THE 'BILLION SENSORS' OPPORTUNITY:

POWERING AUTOMOTIVE SENSORS WITH HIGH POWER DENSITY MEMS VIBRATION ENERGY HARVESTERS

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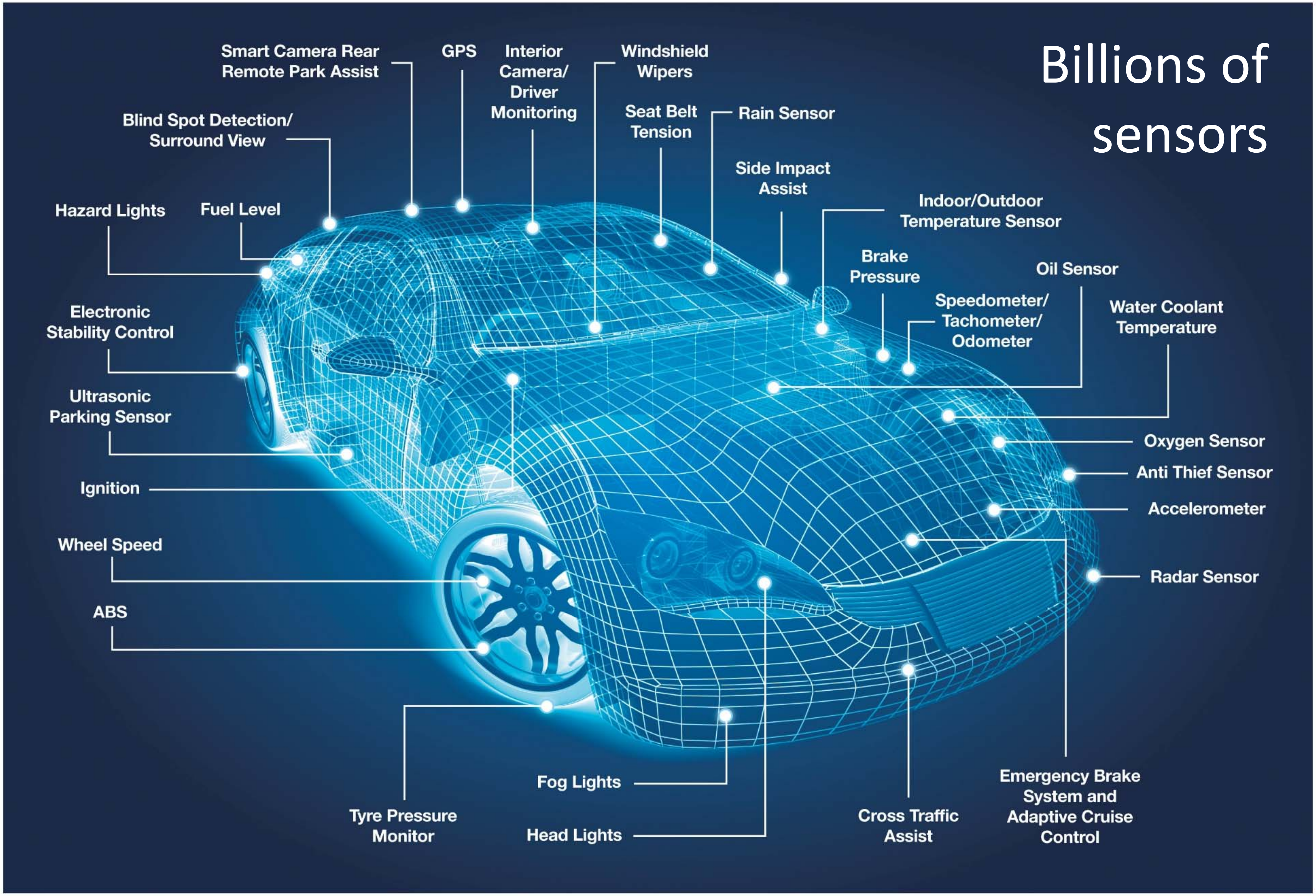
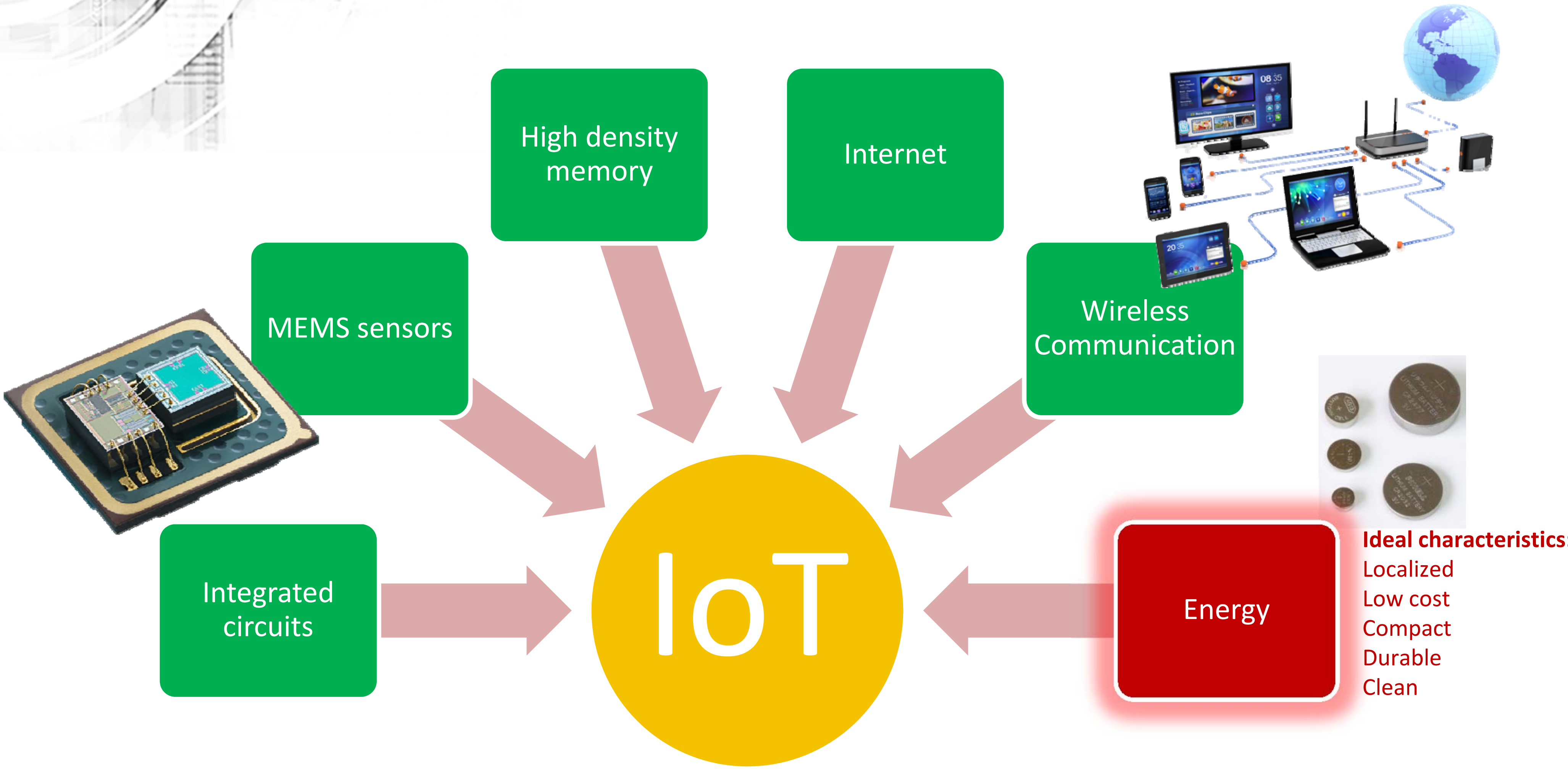
April 5th, 2022


