Advances in vibrational energy harvesting for applications in IoT

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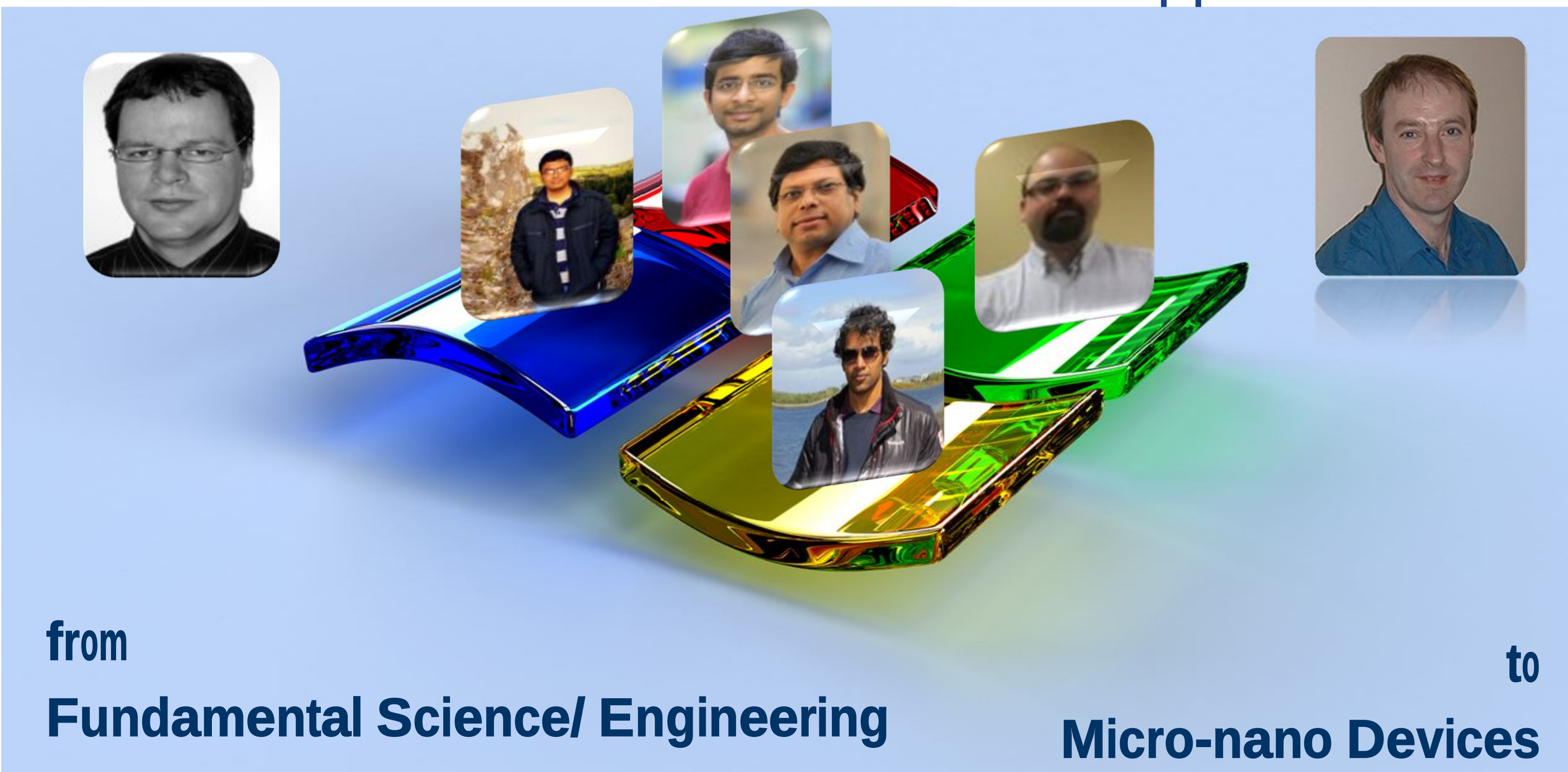
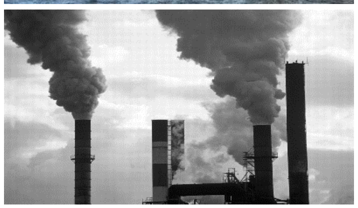
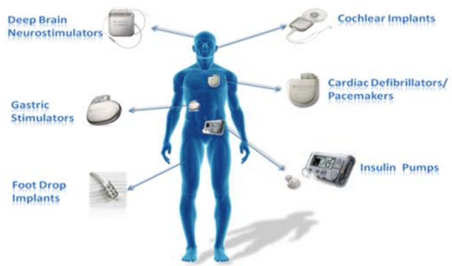


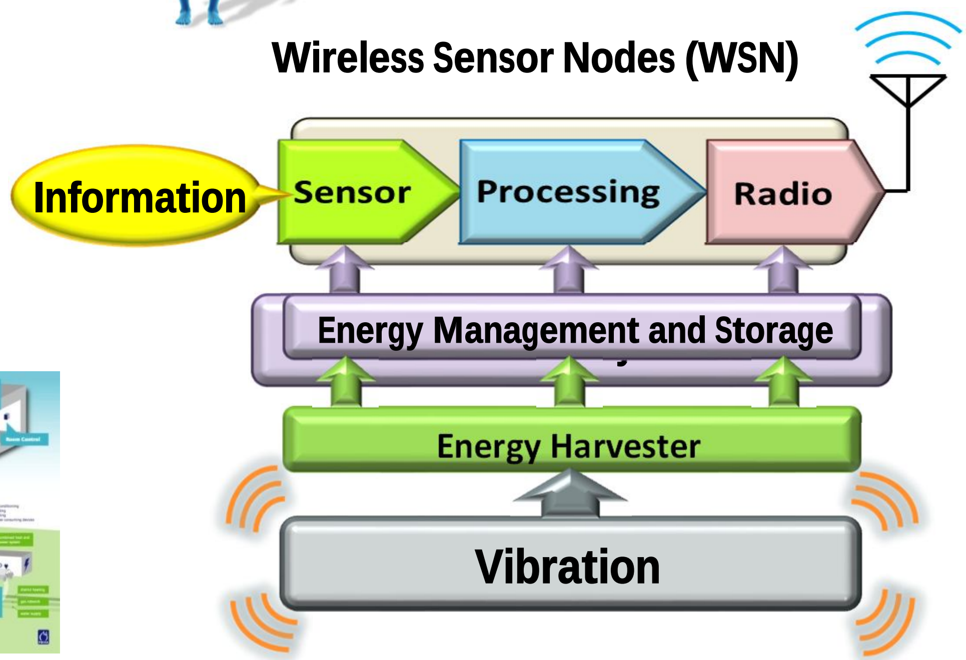
WSN and Vibrational Energy Harvesting for IoT

By 2020: 25 billion WSNs, $10 billion WSN market.

Application Environment

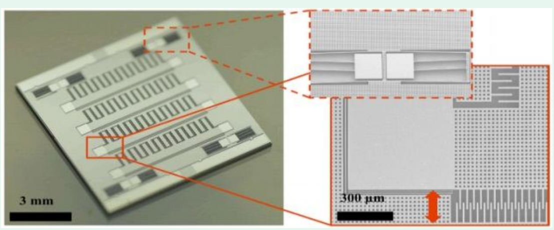
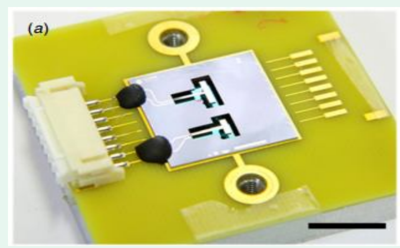
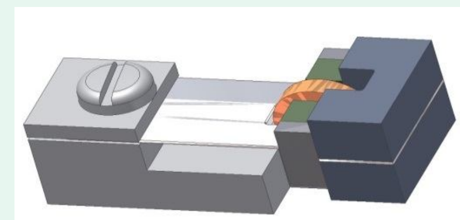






