Pre-Conference Symposium 1: Leveraging mechanical MEMS energy harvesting for IoT applications

June 20, 2023 | Santa Clara, CA

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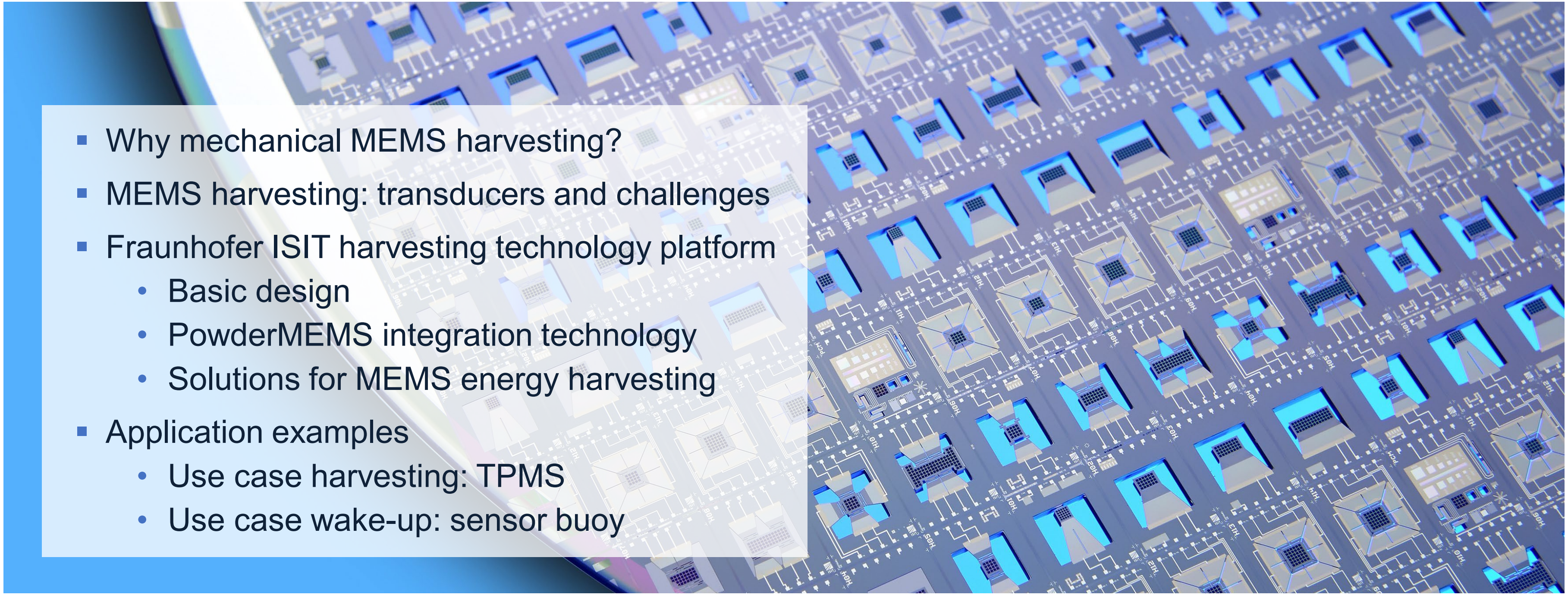
#SensorsConverge

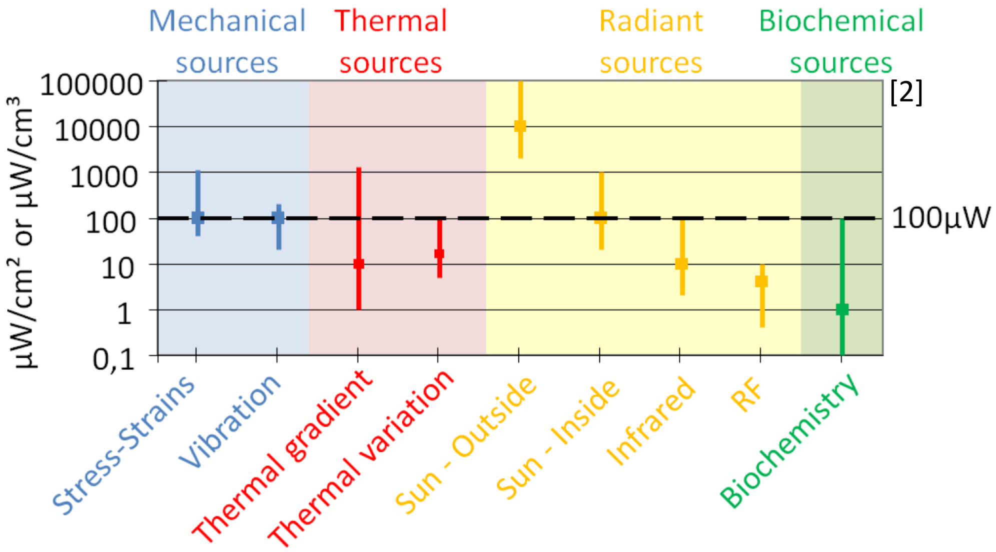
Agenda



- Why mechanical MEMS harvesting?
- MEMS harvesting: transducers and challenges
- Fraunhofer ISIT harvesting technology platform
  - Basic design
  - PowderMEMS integration technology
  - Solutions for MEMS energy harvesting
- Application examples
  - Use case harvesting: TPMS
  - Use case wake-up: sensor buoy

Why MEMS energy harvesting?