Billions of sensors
Smart Camera Rear Remote Park Assist
GPS
Interior Camera/ Driver Monitoring
Windshield Wipers
Blind Spot Detection/ Surround View
Seat Belt Tension
Rain Sensor
Side Impact Assist
Hazard Lights
Fuel Level
Indoor/Outdoor Temperature Sensor
Brake Pressure
Oil Sensor
Electronic Stability Control
Speedometer/ Tachometer/ Odometer
Water Coolant Temperature
Ultrasonic Parking Sensor
Oxygen Sensor
Anti Thief Sensor
Ignition
Accelerometer
Wheel Speed
Radar Sensor
ABS
Fog Lights
Tyre Pressure Monitor
Head Lights
Cross Traffic Assist
Emergency Brake System and Adaptive Cruise Control

OUTLINE

- Automotive sensors and vibrations
- Vibration energy harvesting
- High power density MEMS piezoelectric vibration energy harvesters
  - Fabrication approach with high density mass – Tungsten in MEMS
  - Experimental characterization
- Perspectives

WSN and IoT: A Confluence of Technologies



Although batteries are a mass produced cheap commodity, they are not able to supply IoT devices/WSN adequately

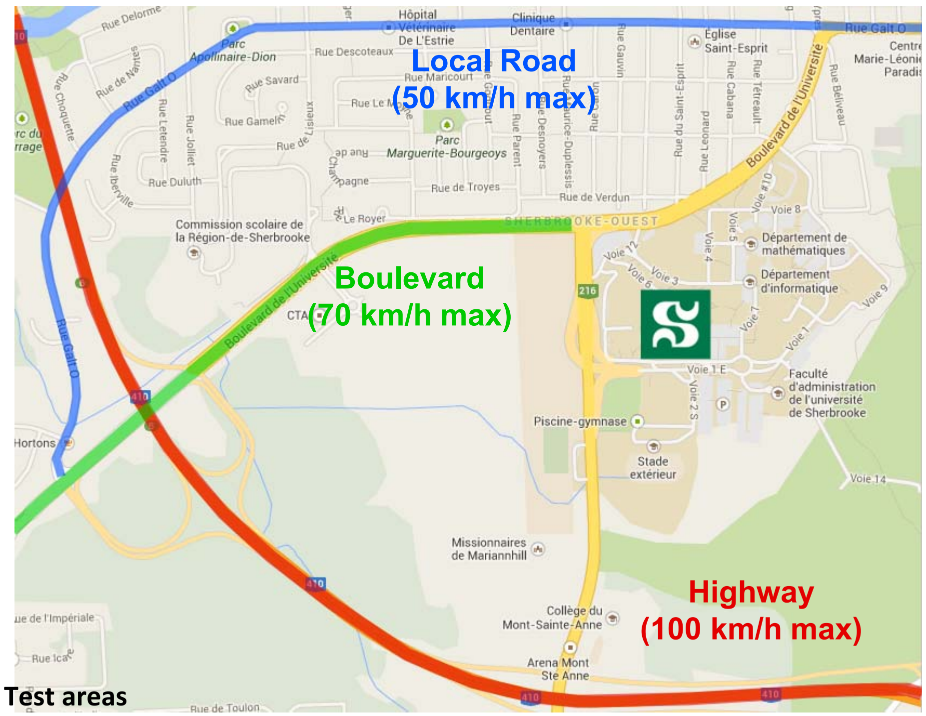
WIRELESS AUTOMOTIVE SENSORS

- Why go wireless?
  - Over **100 sensors / car**, and increasing with autonomous driving and enhanced cabin intelligence
  - **Miles of cables / car**: height, assembly time and cost, distributed

- Which sensors on a car could / should be wireless?
  - **Non-critical** applications - ensures safety
  - **Periodic** measurements (low sampling rate) - enables harvesting

