Energy Harvesting 2015

Feasibility of MEMS Vibration Energy Harvesting for High Temperature Sensing

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Scope of Presentation

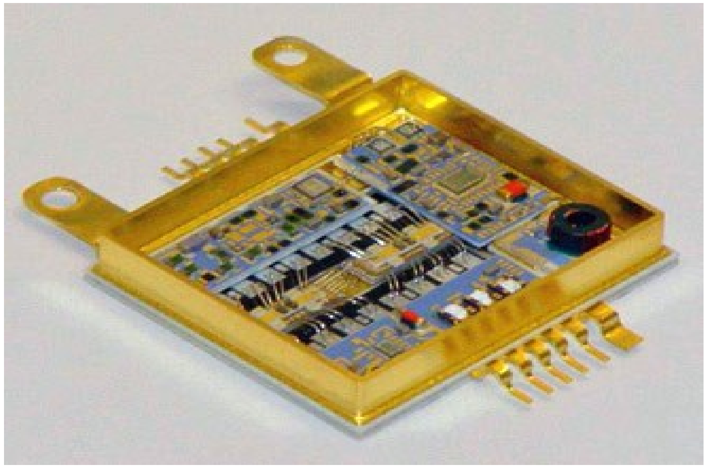
- GE Aviation – Newmarket/University of Cambridge Nanoscience Centre
- High Temperature Sensing
- MEMS devices for Vibration Energy Harvesting
- Energy Conditioning Electronics
- Summary

Background
GE Aviation Systems – Newmarket
University of Cambridge – Nanoscience Centre

GE Aviation Systems – Newmarket

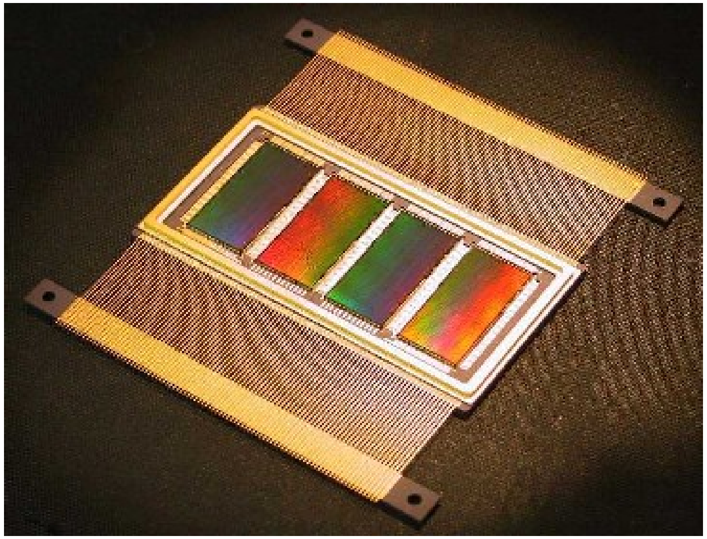
Design, manufacture and test of:

- Hybrid Circuits
- ASICs
- Solid State Power Modules
- High Temperature Electronics
- Ruggedised Displays



Solid State Power Controller

Ruggedised Displays



Multi ASIC Module

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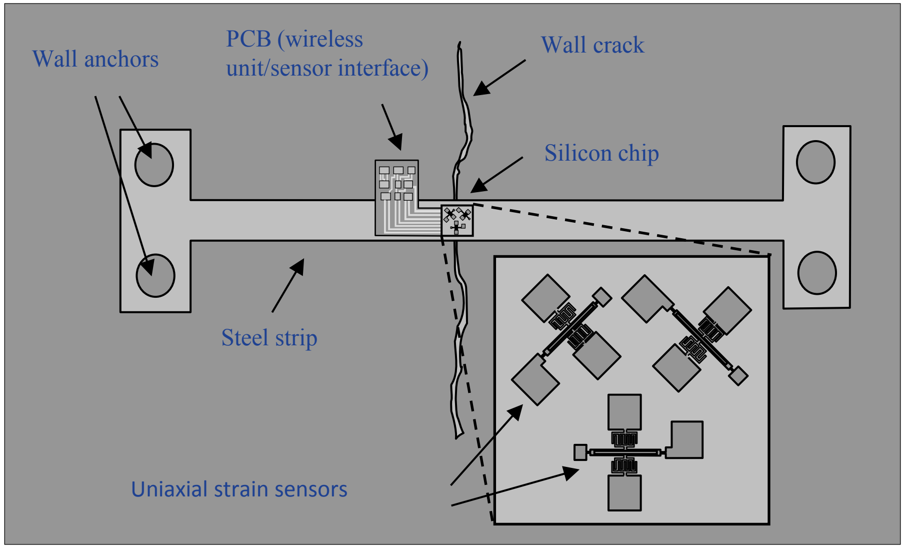
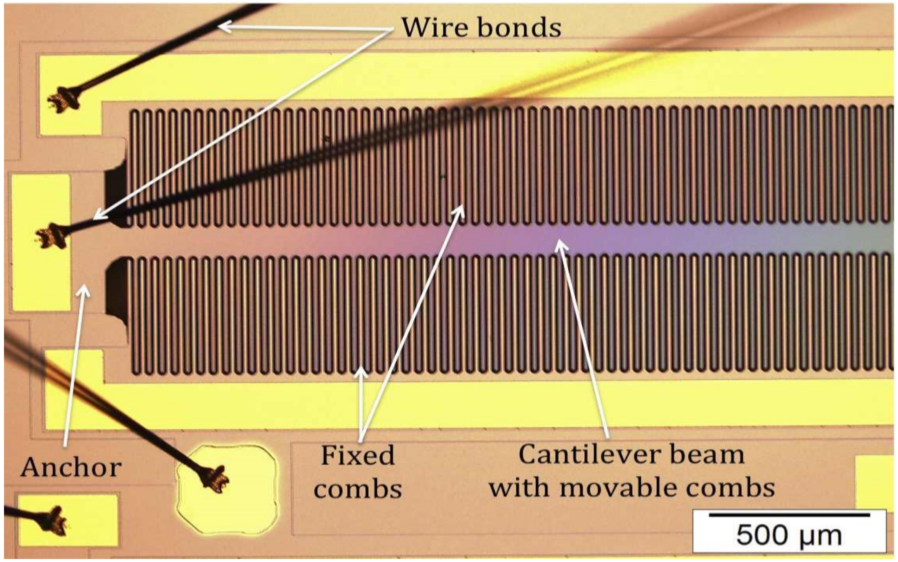
University of Cambridge – Nanoscience Centre