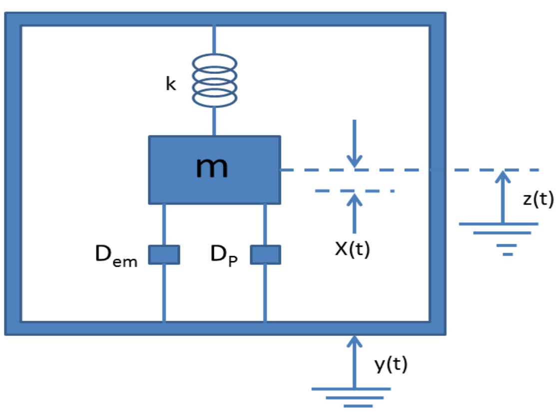
Ambient vibration sources

Different Transduction Methods

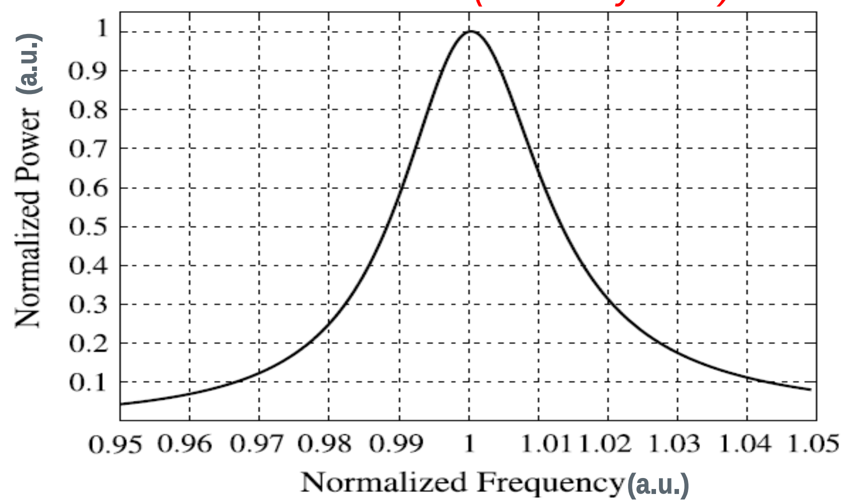
Electrostatic	Piezoelectric	Electromagnetic
These are based on changing capacitances that plates will undergo due to vibration.	**A potential difference occurs in Piezoelectric materials under strain.**	**Based on Faraday's Law, when a conductor moves through a magnetic field, a potential difference is induced.**
		
• High o/p voltage at low operational voltage • High impedance values > matching network, design complexity, extra power loss	• Active materials for fabrication • High output Voltage • Low output Current	• Do not need any extra component like electret. • Output current is high but voltage is low

Vibration Energy Harvesting

- Mechanical vibration energy converted into useable electrical energy.
- Systems are based on mass-spring-damper topologies.
  - Resonance optimal condition for maximum energy conversion
  - Transduction mechanisms: electrostatic, piezoelectric, electromagnetic



(Linear system)

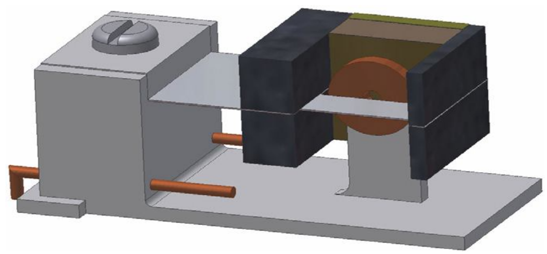


$$m\ddot{z}(t) + (D_P + D_e)\dot{z}(t) + kz(t) = -m\ddot{y}(t)$$

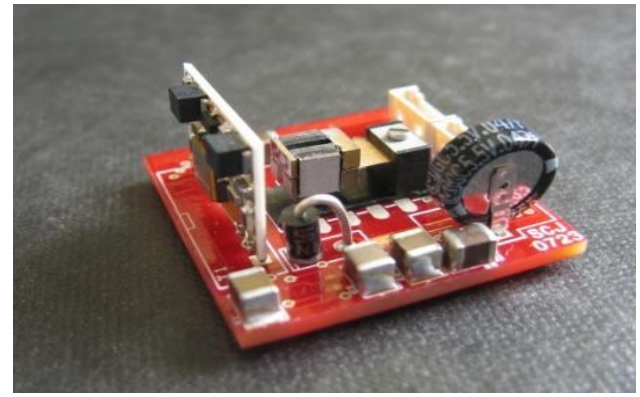
Comparison of vibration based linear power generators-EU project: 'VIBES' (In collaboration with University of Southampton)

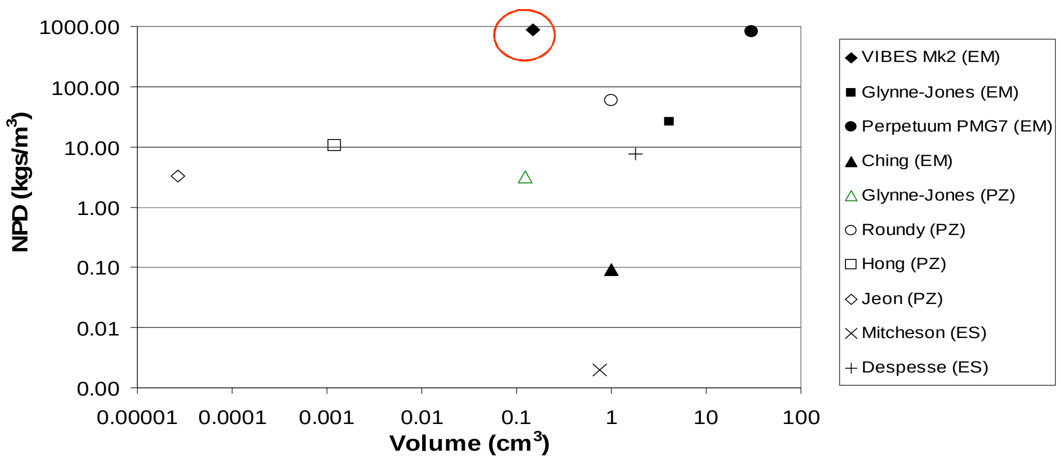
Highest Normalized Power Density $NPD = \frac{P}{A^2 V}$

P- Stated power, A- acceleration, V- volume



EM-VEH in an autonomous sensor module



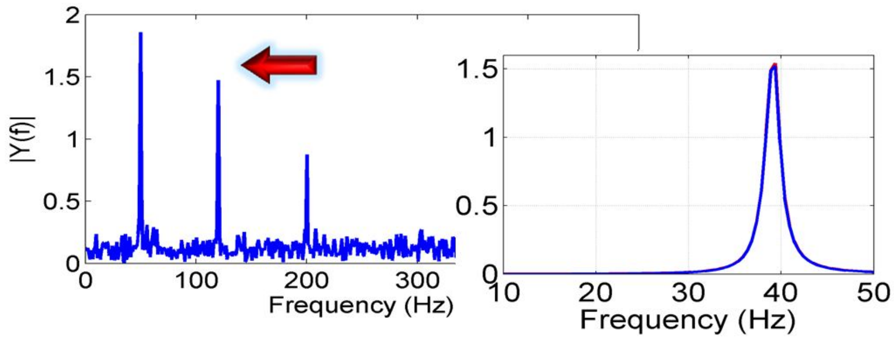


State	Time	Avg. Power	Energy/cycle
Ref. Voltage	68 µs	1.95 mW	133 nJ
Sensor reading	32.7 ms	1.62 mW	51.9 µJ
Transmit	9 ms	2.4 mW	10.8 µJ
Sleep mode	3.24 s	0.784 µW	2.54 µJ
Total duty cycle	3.28 s	21.3 µW	65 µJ

- Measurement Science & Tech, ***19***, *125202 (2008)*
- BBC technology news *http://news.bbc.co.uk/2/hi/technology/6272752.stm*