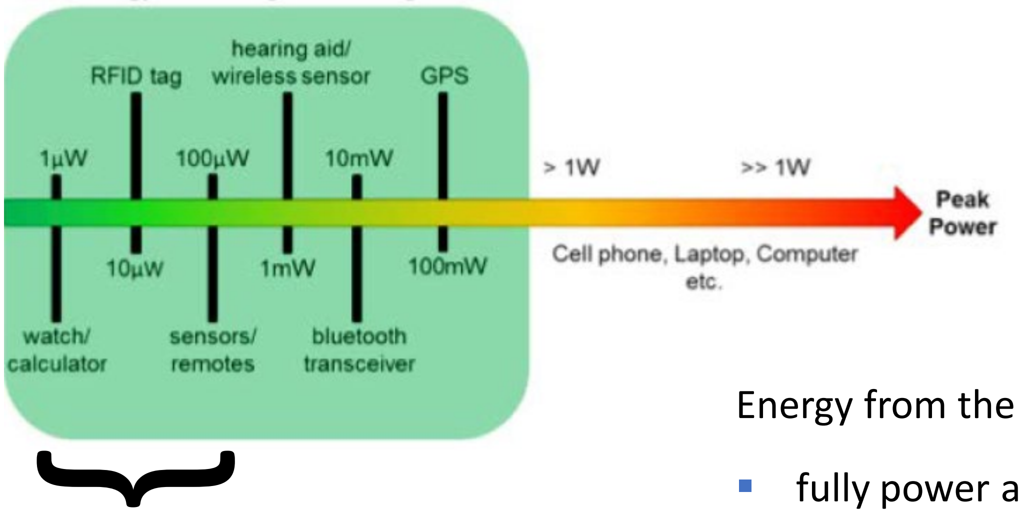
"A huge challenge ahead of us for the 20 next years, is to **reduce the energy footprint** of the IoT by designing objects that … **use any source of energy** one could think about such as **vibration, heat and light**." - *Prof. Reinhold Dauskardt, Stanford University [1]*



- Light great energy source
- No light, no thermal gradients?
  → mechanical sources required
- Miniaturized, autonomous wireless sensor nodes
  → micro energy harvesting

[1] World Materials Forum, France (2018), Big Data/AI for Materials Efficiency
[2] S. Boisseau et al. (2012), https://doi.org/10.5772/51360

Extension of battery life – what's realistic?



MEMS energy harvesting

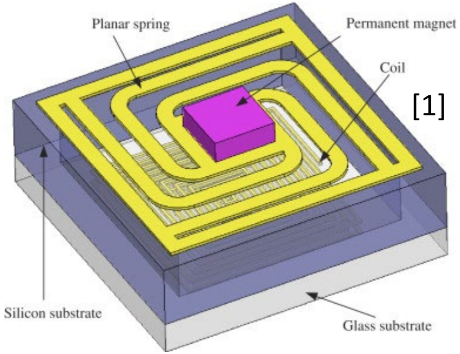
Energy from the environment can be harvested to…

- fully power an electronic device
- complement a battery
- lossless stand-by, i.e. zero-power wake up

[1] ConFlow Power Group, "Market Research on Energy Harvesting for IoT Devices" (2020)

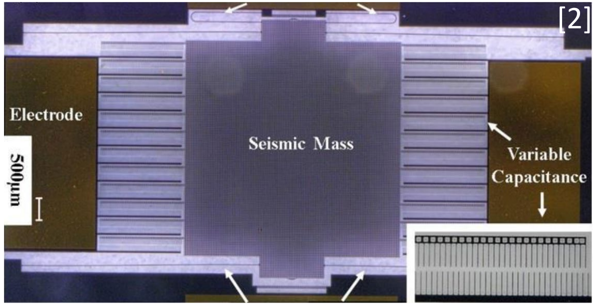
Transducers for mechanical MEMS harvesters

Electromagnetic



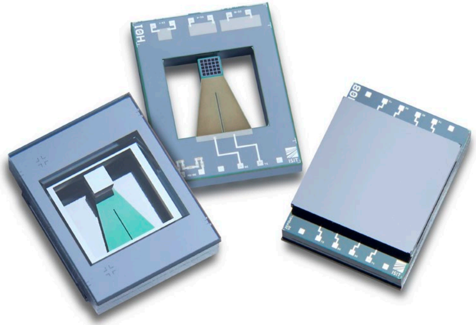
- Typical configurations yield <100 mV order of magnitude
- Monolithic manufacturing of magnets and coils challenging

Electrostatic



- Power scales with mass vs. fragile comb structures
- Voltage/charge source required

Piezoelectric



- High power density
- Useful voltage level
- Established for mass manufacturing

[1] Wang et al. (2007), https://doi.org/10.1016/j.mejo.2007.10.002
[2] B. Vysotskyi (2019), https://theses.hal.science/tel-01968067

Piezoelectric energy harvester

Table 1. Summary of maximum energy densities of three kinds of transducers.[1]

Type	Energy density (mJ cm^{-3})	Equation	Assumptions
Piezoelectric	35.4	$(1/2)\sigma_y^2 k^2/2c$	PZT 5 H*
Electromagnetic	24.8	$(1/2)B^2/\mu_0$	0.25 T
Electrostatic	4	$(1/2)\varepsilon_0 E^2$	3×10^7 V m^{-1}

* replacing PZT with AlN / AlScN piezoelectric power density becomes even more superior

Advantages of piezoelectric energy harvesters

- Well-suited for mass microfabrication
- Typical output voltages 1-20 V
- Highest power output density
- Current development of AlScN potentially increases power output 2-4-fold