Research and innovation in:

- MEMS
- Sensors and sensor systems
- Vibration energy harvesting
- Interface electronics



Cambridge Centre for Smart Infrastructure and Construction (CSIC)



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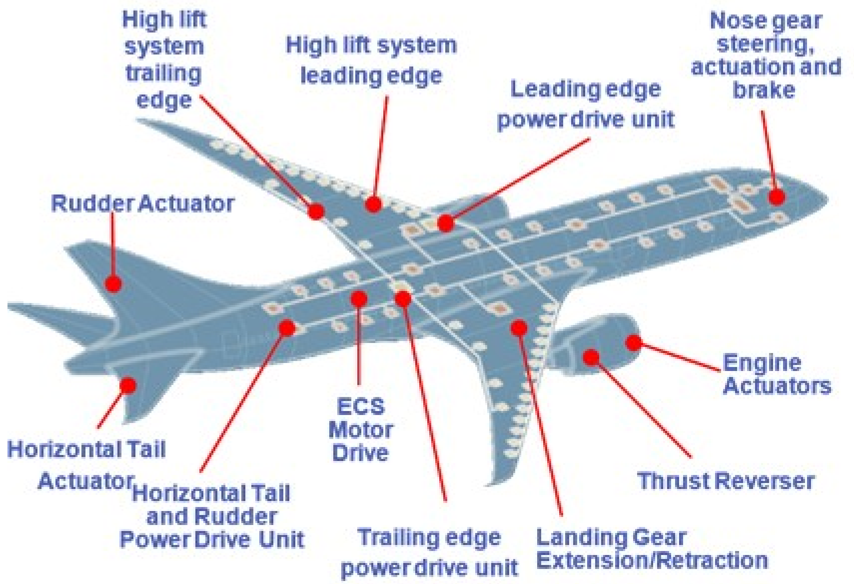
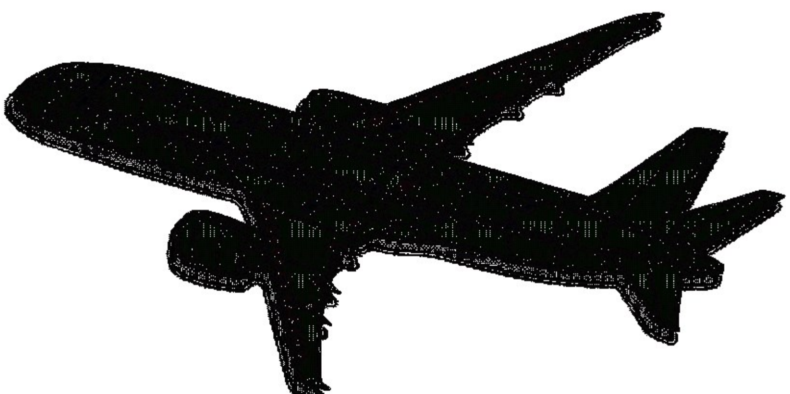
High Temperature Sensing

Distributed Power and Control



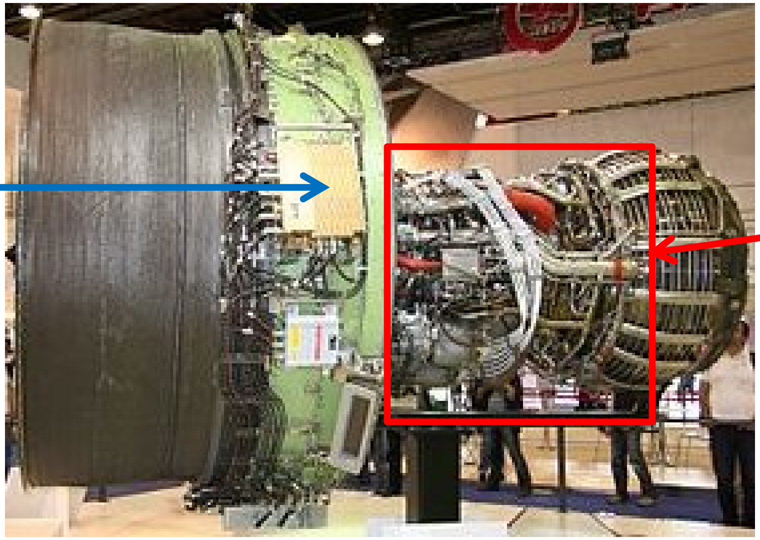


Tier 1 Integrated Power System

- Distributed electronics around aircraft to reduce cables, harnesses and cooling requirements
- Electronics to fulfil sensing, control, data transmission, drive and power requirements
- Localised control can improve accuracy and reduce noise
- Distributed electronics may need to withstand higher temperatures and wider temperature range and survive in harsher environments (e.g. vibration)
- Energy harvesting to reduce power load locally
- Wireless communication to reduce need for cables
- High voltage power distribution – reduction in wiring weight

Why High Temperature Electronics for Aero-Engines?

Typical Electronics Location



Intended High Temp Electronics Area

Distributed Controls

- Electronics near to sensor
- Improved fault isolation
- Improved sensor accuracy
- Reduced number of electrical cables
- Reduced need for cooling
- Flexibility in component placement