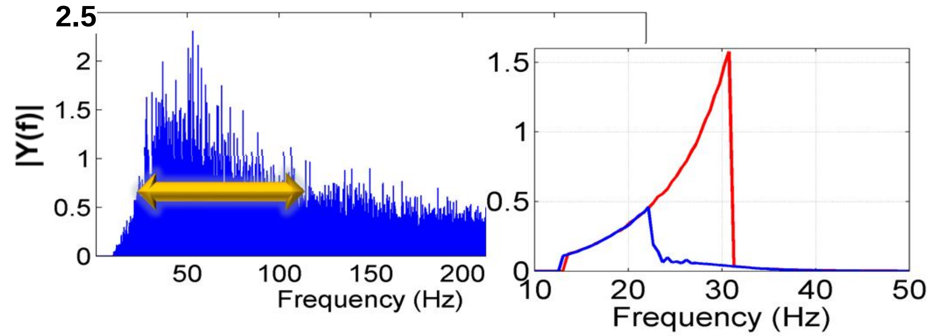
Vibration Sources – low frequency

Resonant, Impulse, Shock



Linear VEH

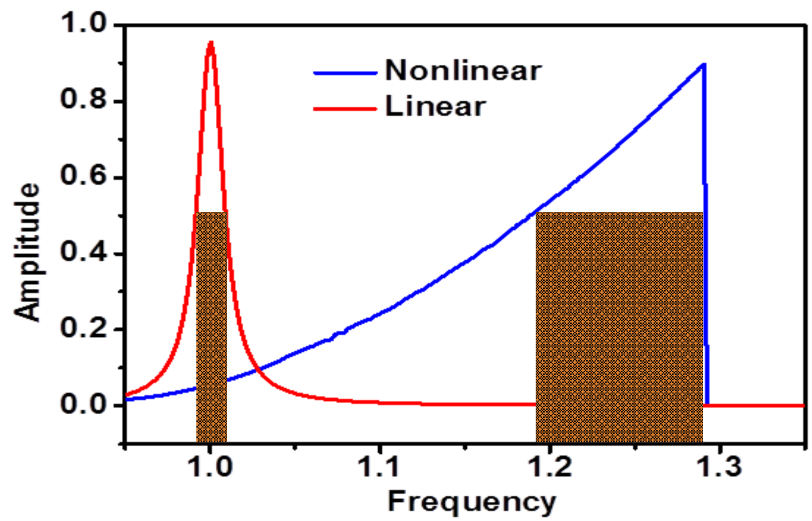
Broadband, Random, Noise

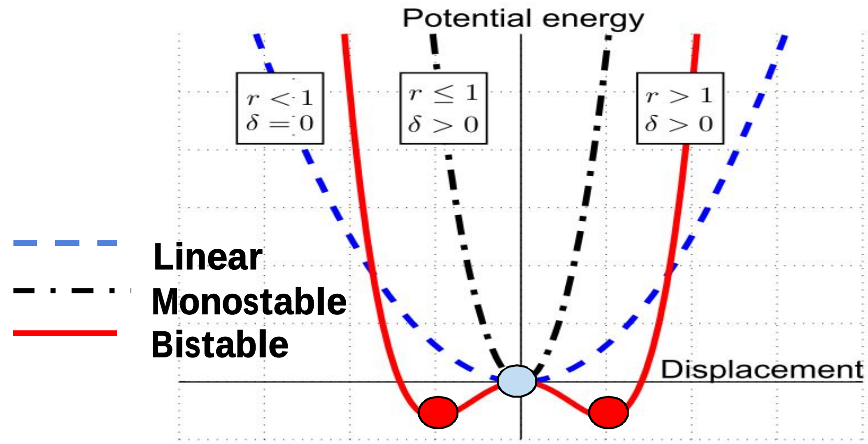


Wideband VEH

Nonlinear Energy Harvesting

Nonlinearity introduced through modified stiffness of the devices → **broader frequency response**





$$\ddot{x} = -\frac{dU(x)}{dx} - \gamma\dot{x} + f(t)$$

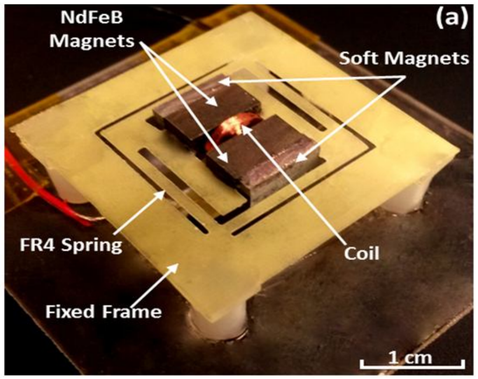
$$U(x) = -\frac{1}{2}\alpha(1-r)x^2 + \frac{1}{4}\beta x^4 \qquad \delta = \frac{\beta}{\alpha}$$

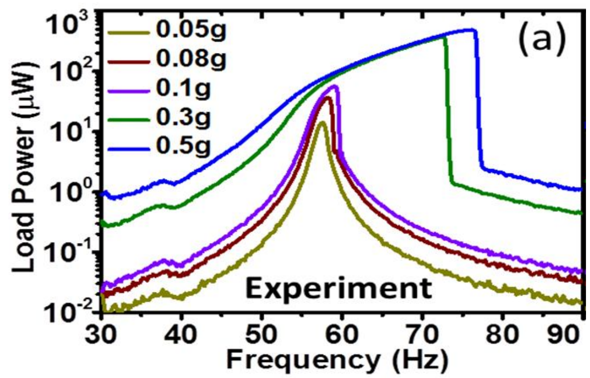
α, β are constants

r - determines nature of nonlinearity

Miniaturized Nonlinear EMPG Systems

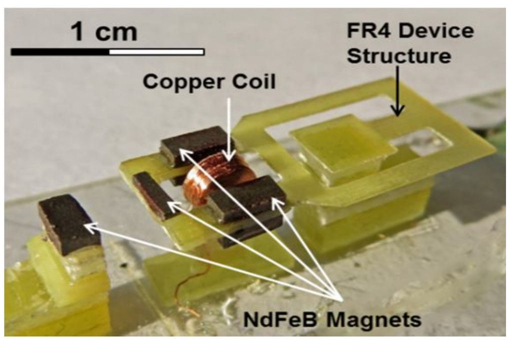
Monostable Nonlinear EMPG

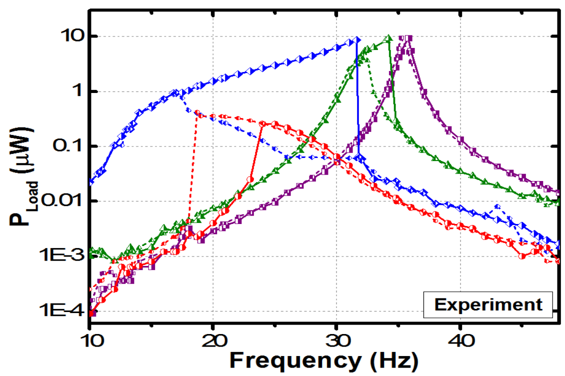




- Monostable nonlinearity from stretching strain in addition to bending of fixed-fixed beams.
- 0.5 mW of peak power under 0.5g acceleration

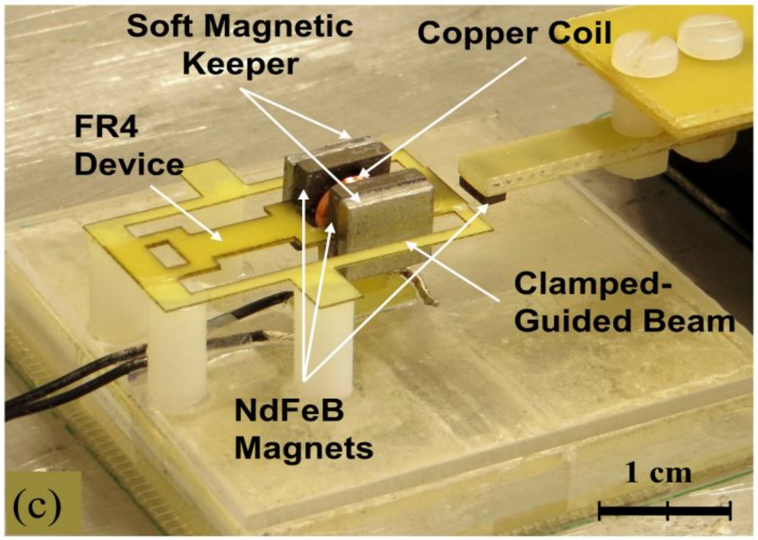
Bistable Nonlinear EMPG

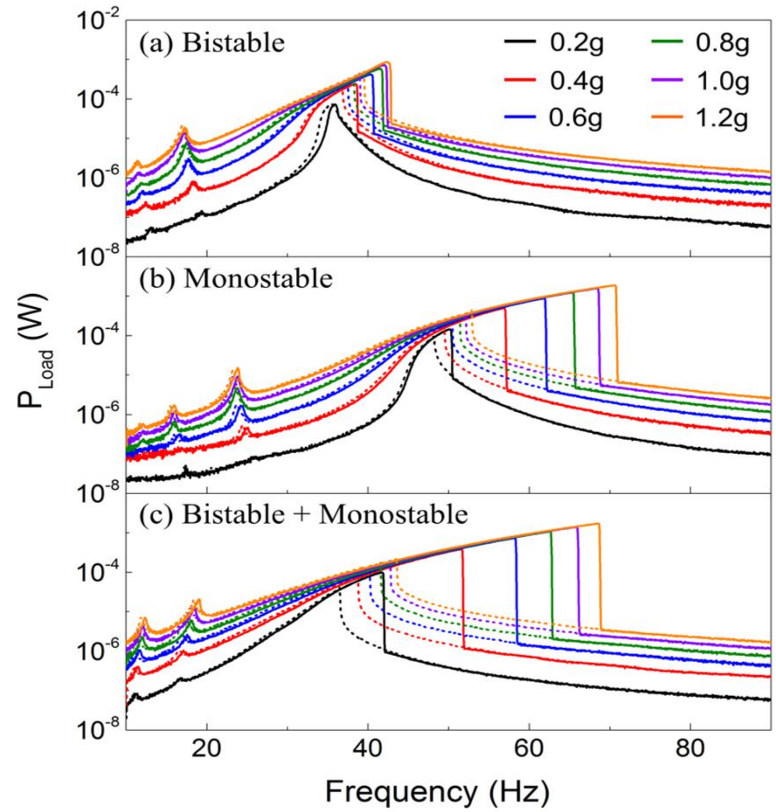




- Bistable nonlinearity from magnetic repulsive interaction.
- 29µW of power under 0.5g acceleration.