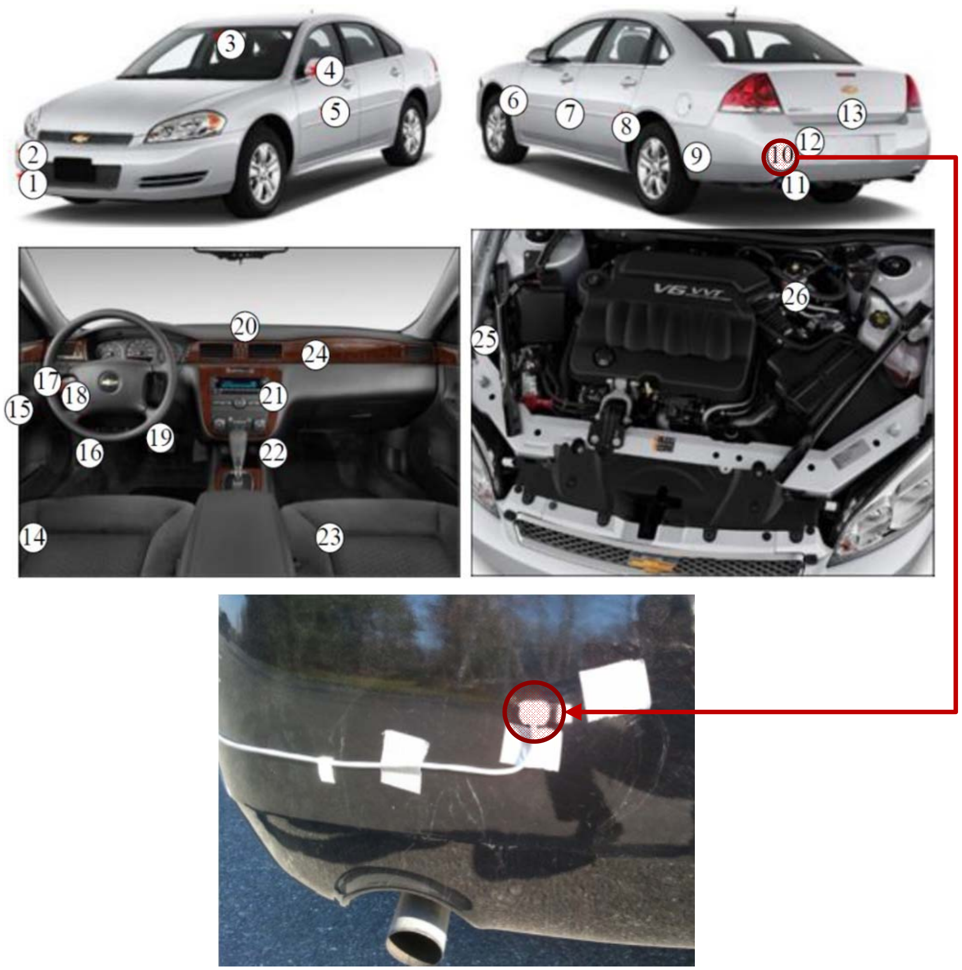
SCOPE OF STUDY

- Identify most amenable sensors for wireless operation and energy harvesting
- Measured vibrations at 26 locations on car