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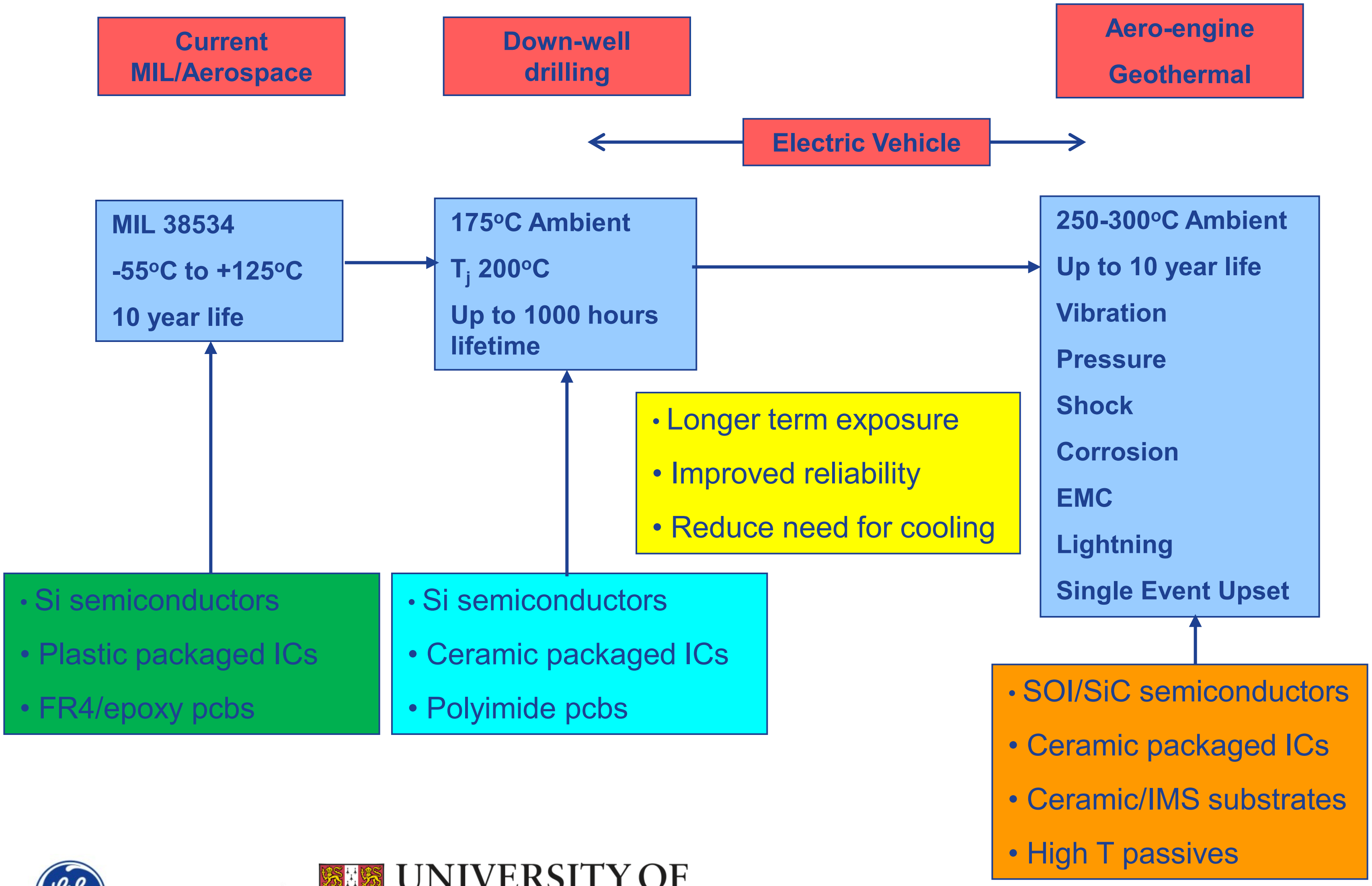
Roadmap for Extreme Environment Electronics



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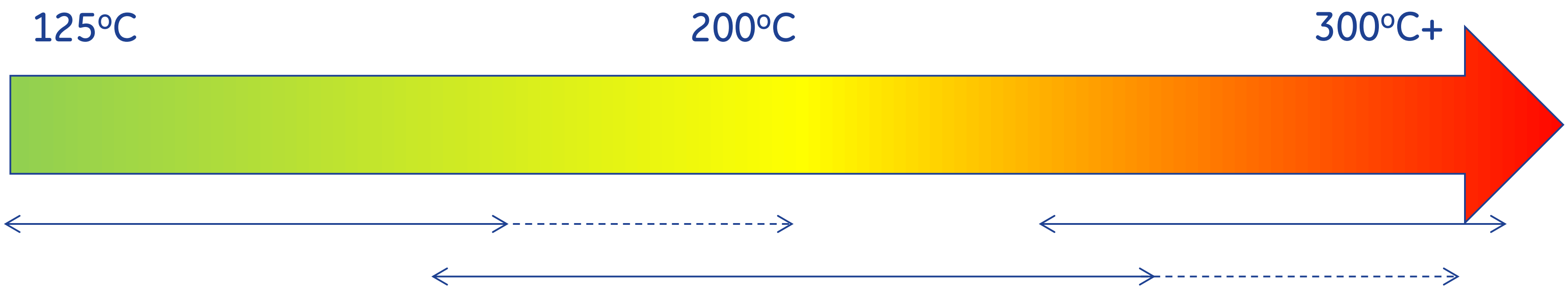
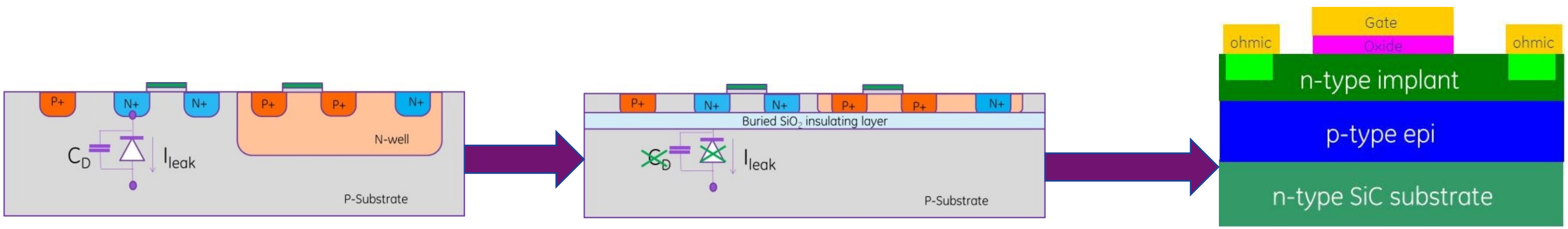
High Temp Electronic Device Technologies