Combined Effect – Multiple Nonlinearity



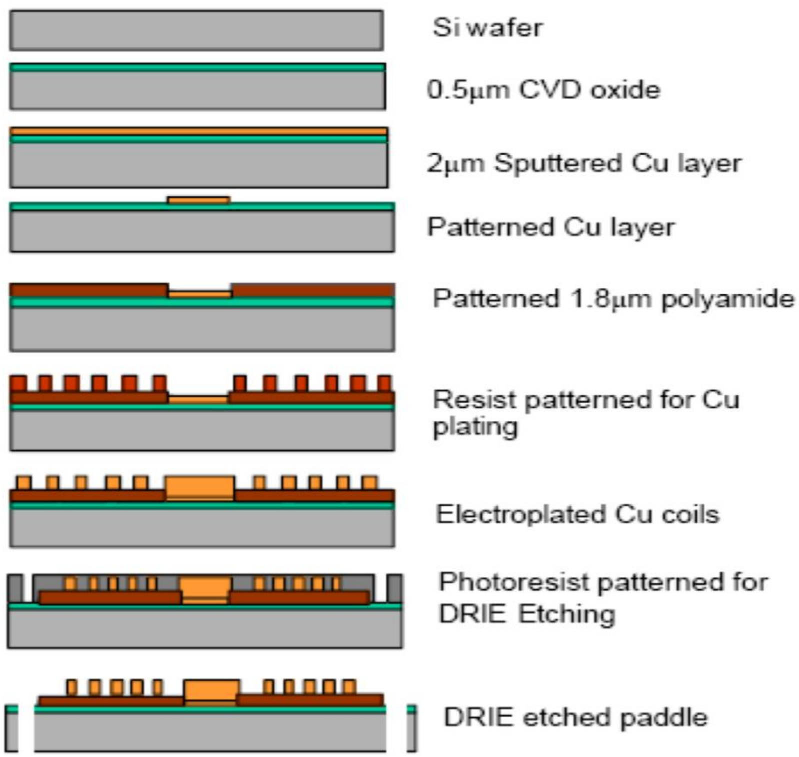


- Monostable and Bistable nonlinearity combined in a single device
- Engineered potential energy for better performance
- 107.2μW and 1403 μW at accelerations of 0.2g and 1g respectively.

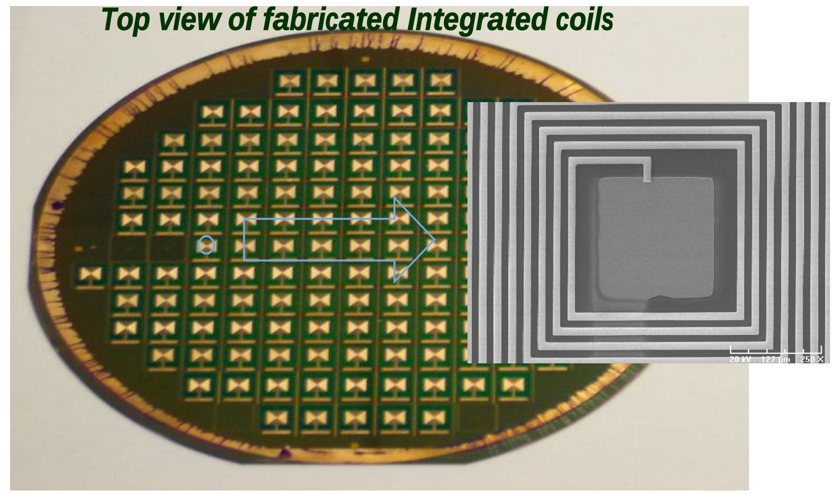
UK Patent & PCT Filed (2015 & 2016): S. Roy, P. Podder, D. Mallick, A. Amman; *The effect of multiple nonlinearity on the performance of a vibrational energy harvester.*

MEMS EM Energy Harvesters - Integration

Single Layer Cu Coil Process Flow



Process steps for Integrated coil fabrication



Top view of fabricated Integrated coils

SEM image of fully fabricated silicon paddle with integrated Cu coils

MEMS EM Energy Harvesters - Integration

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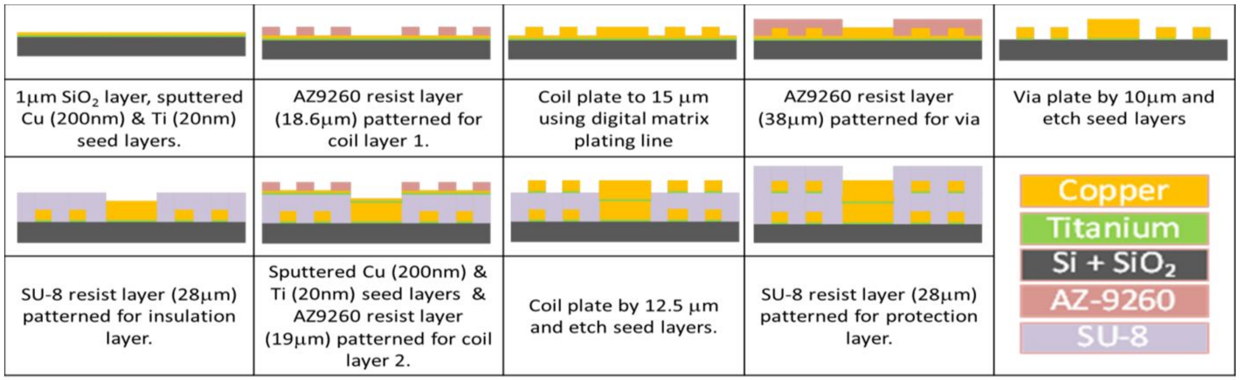
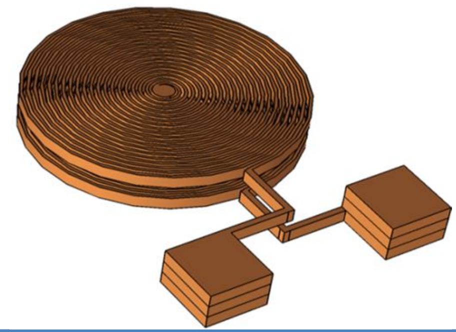
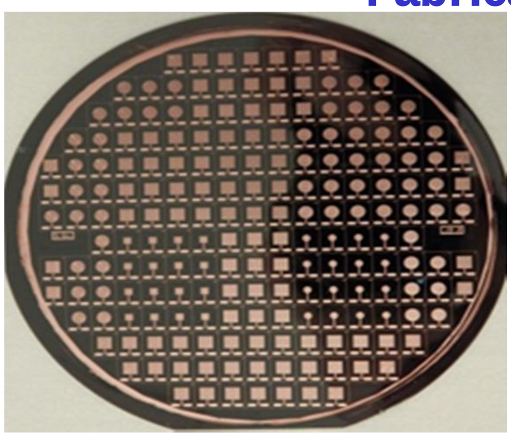
Double Layer Cu Coil Process Flow