[1] S. Roundy et al. (2003), https://doi.org/10.1088/0964-1726/13/5/018

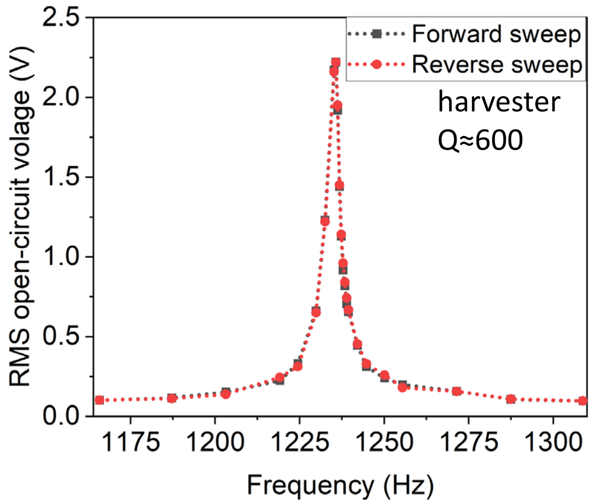
Challenges of MEMS energy harvesting

- Generation of sufficient power output
- High q-factors of MEMS oscillators -> narrow excitation frequency band; typ. f_{res} = 1-3 kHz
- Application-specific excitation geometries: linear, rotational, shock, contact, non-contact

Solution?

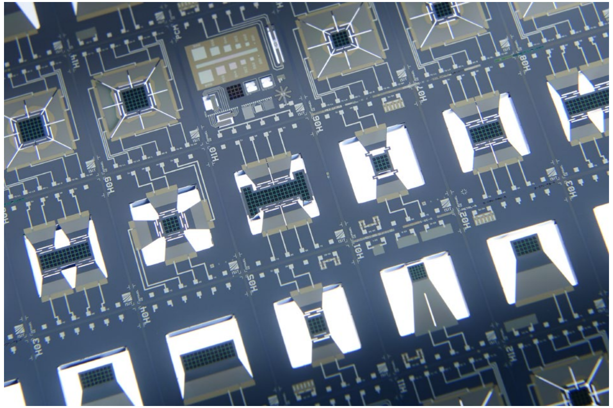
- A dedicated MEMS design for each application scenario?
  - MEMS need volume (or high cost per device)

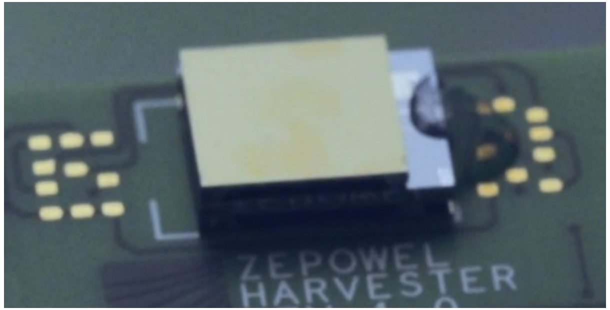
→ Versatile MEMS harvesting technology platform required

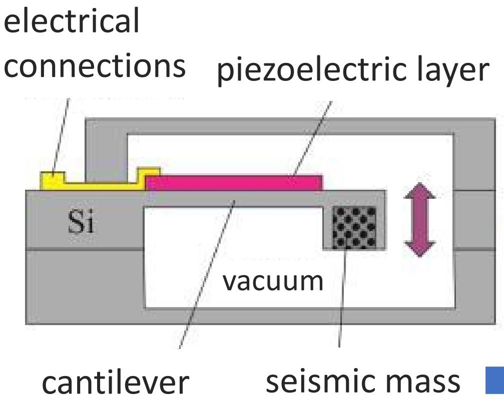


M.T. Bodduluri (2022), https://doi.org/10.3390/mi13060863

Fraunhofer ISIT MEMS Energy Harvester





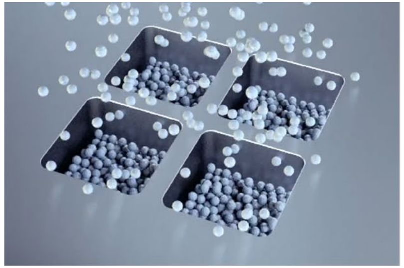


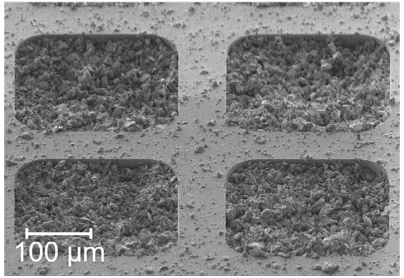
3. Aluminum (Scandium) Nitride AlN / AlScN

PowderMEMS
1. Variable mass density
2. Integrated Micromagnets

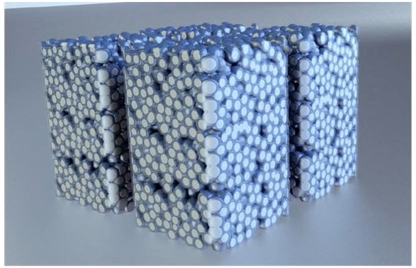
PowderMEMS micromanufacturing

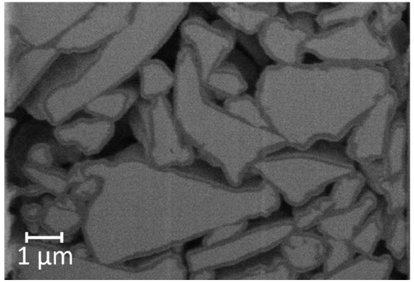
1. Dry filling of microcavities



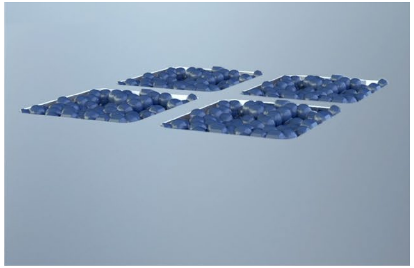


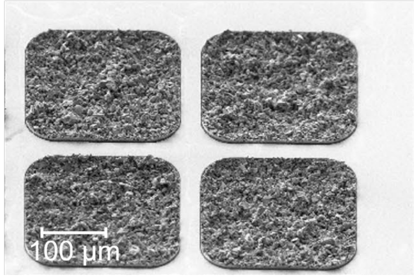
2. Solidification by atomic layer deposition