Bulk Silicon

Silicon on Insulator

Silicon Carbide



Leakage current increases with temperature

Reduced junction area reduces leakage

Inherently low leakage -- low intrinsic carrier concentration

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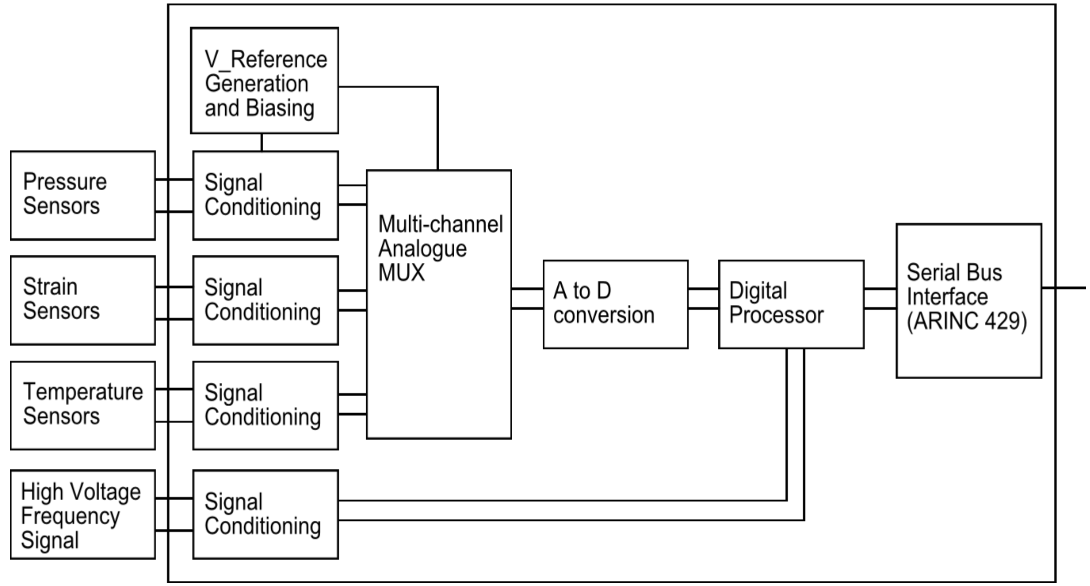
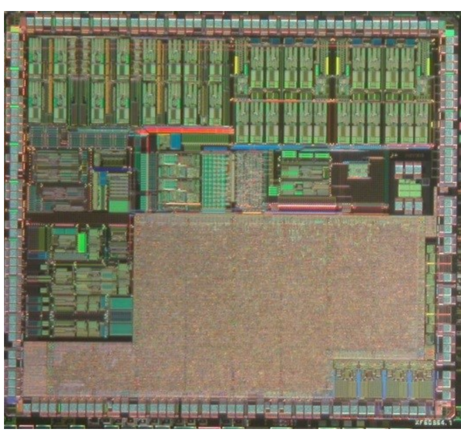
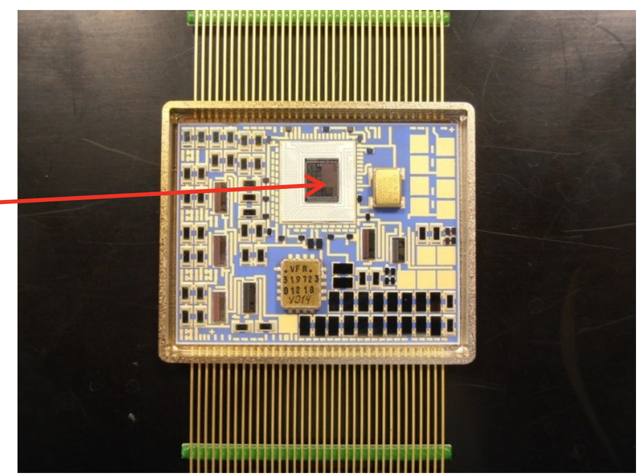
High Temperature Multi-Sensor Signal Conditioning

- Digitise information from sensors to reduce cables and improve accuracy
- Input from multiple sensors, integrated with logic and databus on ASIC
- High temperature electronic packaging