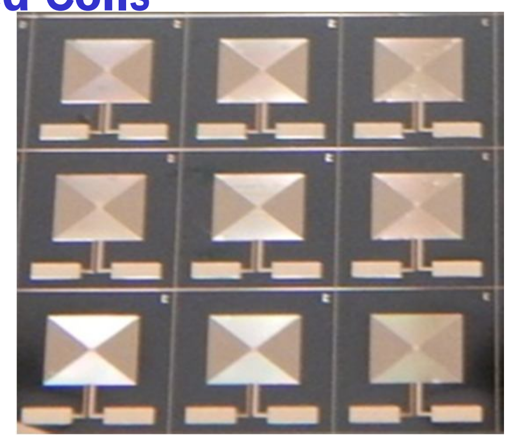


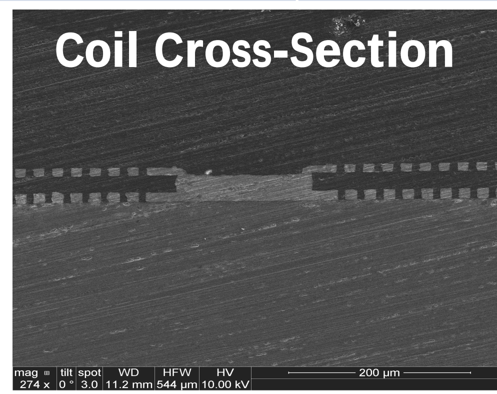


Coil Properties	
Track Widths / inter track gaps	8-15μm
Aspect Ratio	1 → 2
Number turns	up to 150

Fabricated Coils







MEMS EM Energy Harvesters - Integration

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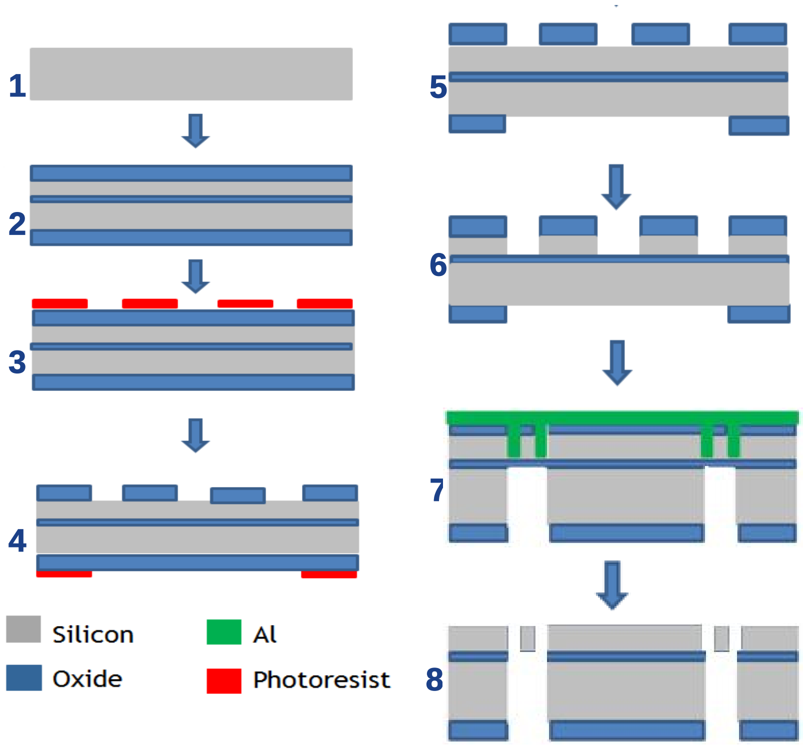
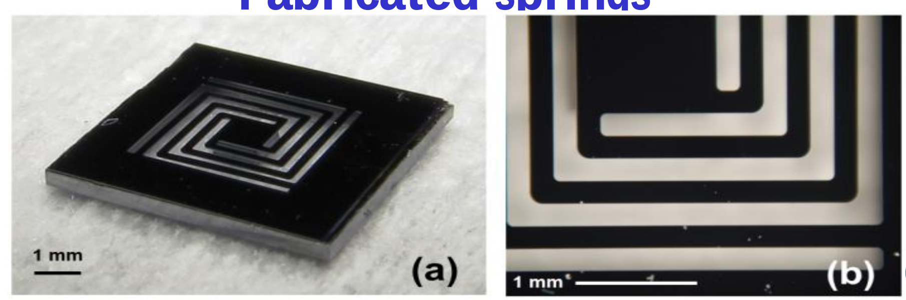
Spring structure- SOI Process Flow



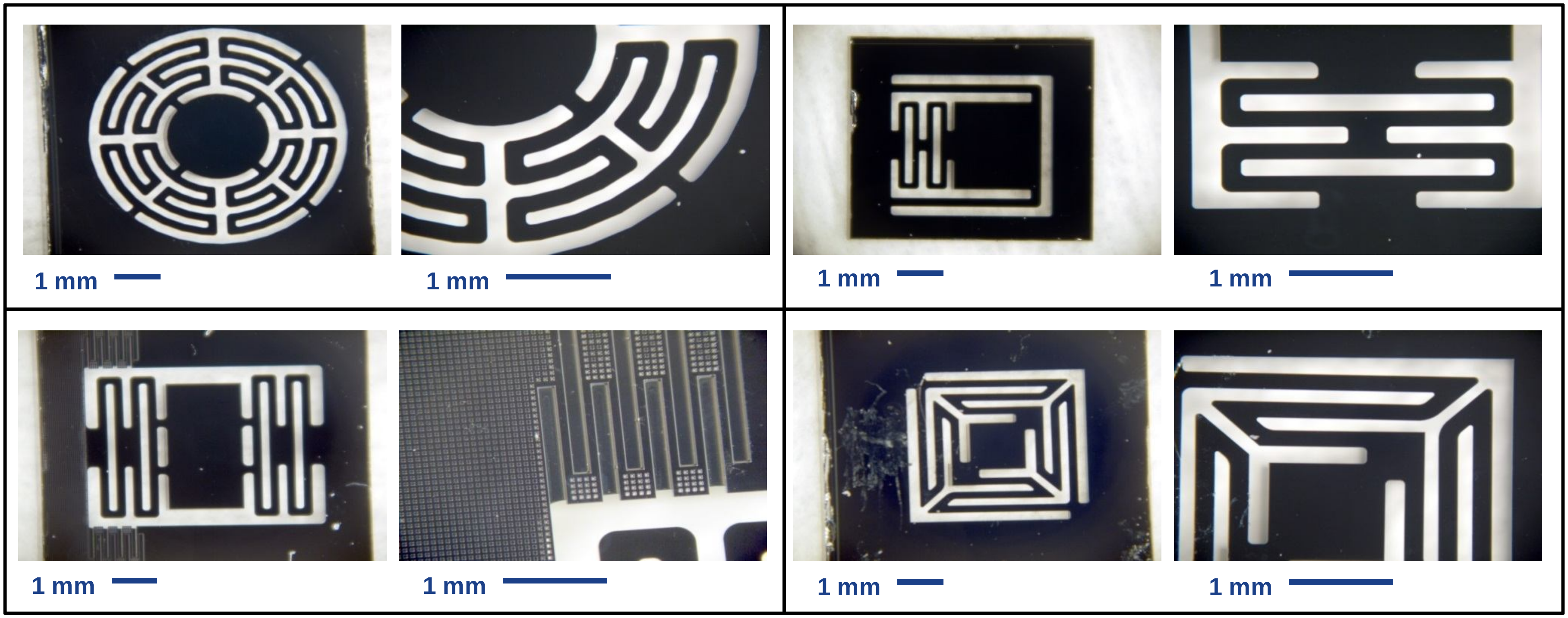
- Si device layer – 50 µm
- Buried oxide layer – 3 µm

1. *Starting Substrate Silicon SOI 40—50um*
2. *Oxidation 3um*
3. *Lithography Front*
4. *Front Oxide Etch DRIE & Litho Back*
5. *Pattern Transfer Oxide Etch Back*
6. *Bosch Etch Front*
7. *Al Support &Bosch Etch Back*
8. *Al & Oxide Etch after Dicing = Device Release*

Fabricated springs



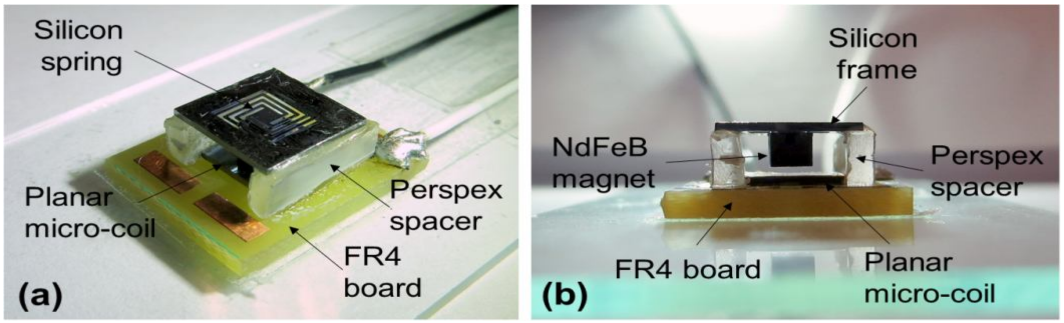
Micro-EMVEH using more SOI spring topologies