3. Substrate conditioning for post-processing





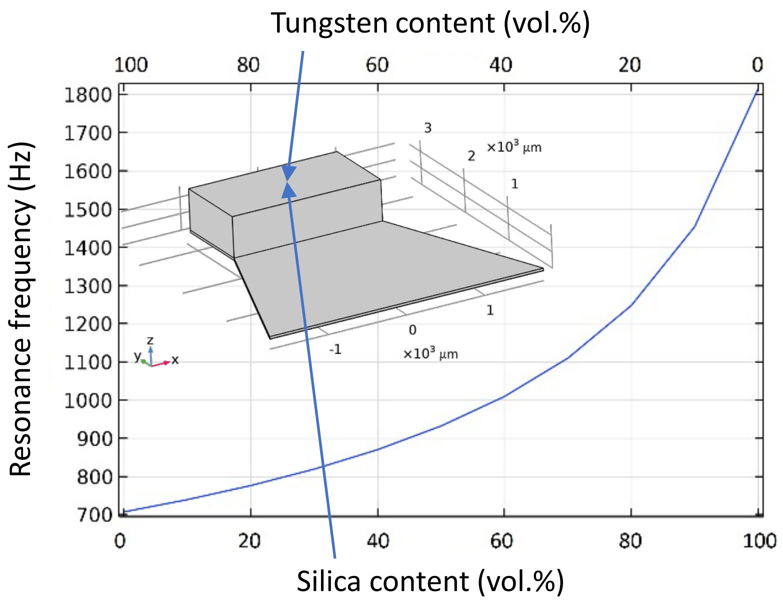
Unique set of micromanufacturing properties:

- free choice of materials
- tuning of local mass density
- precise wafer-level integration of 3D micromagnets

T. Lisec et al. (2022), https://doi.org/10.3390/mi13030398

1. PowderMEMS: variable mass density

Same design, variable resonance frequency



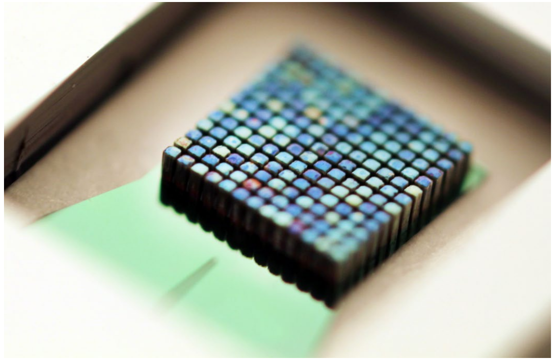
Proof mass made of powder mixtures

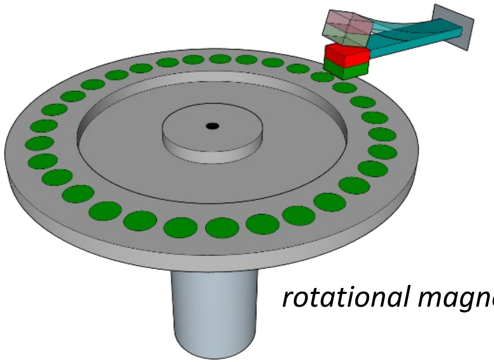
- variation of mass density in the same MEMS design
- tuning of resonance frequency without changing the design
- adaption to different excitation spectra with same design and same manufacturing flow

2. PowderMEMS: integration of micromagnets

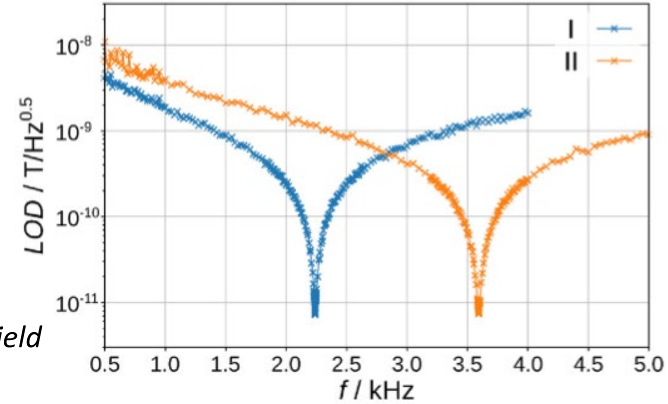
Same design, various excitation modes

- contactless harvesting
- linear, rotational, shock excitations
- magnetic field sensing