High Temp ASIC

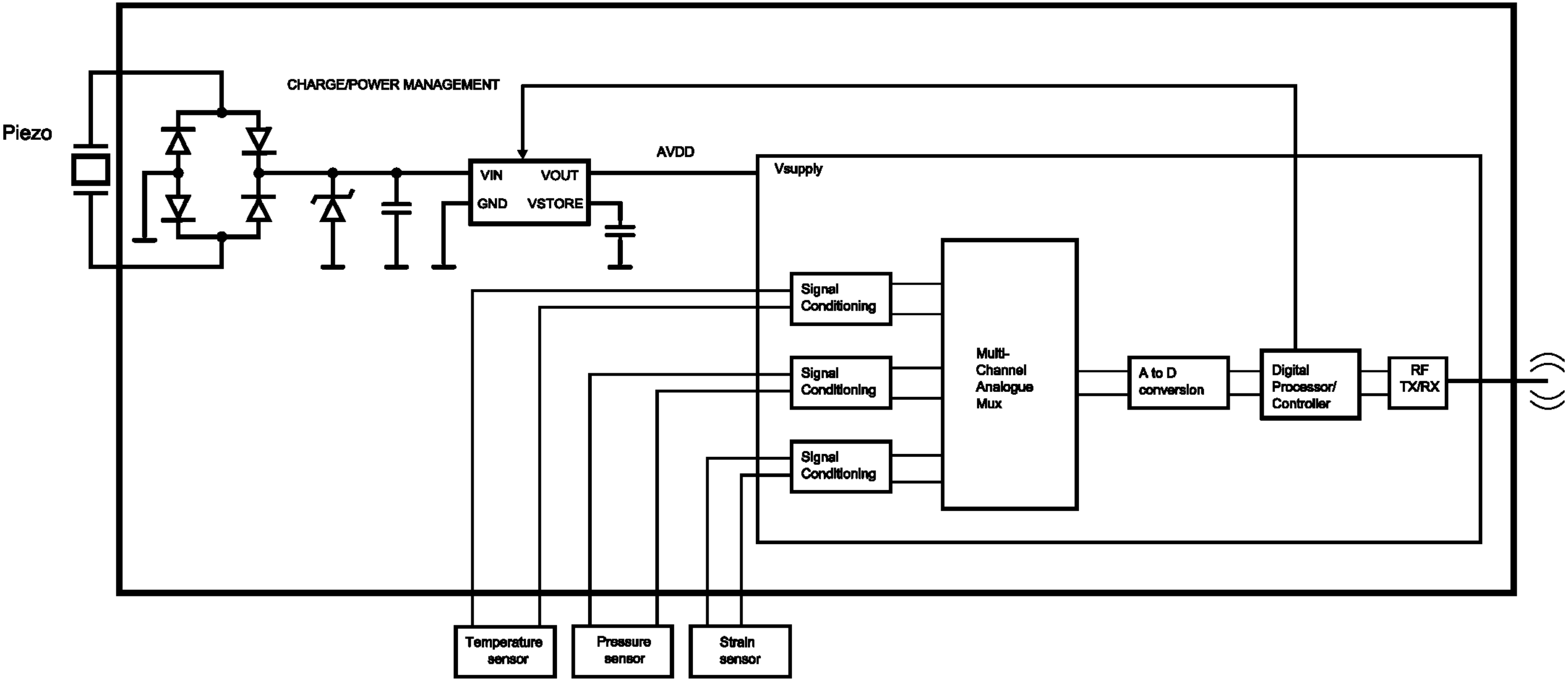


High Temp Hybrid Circuit

Energy Harvester, Sensor Signal Conditioner and Wireless Transmission

Piezo sensor + power management
RF transceiver
Signal conditioning

250 ^{0}C
Strong interference
Harsh propagation environment



MEMS Vibration Energy Harvesting

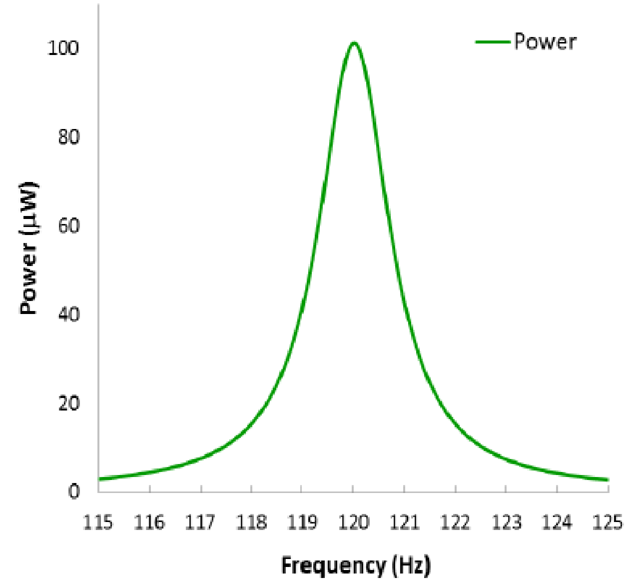
Definition of Vibration Environment

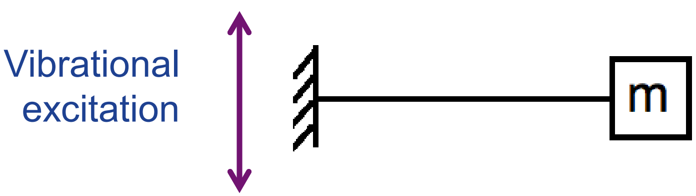
- DO-160 Section 8 defines a range of vibration tests that are carried out on aircraft equipment to demonstrate that the equipment can withstand the vibration environment
- The vibration environment changes depending on the type of aircraft (e.g. turbojet, turbofan, propeller, helicopter) and the location within the aircraft (e.g. engine and gear box, landing gear, wheel well)
- The vibration profile can be random, sine wave and more complicated random on random or sine on random waveforms
- For the initial exercise a random profile of 0.1g2/Hz from 10Hz to 2000Hz was selected to create some baseline data to assess the potential energy levels from a MEMS harvester

Vibration Energy Harvesting

Challenges

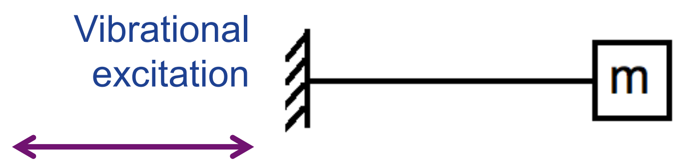
- Limited power levels from conventional directly forced resonance
- Confined frequency response despite broadband nature of real vibration





$$m\ddot{x}+c\dot{x}+kx+\mu x^3 = F(t)$$

Direct resonance



$$m\ddot{x}+c\dot{x}+k(t)x+\mu x^3 = F(t)$$

Parametric resonance

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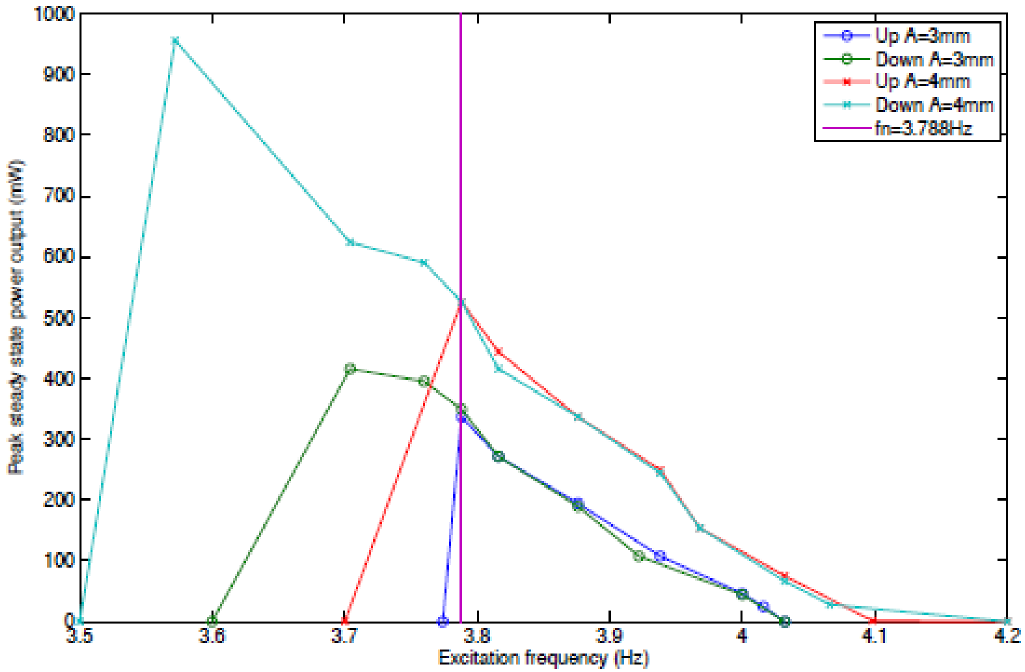
Advantages of parametrically excited systems



- Stores an order more energy in the system: significantly improved mechanical-to-electrical transduction efficiency.
- Offers non-linear resonant peaks: this widens frequency band.
- Demonstrated:
  - 10x improvement in harvested power densities.
  - 3x improvement in the bandwidth for a given order of resonance.