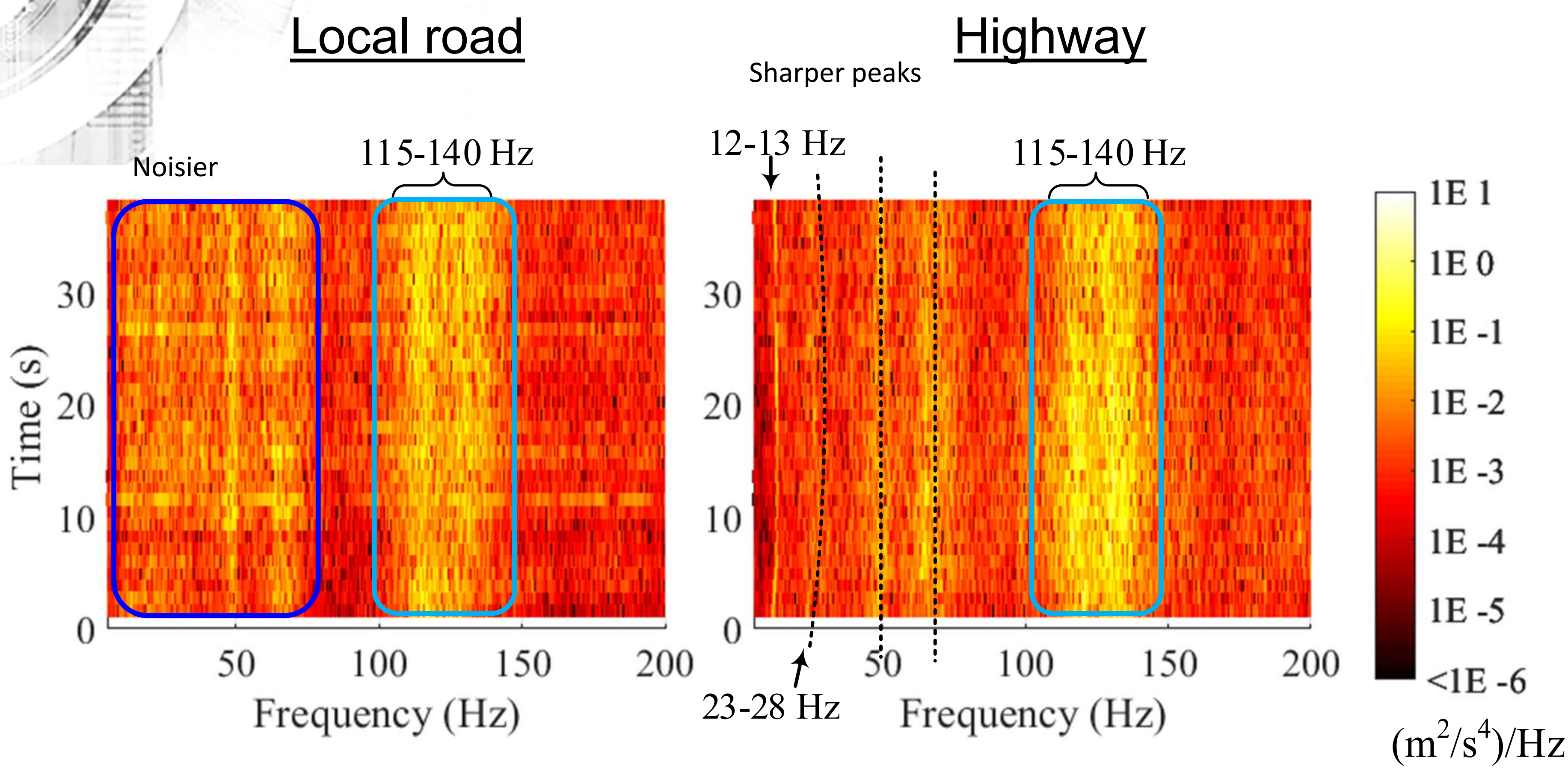


Test areas

Mounting locations of 26 measurement points on a Chevrelet Impala 2012



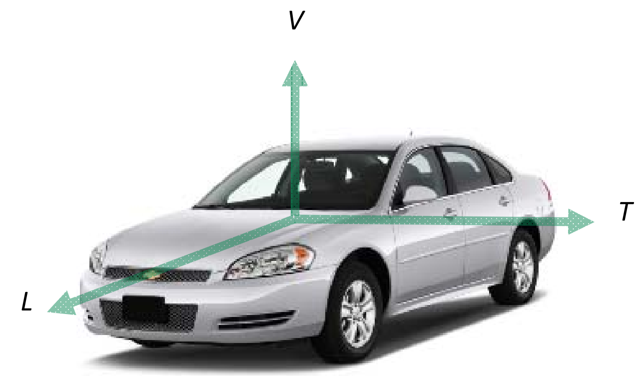
MEASURED VIBRATIONS - TRENDS

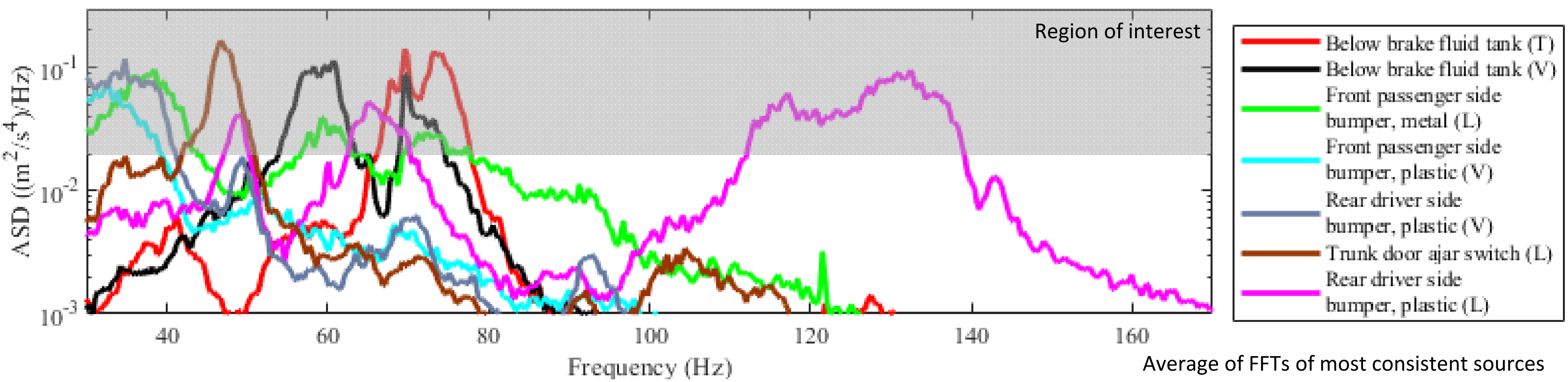


- Strong, broadband and random vibrations observed < 30 Hz
  - Not suitable for resonant MEMS harvester (space constraints)
