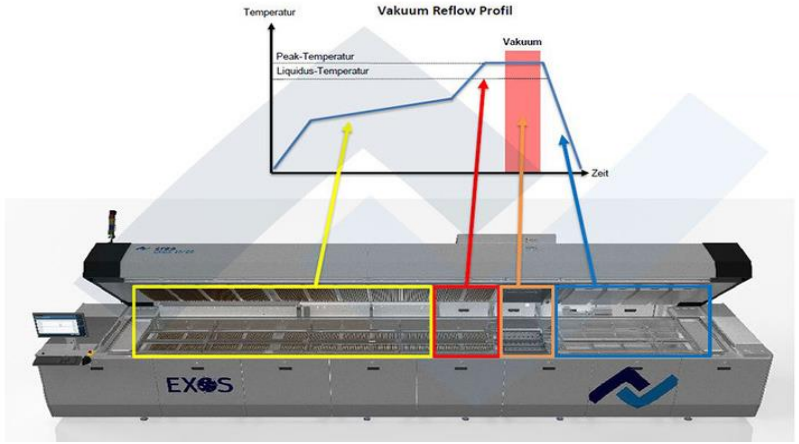
Industry 4.0 applications:
Eg - Industrial health & condition monitoring. medium complexity

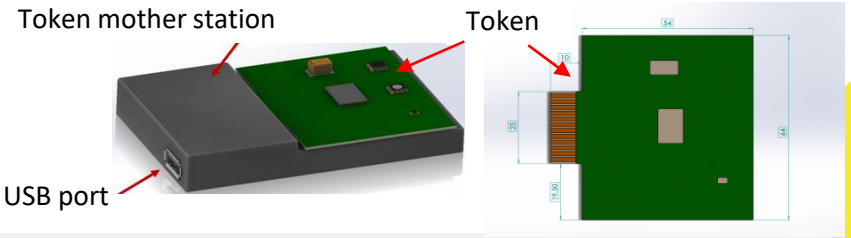
~10K devices / chip

ZeroAMP Token

- Industrial oven temperature recording “Token”
- Problems with wireless sensing in high temperature environment
  - The process has to stop to take a profile measurement
  - Electronics has to be shielded in an insulated steel box
- NEMS solution
  - Just a PCB, powered by tantalum caps, no batteries
  - Process does not have to stop- automated SPC possible
- Platform for wider IIoT / Industry 4.0
  - A “Token” tracking the entire manufacturing sequence
  - Real data…. What really happened!