rotational magnetic excitation

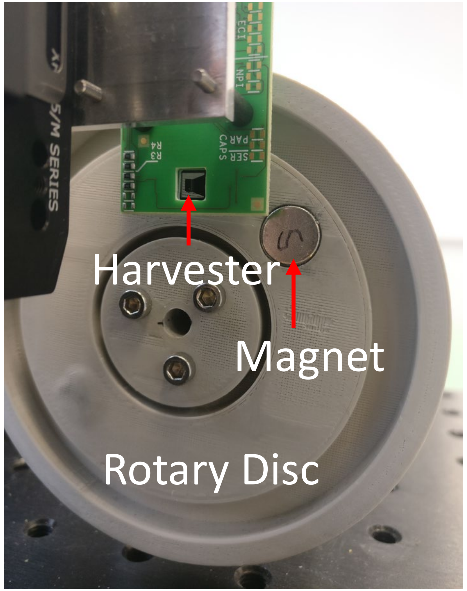


excitation by ac magnetic field

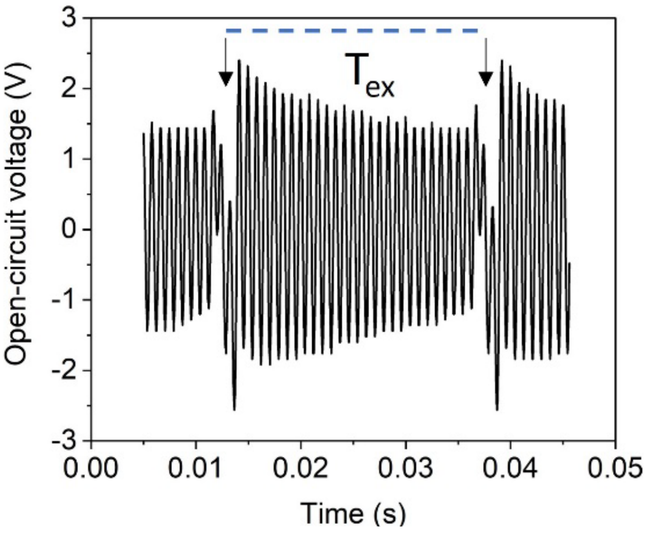
F. Niekiel (2019), https://doi.org/10.1016/j.sna.2019.111560

Rotational contactless harvesting

Magnetic plucking setup



Harvester response



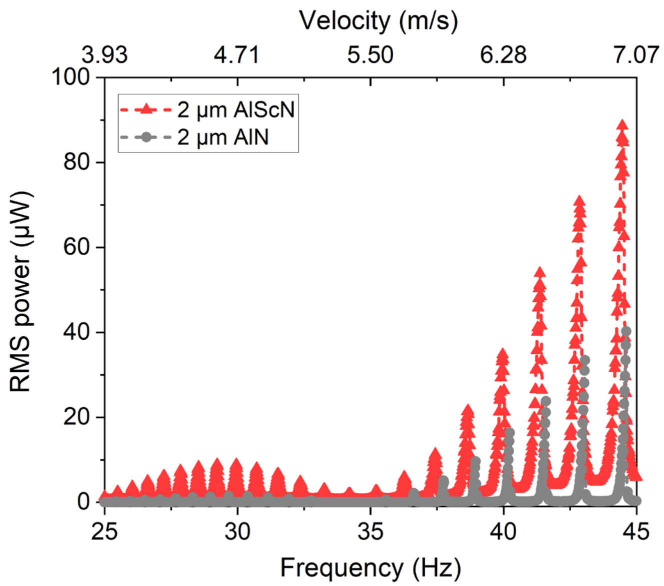
Frequency up-conversion:

- Harvester f_{res}≈1kHz
- f_{exc}=42 Hz
- „shock“-like excitation

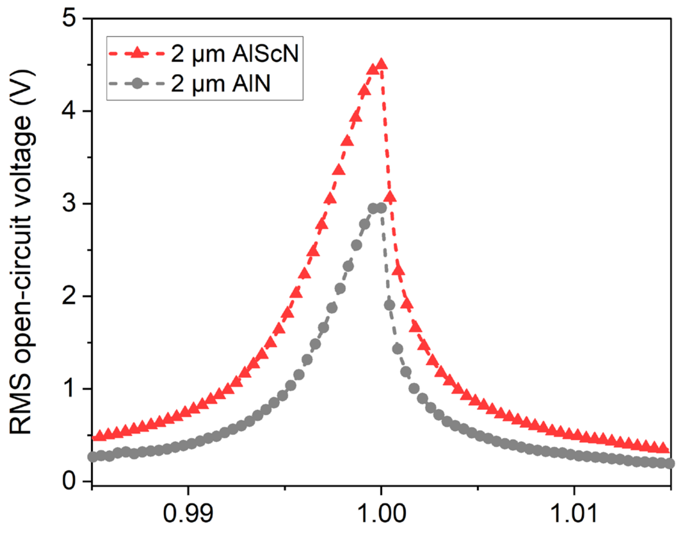
M.T. Bodduluri (2022), https://doi.org/10.3390/mi13060863