- Consistent, repeatable wideband peaks measured on specific locations < 150 Hz
  - Potentially suitable linear resonant devices

Measured Vibrations – Outcome

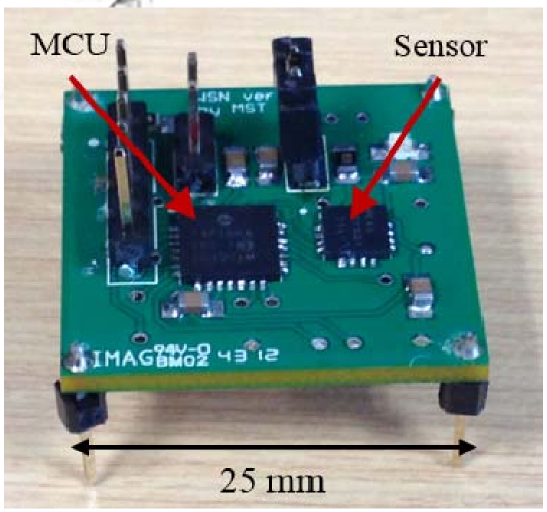
- Peak intensity range: **≈ 0.02 – 0.17 $(m^2/s^4)Hz^{-1}$**
- Assuming Q_m=Q_{el}=250 ➡ P_{el}^* ≈ 5-10 µW/g