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MEMS Vibration Energy Harvesting Device

Design of MEMS Energy Harvester for Random Vibration Specification

- Optimisation of output from random vibration profiles
- Multi-resonant regime design to capture broader band of frequency
- Implement design principle from macro-scale
- Adding weight to cantilevers
- Effect of pressure on performance

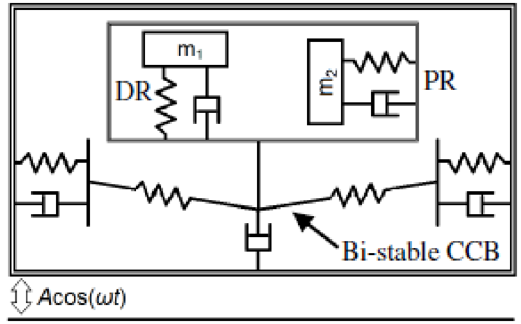


Figure 5: Model view of directly and parametrically excited bi-stable resonator with side springs.

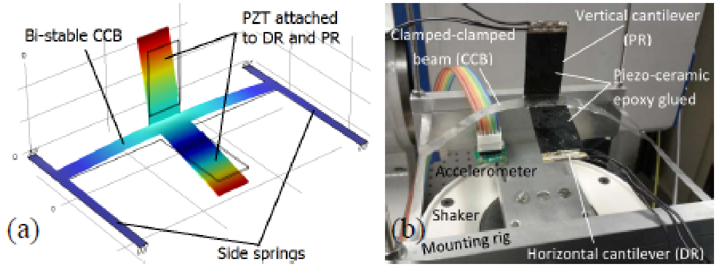
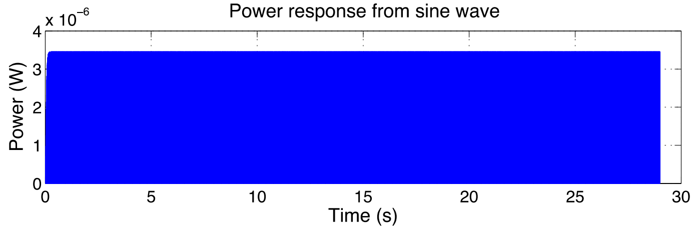


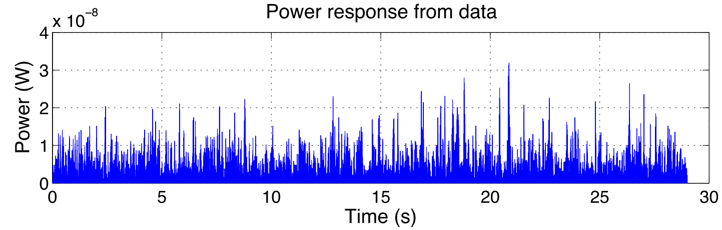
Figure 6: COMSOL model and experimental prototype for the concept presented in Figure 5.. With vertical excitation, the vertical cantilever acts as PR and the horizontal cantilever acts as DR. Both subsidiary resonators rest on a pre-stressed CCB. The two side springs aid the modulation of the potential barrier and increase the probability of snap-through.

Piezoelectric Material Properties and Predicted Power Output

	AlN	PVDF	PZT5-H2	PZT806	ZnO	LiNbO3	PMN-PT
E (Pa)	**3.30E+11**	**2.50E+09**	**6.30E+10**	**8.86E+10**	**2.10E+11**	**2.00E+11**	**1.20E+10**
Density (kg/m^3)	3260	1780	7450	7600	5610	4700	8069
Curie temperature (C)	2000	195	195	300		1140	138
Max. operating (C)	700	150	110	175			
d31 (C/N)	**2.00E-12**	**2.80E-11**	**-2.74E-10**	**-1.04E-10**	**-5.00E-12**	**-5.95E-12**	**-7.97E-10**
relative permittivity	**9**	**12**	**3400**	**1250**	**10**	**84**	**5650**