3. Power boost: AlScN vs. AlN

Magnetic plucking

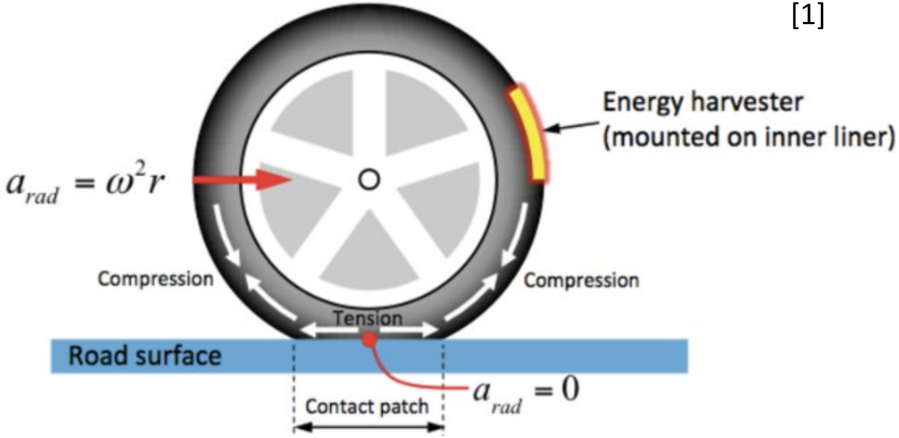


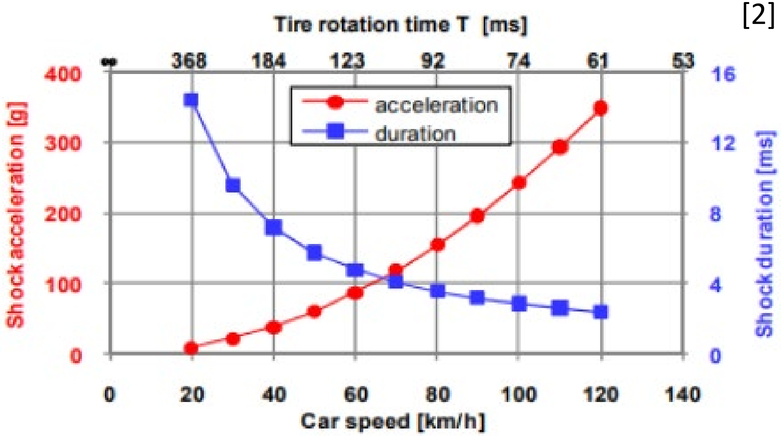
Excitation in resonance

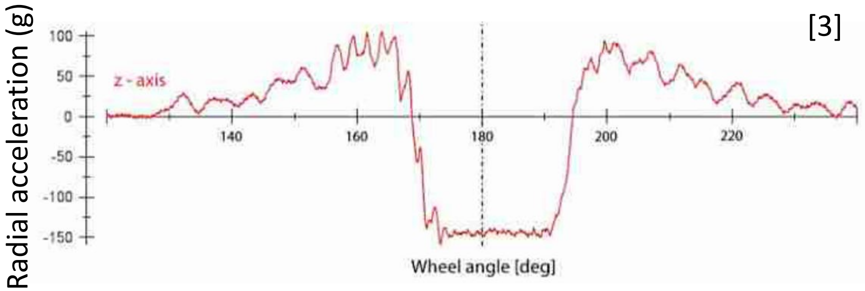


→ AlScN power output 2-4 times higher than AlN, under development

Application: tire pressure monitoring system (TPMS)



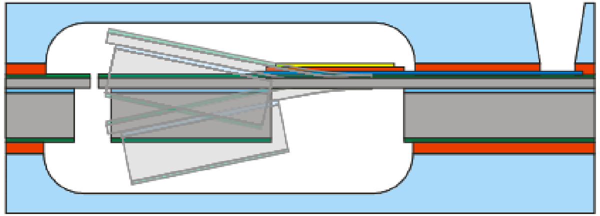




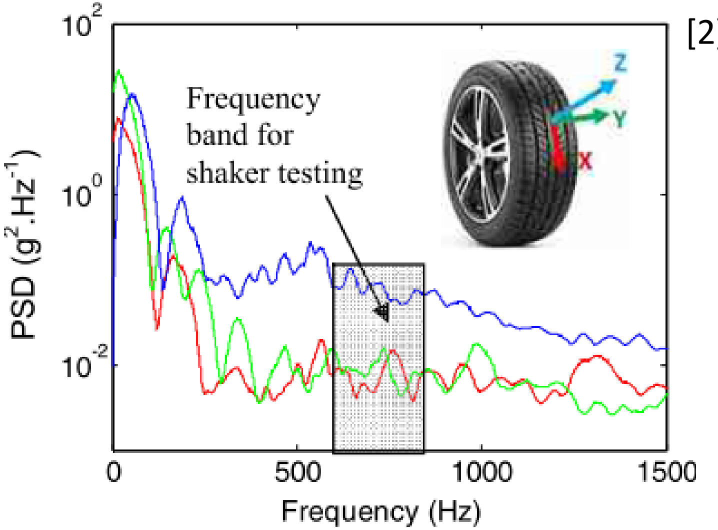
- no light; abundant mechanical energy
- power consumption 20-100 µW [4]

[1] C. R. Bowen et al. (2015), https://doi.org/10.1002/aenm.201401787
[2] R. Elfrink (2011), https://doi.org/10.1109/IEDM.2011.6131639
[3] Niskanen et al. (2014), https://doi.org/10.1080/00423114.2014.898777
[4] M. Germer (2022), https://doi.org/10.1109/JIOT.2022.3152547

Piezoelectric MEMS for TPMS



[1]



[2]

- Power output [1]: 42µW @ 70 km/h
- ISIT technology platform estimated to reach 100µW @ 50 km/h
  - integration of PowderMEMS tungsten mass
  - AlScN instead of AlN
  - challenge: output vs. stability

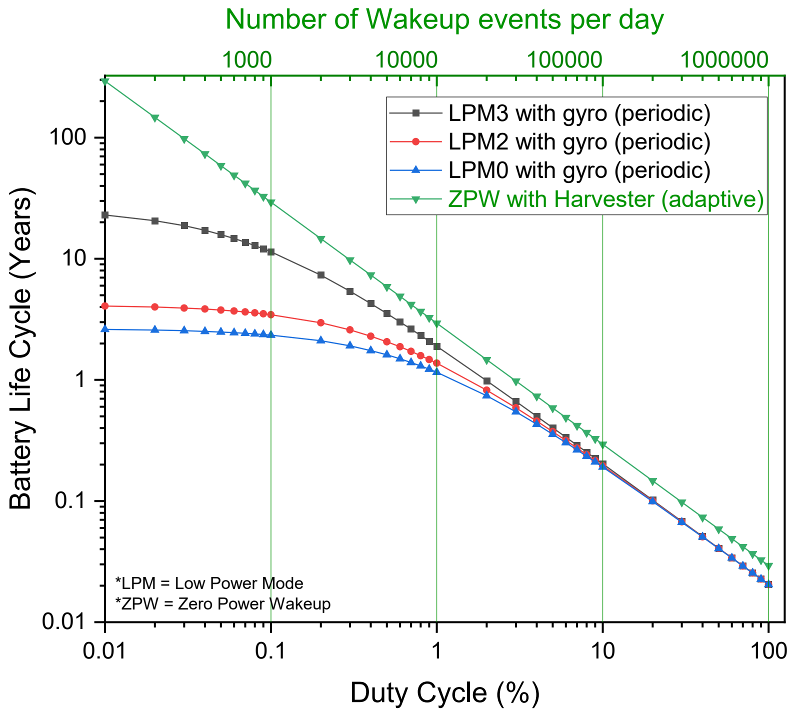
[1] Elfrink et al. (2011), https://doi.org/10.1109/IEDM.2011.6131639
[2] Renaud et al. (2013), https://doi.org/10.1109/Transducers.2013.6626861