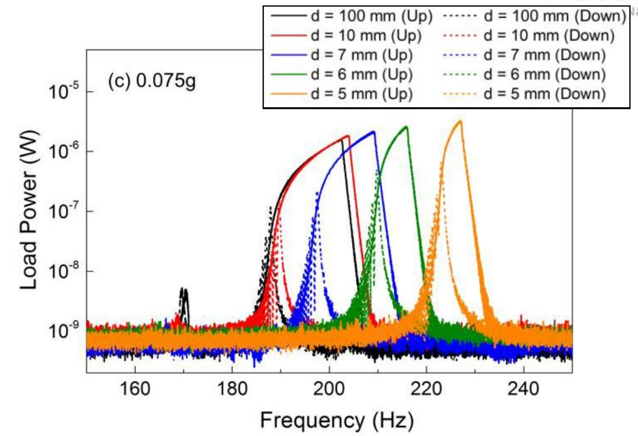


- ❑ Silicon-on-insulator springs have been fabricated in the Central Fabrication Facility, Tyndall National Institute using MEMS fabrication process.
- ❑ Square and circular planar micro-coils and micro-magnets are to be used to assemble VEH.

MEMS Fabricated Nonlinear EM-VEH

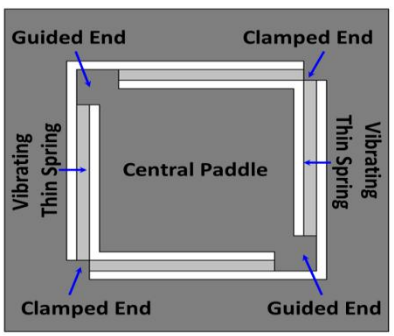
MEMS Nonlinear EMPG (Impact Effect) :

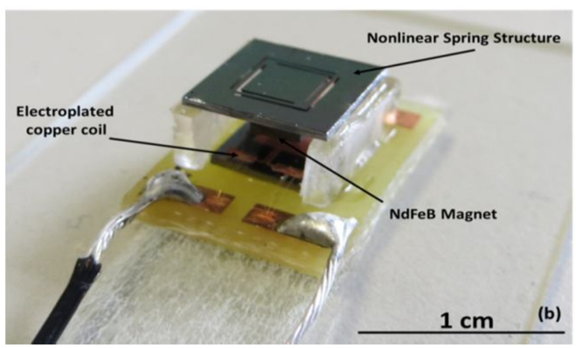


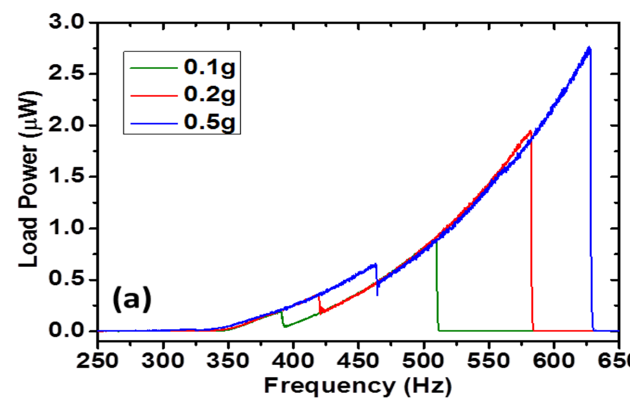


8.45 μW at 0.125g acceleration, BW-12Hz

MEMS Nonlinear EMPG (Stretching):



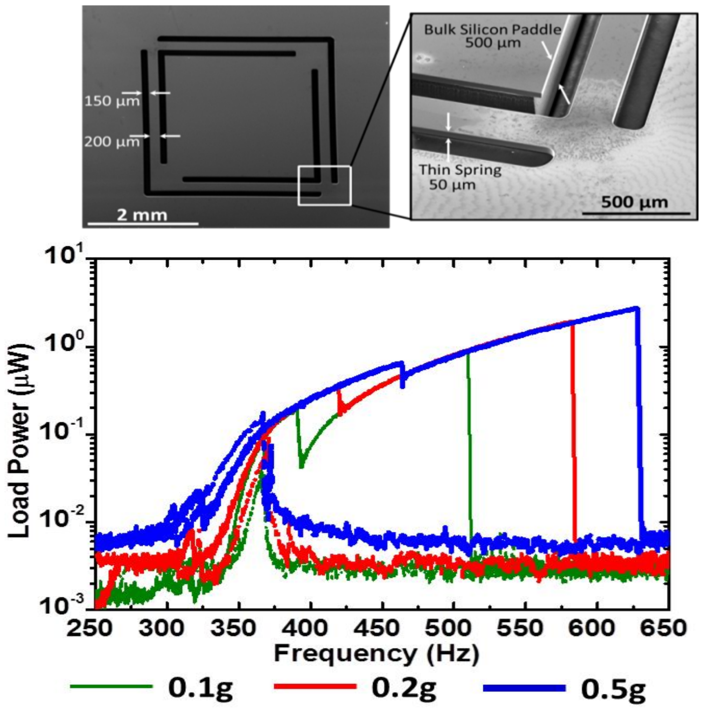




0.8μW and 2.5μW at 0.1g and 0.5g acceleration respectively; BW-82Hz

Nonlinear Wideband Operation

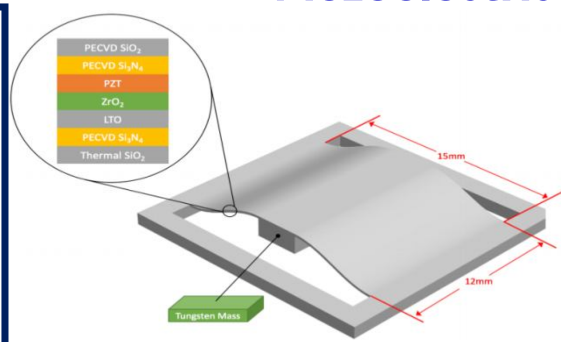
Electromagnetic- stretching

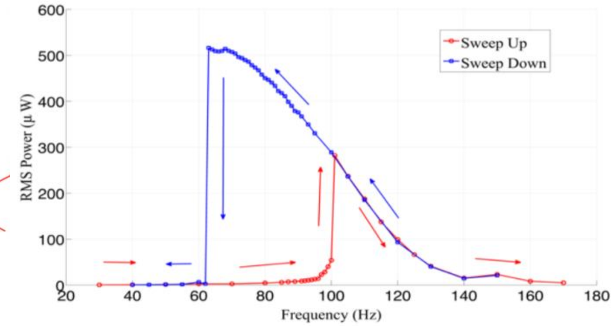


D. Mallick et al., J. MEMS., 26(1): 273-282 (2017).

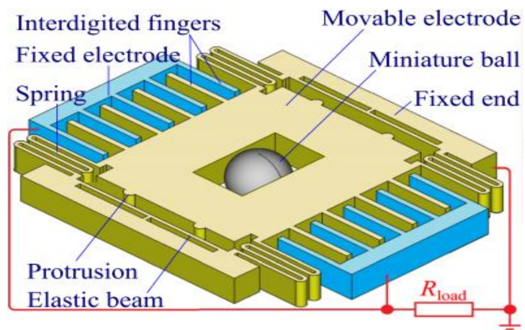
Tyndall - 2016

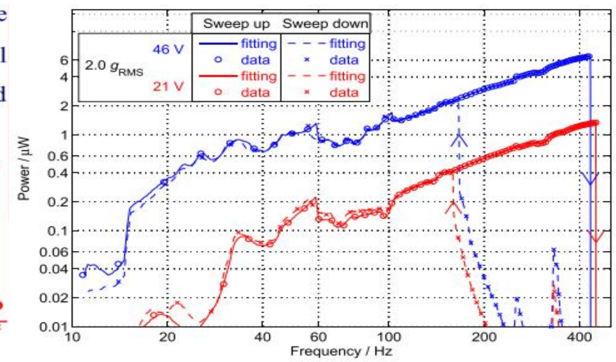
Piezoelectric- buckled beam





Electrostatic – movable ball

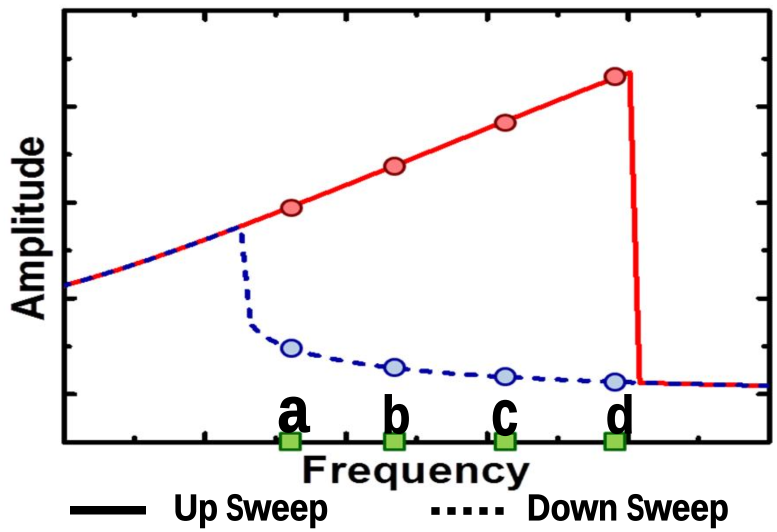




- **Bandwidth – 82 Hz @ 0.5g** (one of the highest reported in literature)