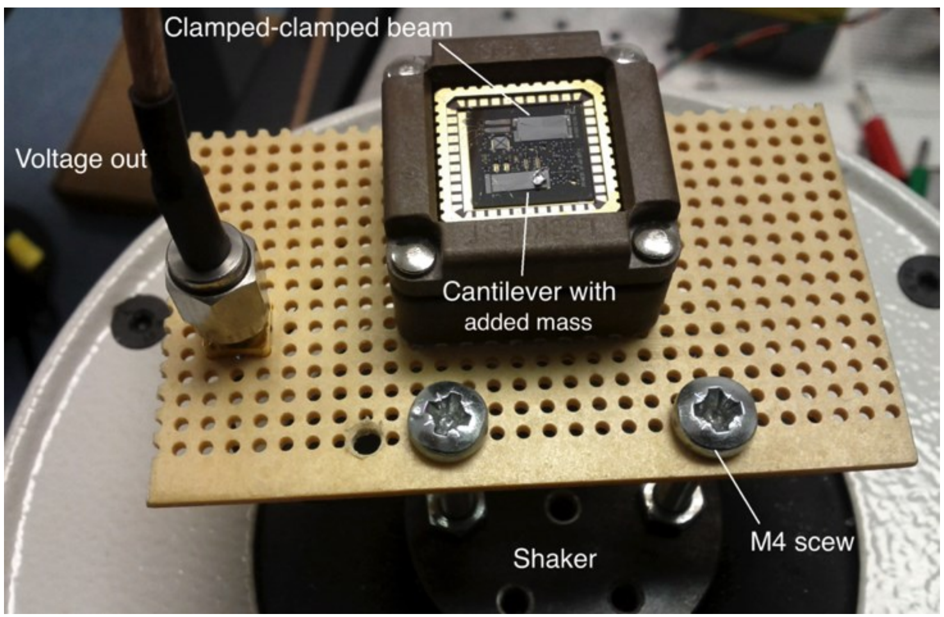
Power Output and Cantilever Design

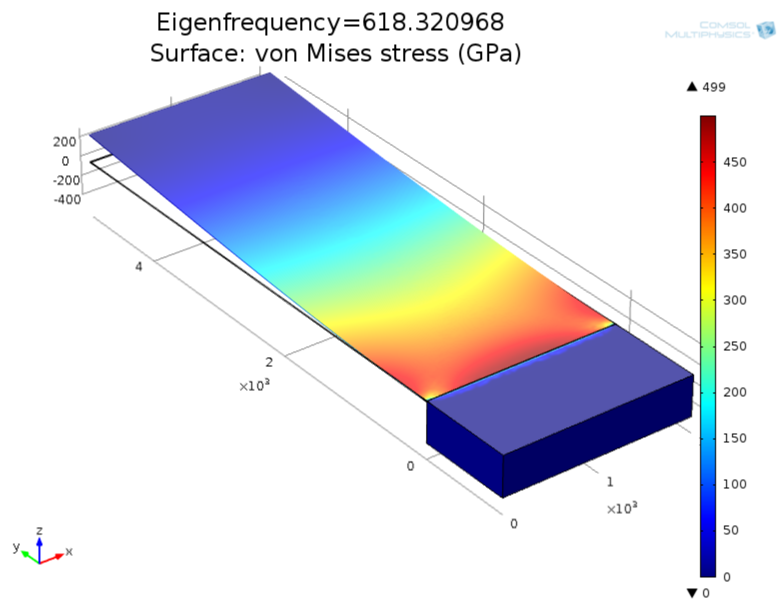




Theoretical >3μW from sine wave

Theoretical 0.1μW from random vibration





Random Vibration Power Output

Average power: 0.73 μW

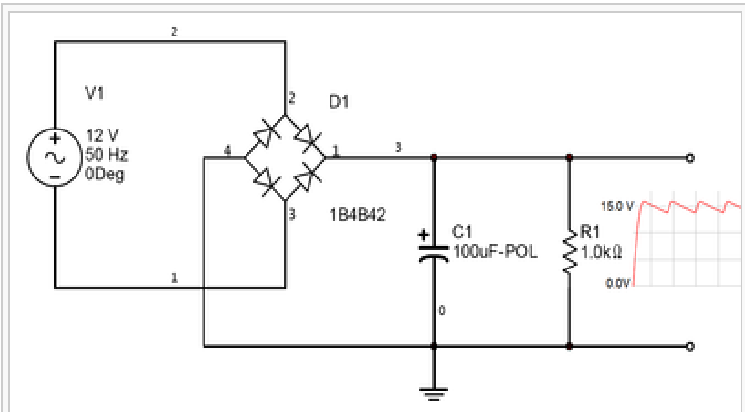
Peak power: 3.29 μW

Max attainable: ~10 μW

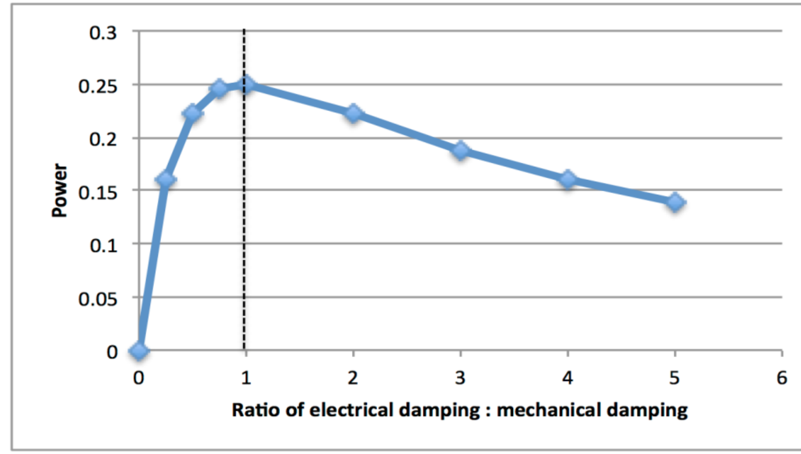
Energy Conditioning Electronics

Energy Conditioning Electronics

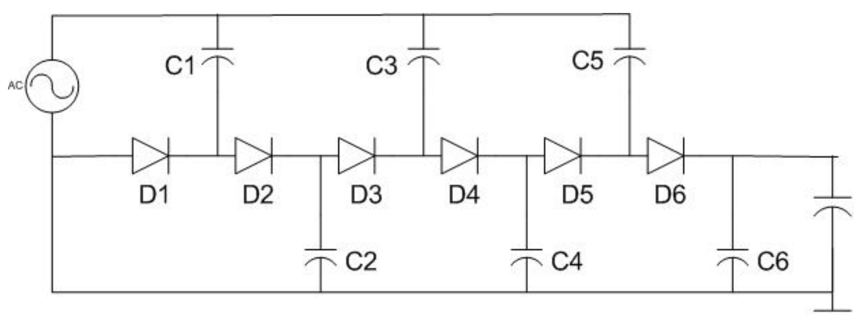
Energy Rectification



Impedance Matching



Voltage Multiplication



- Impedance matching is critical to ensure maximum power transfer by matching the source impedance to the load impedance
- Capacitors may be required for smoothing and/or as an energy reservoir

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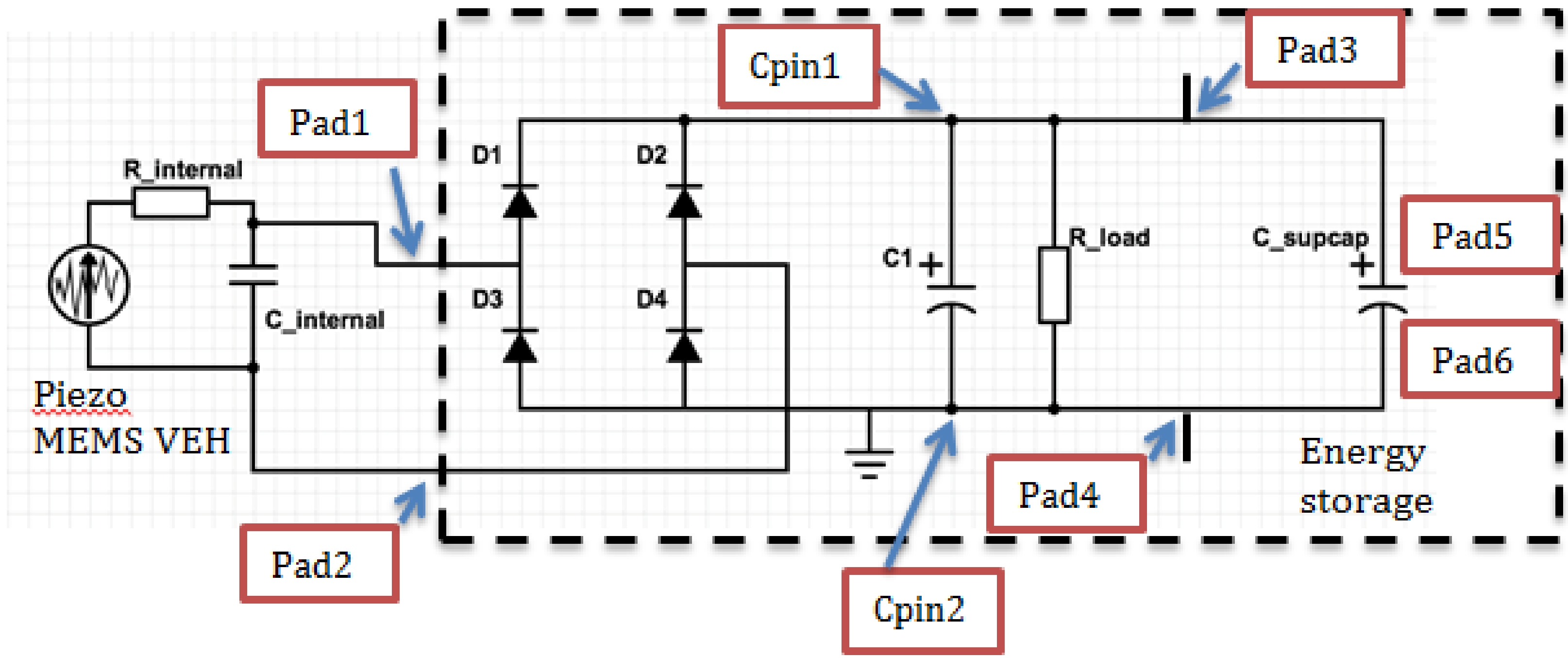
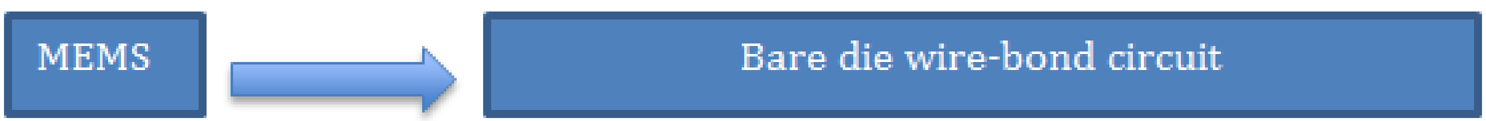
Full Wave Rectifier Circuit Outline