Application: zero power wake-up

General idea:

- battery-powered system
- few relevant events; completely off
- harvester generates wake-up voltage
- virtually no power consumption during off time, P_{leak}<0.1 nW

Right: comparison of periodically listening sensor module vs. event-based passive wakeup
(eZ430-RF2480 board, MSP430F2274 microcontroller, CC2480 radio module and LSM6DSOX gyro)



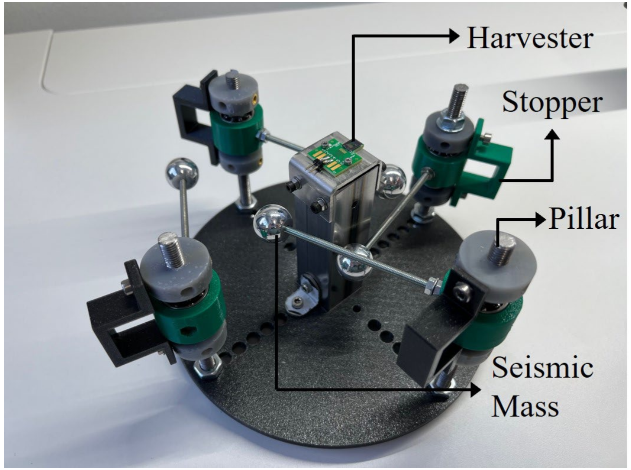
M. Ahmed et al. (2022), https://doi.org/10.3390/mi13030407

Example: Autonomous sensor buoy

Scenario:

- Few relevant sensor events, e.g. freak wave
- very long lifetime without battery replacement
- „dirty“ conditions

Illustration of scenario

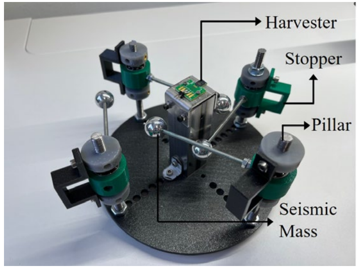


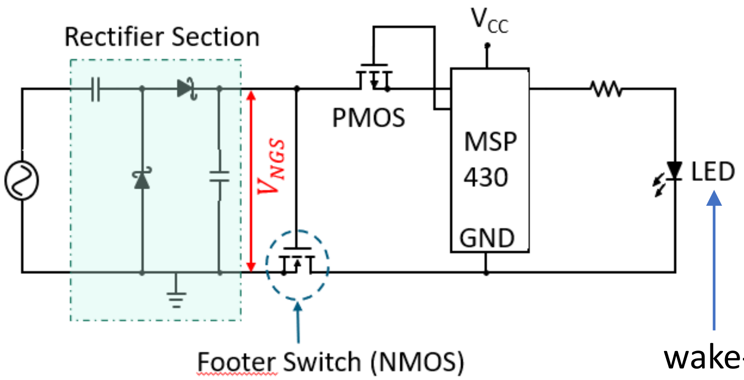
Project OTC-BASE, funded by the German Federal Ministry for Education and Research

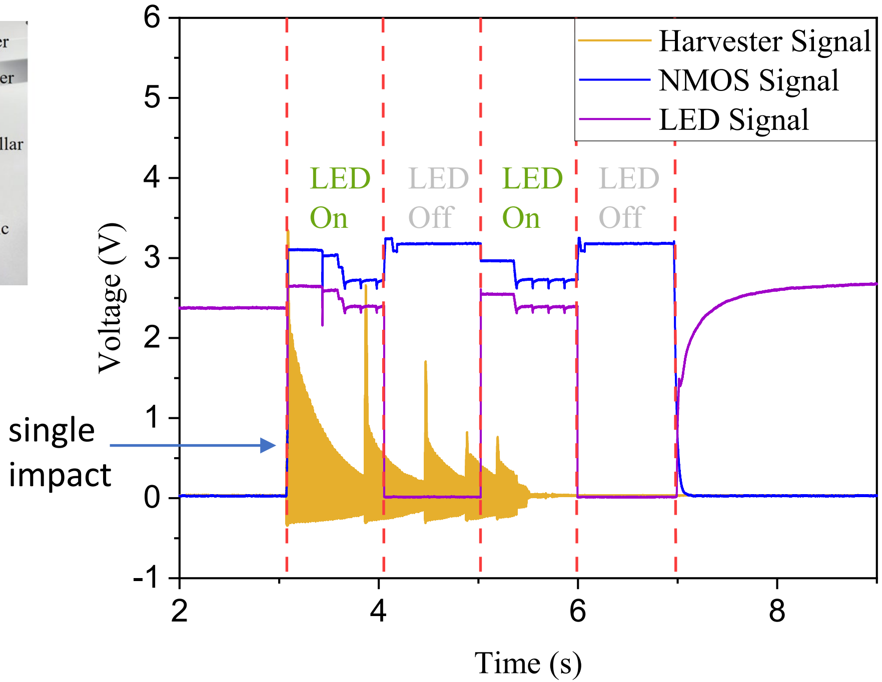
Example: Autonomous sensor buoy

Wake-up demonstrator

- single event/impact suffices
- no sophisticated electronics required







Project OTC-BASE, funded by the German Federal Ministry for Education and Research