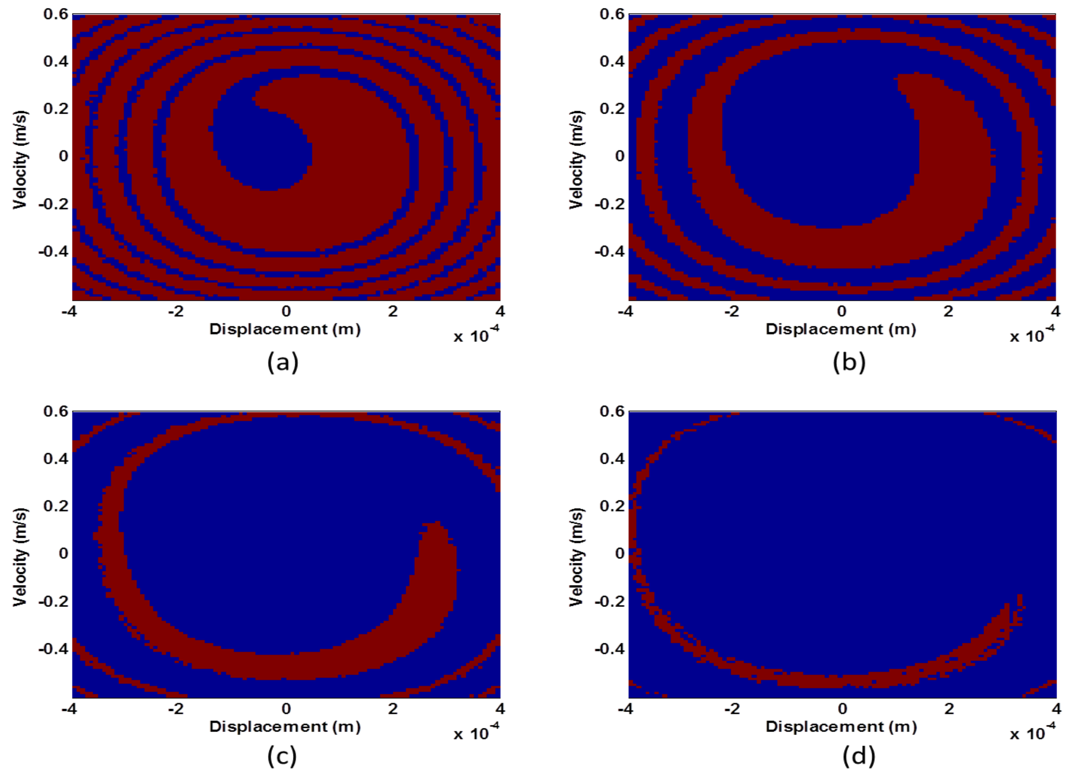
Nonlinear Hysteresis

Frequency Domain Response



- Multiple steady state solutions - Hysteresis
- How to operate in the frequency varying environment?

Basin of Attraction Plots within Hysteresis

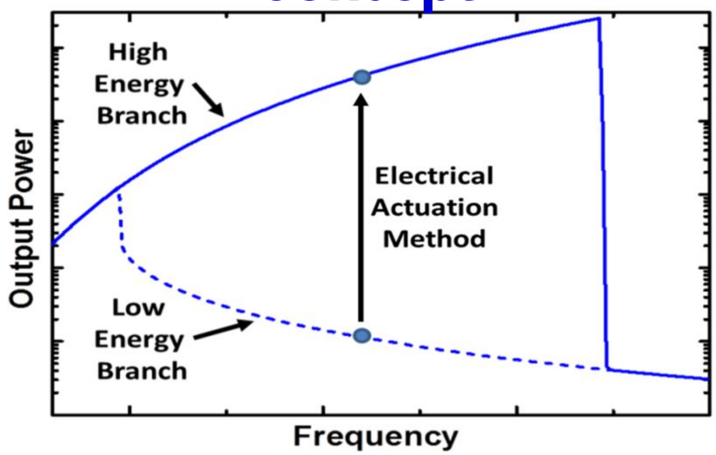


Blue – Low Energy **Red – High Energy**

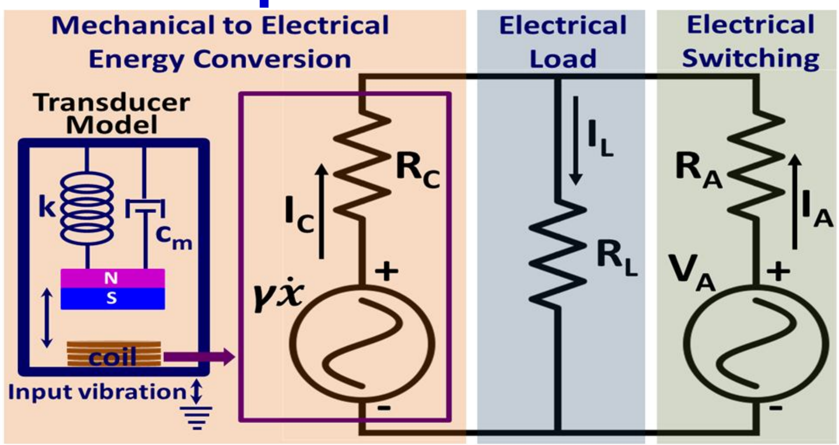
D. Mallick, A. Amman, S. Roy, Smart Mater. Struct., 24, 015013 (2015)

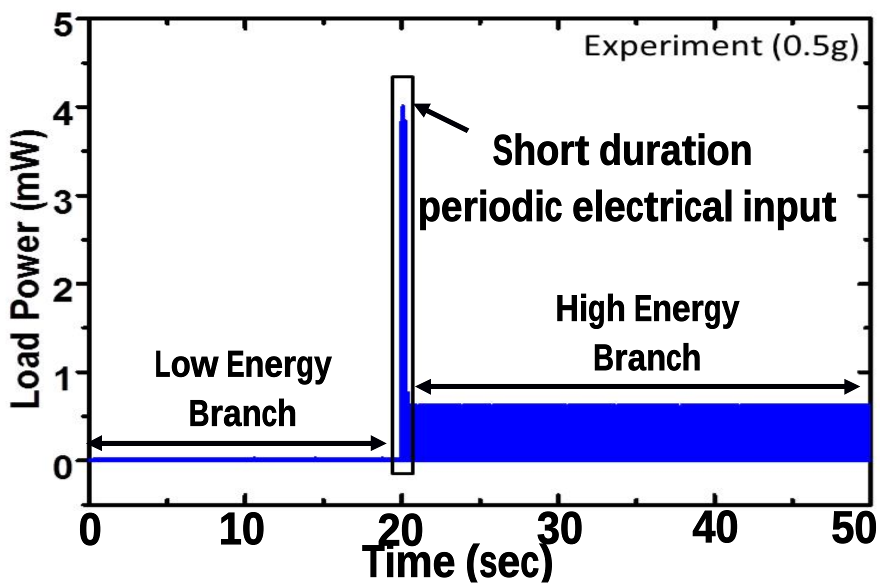
Surfing the High Energy Branch (I)