Simple full wave rectifier circuit





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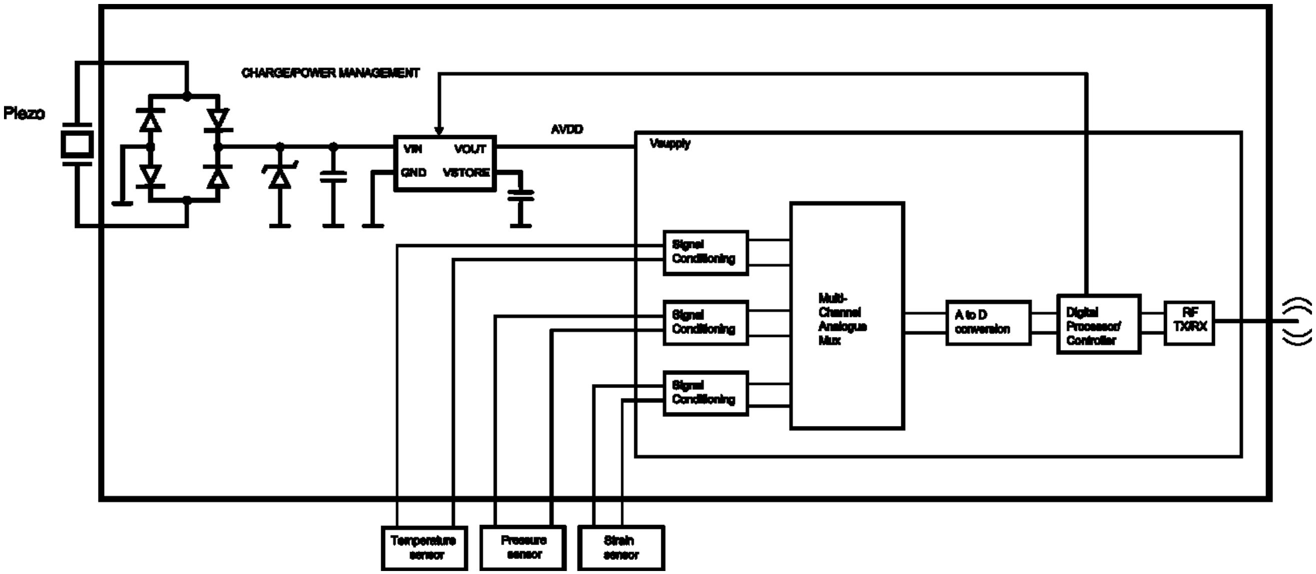
Desired Outcome:
Remote Smart Sensors for HT Distributed Control



Piezo sensor + power management
RF transceiver
Signal conditioning
Signal feedback to close loops

250 ^{0}C ambient
Strong interference
Harsh propagation environment

Remote Smart Sensors

- Reduces tubing weight
- Reduces I/O on FADEC and EMU
- Improves dynamic response on loops
- Reduces cable weight
- Simplifies FADEC circuitry
- Reduces heat load
- Actuators provide own diagnostics

Remote Self-Powered Smart Sensors

- Scavenge vibration and/or heat
- Reduces cable weight
- Eliminate batteries
- Reduces FADEC power requirement
- (Wireless) - Eliminates wiring between FADEC and sensors

Power Harvested vs Power Required for HT Sensing

1 µW

10 µW

100 µW

1000 µW
1mW

10000 µW
10mW

100000 µW
100mW

1000000 µW
1000mW
1W

AlN EH
Random
Vibration

Simple sensor conditioning
Op-amp gain

Complex sensor conditioning and processing
Op-amp gain
Multiplexing
ADC
Logic

Challenges

- Optimisation of MEMS design
- Multiplying no of devices
- Integrated packaging to minimise losses
- Alternative PZ materials
- Ultra low power sensing circuits (e.g. compressed sensing)

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MEMS Vibration Energy Harvesting for HT Sensing Summary

- Within the aerospace and down-well industries, where extreme environment electronics is required for multiple sensing applications, there is interest in reducing weight of cables and eliminating the use of batteries
- MEMS devices for vibration energy harvesting from random vibration profiles have been demonstrated with potential for high temperature sensing applications
- Energy conditioning electronics is being developed for operation in ambient temperatures of up to 250°C
- The power output available from the MEMs vibration energy harvesting needs to match the sensing power budget and further developments in the design of the MEMS devices and the sensing requirements are needed to close the gap between power output/power required

Acknowledgements

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