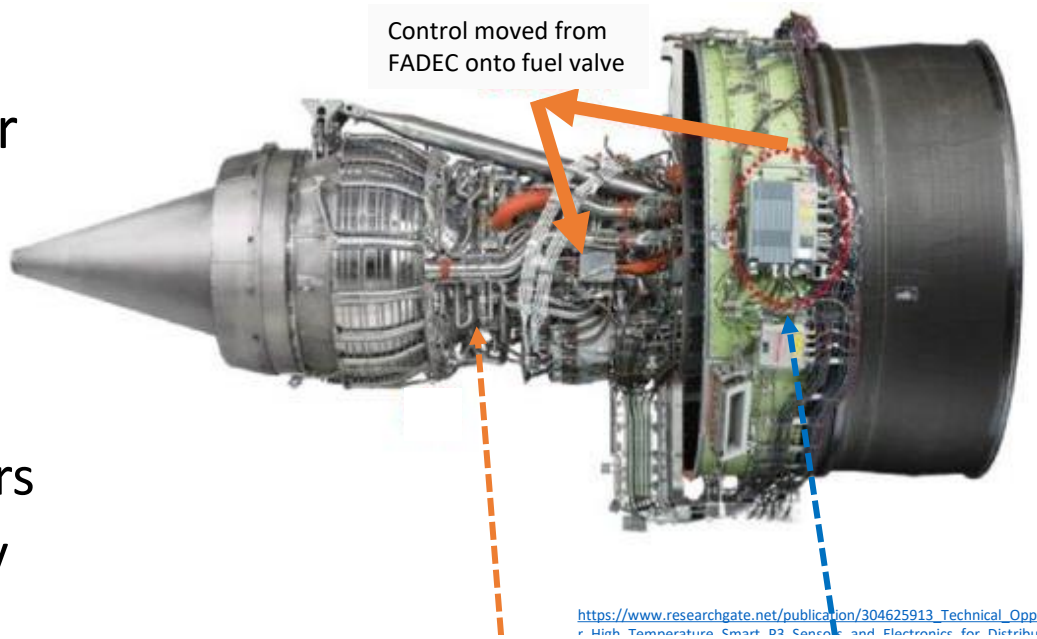




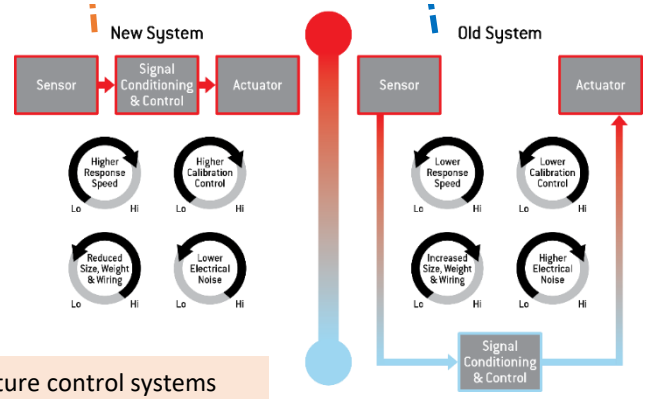
Fuel Valve Control for Jet Engine – a context aware system (NEMICA)

- Jet engine manufacturers now rent thrust/ hour
  - uptime and efficiency are paramount

- Benefits of moving the valve control
  - Local control allows more wires for more sensors
  - More bandwidth for control improves efficiency
  - Health monitoring possible - to help uptime
  - Realisation of distributed engine control (DEC)
  - NVM for boot up memory? (175 °C environment is just OK for CMOS NVM)



https://www.researchgate.net/publication/304625913_Technical_Opportunities_for_High_Temperature_Smart_P3_Sensors_and_Electronics_for_Distributed_Engine_



High temperature control systems

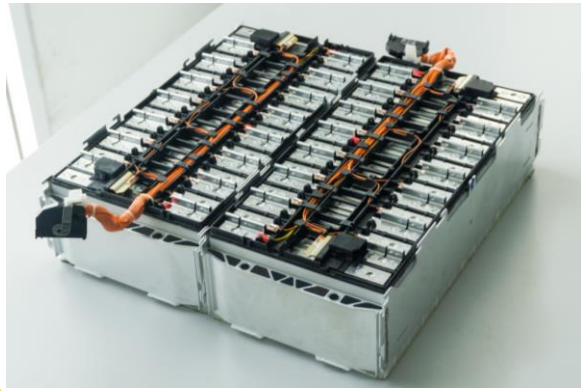
Battery Passport - Overseen by Global Battery Alliance

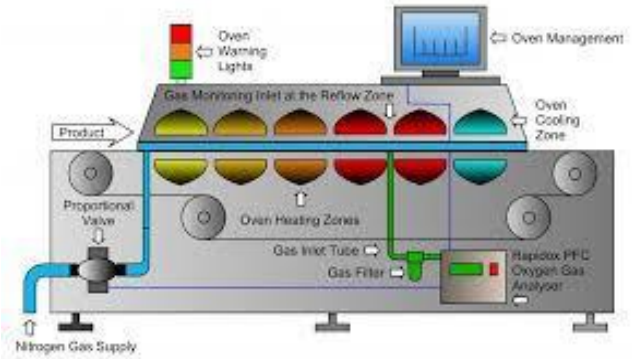
- Four stages of interest in a battery's life
  - Provenance – source of materials
  - Vehicle use: performance, charge speed, life…total energy record
  - 2nd / 3rd life – stationary energy storage….further energy record
  - Disposal and recycling
- Passport provides
  - Accountability
  - Benchmarking
  - Validates sustainability (eg: Path to Paris Agreement by 2030)

- More details in a later presentation by Andrew Moore

What is the point of NEMS switch technology

- It enables electronics for impossible environments
  - Memory and logic that can work in space, accelerators industrial ovens
  - Processing data from sensors in harsh environment… eg industrial ovens
  - Controlling system more effectively……eg jet engines
  - Tracking and recording data forever….battery passport





Zero AMP ULTRA LOW-POWER COMPUTING WITH SURVIVAL SKILLS

CONFIDENTIAL INFORMATION

www.Zero-AMP.eu

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 871740 (ZeroAMP).