Concept



Implementation



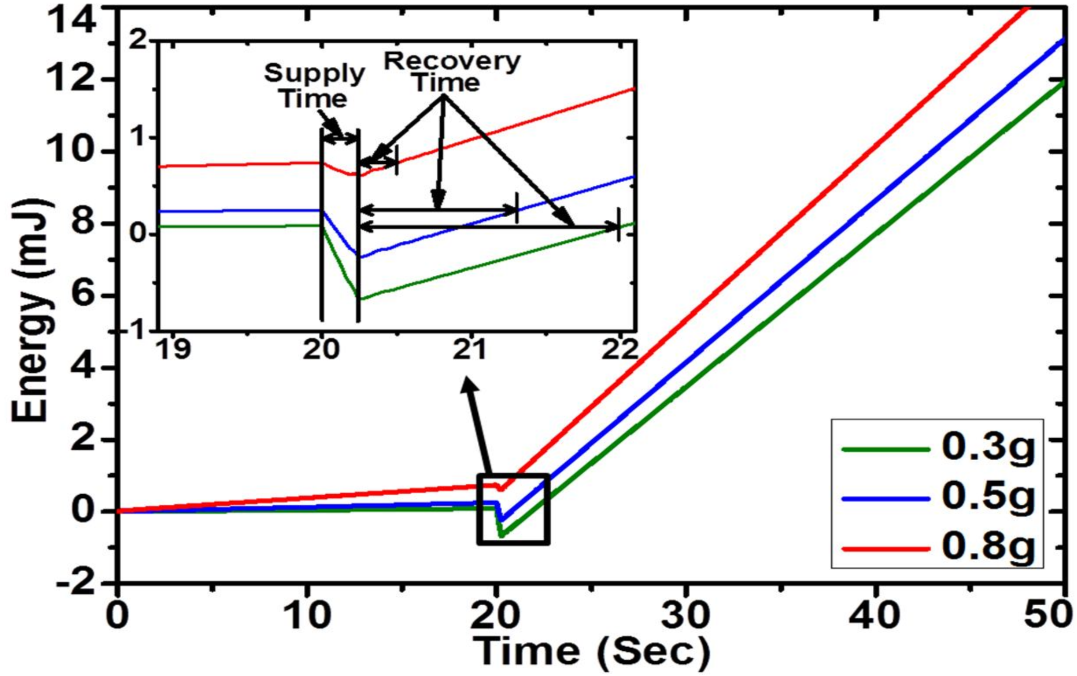


- Maintains steady state – without continuous energy input
- Method independent of device scale or transduction methods

D. Mallick, A. Amman, S. Roy, Phys. Rev. Lett., 119, 197701 (2016)

Surfing the High Energy Branch (II)

Evolution of Net Electrical Energy



E_0 - Energy required to apply switching signal once

P_S - Probability of successful switching in first attempt

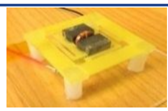
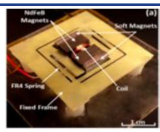
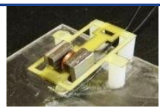
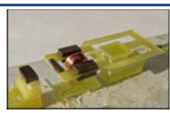
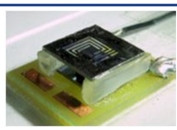
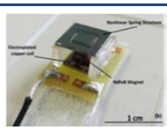
E_T - Total energy spent to switch the state

k - Number of attempts

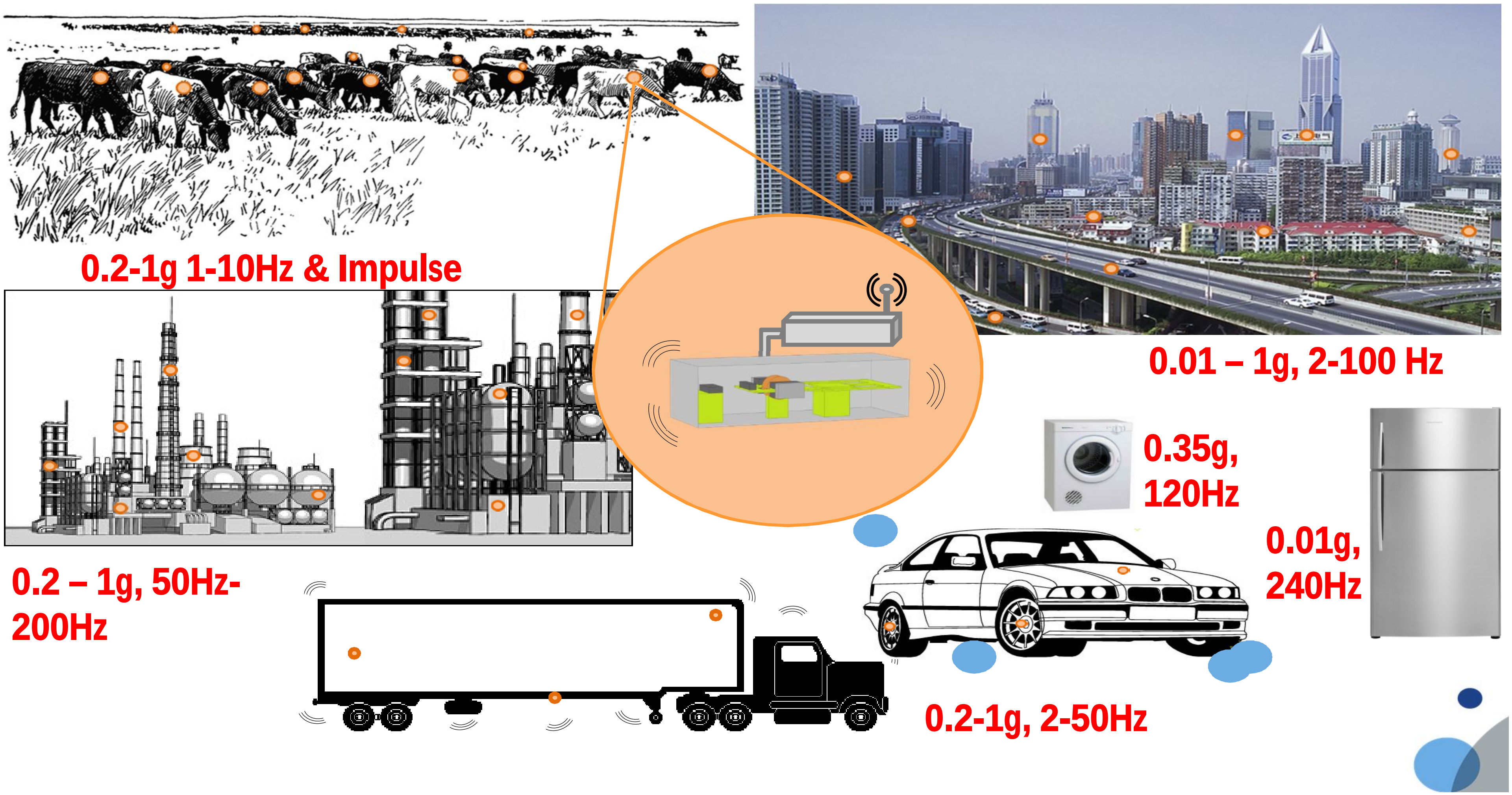
$$E_T = P_S E_0 \sum_{k=1}^{\infty} k(1-P_S)^{k-1} = \frac{E_0}{P_S}$$

As $P_S \sim 0.8$, E_T - not very high

Summary of Demonstrator Performance

Demonstrator	Mechanism	Volume (cm^3)	Frequency (Hz)	Bandwidth (Hz)	Acceleration	Peak Power (µW)
	Linear	4.38	58.6	1-2 Hz	0.5g, 0.1g	1153, 73.5
	Monostable nonlinearity	4.38	58	10 Hz @ 0.5g	0.8g, 0.3g	1330, 383.4
	Combined bistable and monostable nonlinearity	7.2	65.8	10 Hz @ 0.5g	1g, 0.2g	1403, 107.2
	Bistable nonlinearity	2.56	35.2	6.2 Hz @ 0.5g	0.5g, 0.2g	29.2, 14.5
	MEMS/ Magnetically tunable	0.11	230	12 Hz @ 0.125g	0.125g	8.45
	MEMS/ Monostable nonlinearity	0.14	630	82 Hz @ 0.5g	0.5g	2.5
	3D Printed/ Softening Monostable nonlinearity	6	150	4.5Hz@ 1g	1g, 0.1g	2500, 250

Application Environment



Acknowledgement

People

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Andreas Amann
Tuhin Maity
Joe O'Brien

Funding Bodies

EU FP 7- Network of Excellence- 'Nanofunction' - 257375

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More details & full list of publications visit : www.tyndall.ie – email: saibal.roy@tyndall.ie