Summary

Energy harvesting can enhance device life in IoT applications by

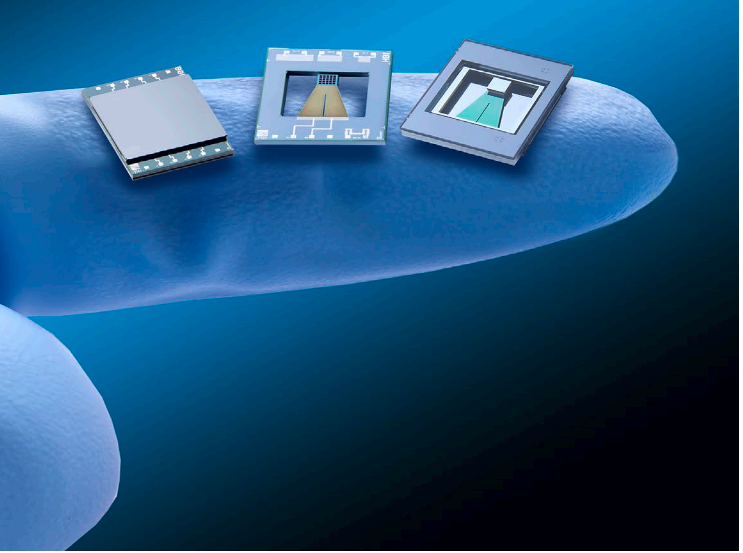
- providing an infinite power source, replacing the battery
- complementing a battery
- extending battery life with zero-power standby

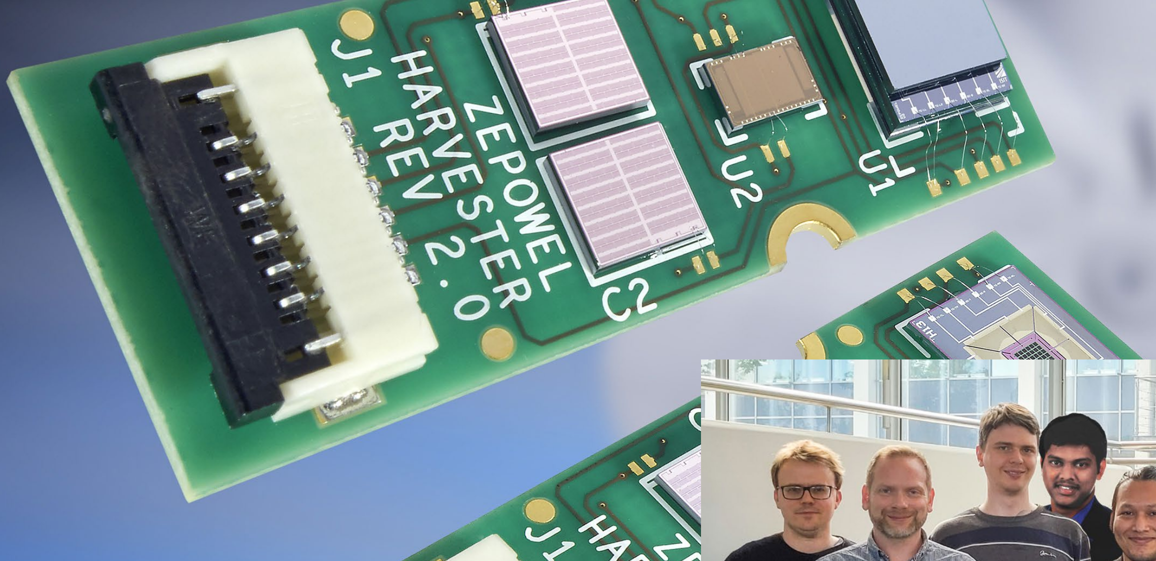
Depending on the application, challenges are

- narrow bandwidth
- sufficient power output
- costs for application-specific designs

Fraunhofer ISIT‘s technology platform

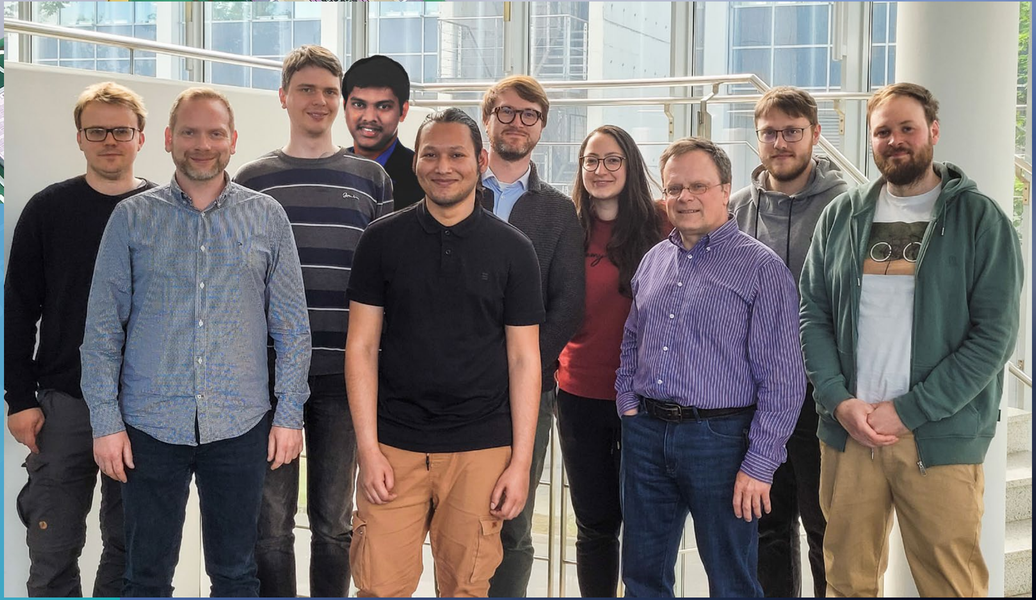
- adaption of resonance frequency in a MEMS design
- high performance AlScN transducer
- flexible excitation





Fraunhofer

Fraunhofer-Gesellschaft



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