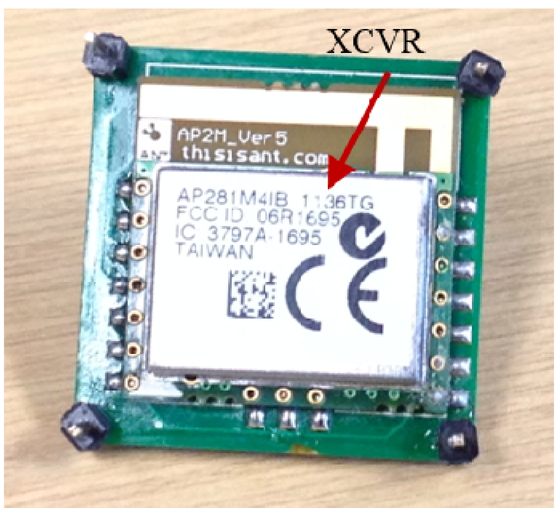


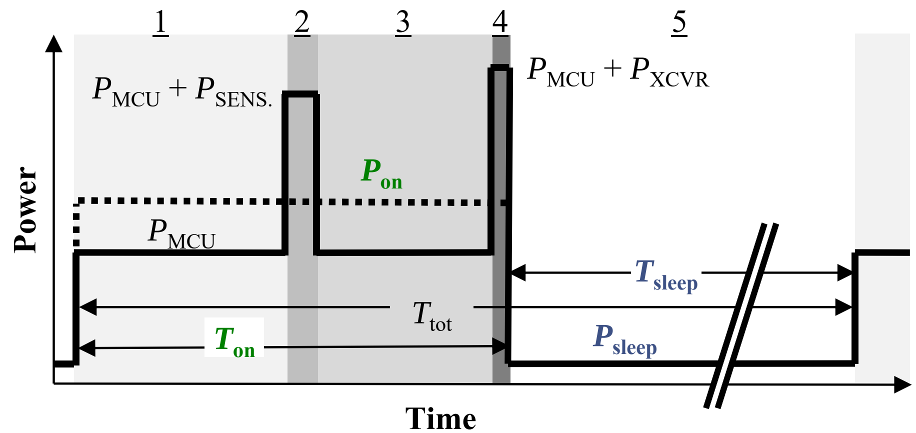


Average of FFTs of most consistent sources

Application Assessment – Temp. Sensor





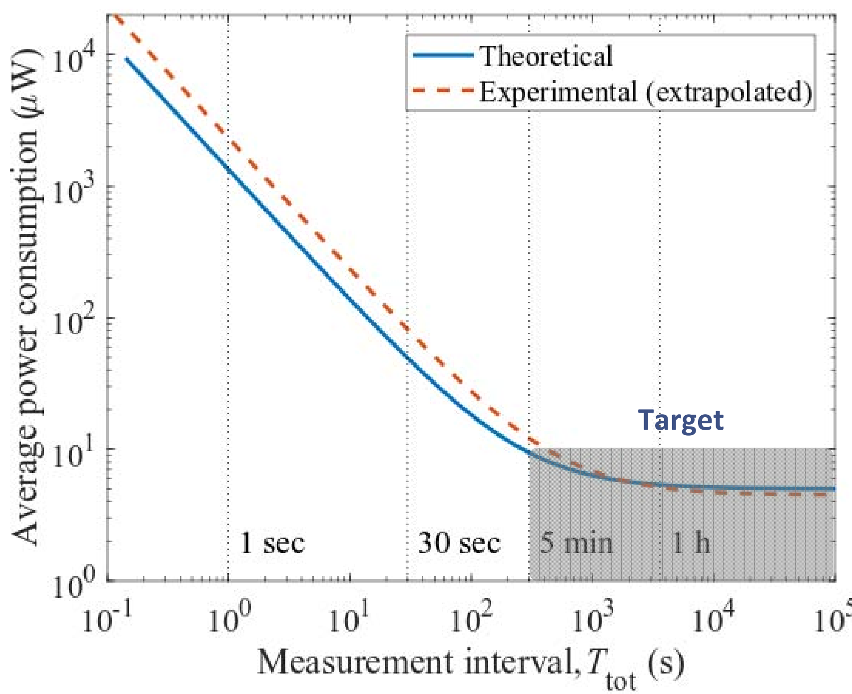


$P_{on} \approx 21$ mW

$T_{on} \approx 110$ ms

$P_{sleep} \approx 1.5$ µA

T_{sleep} = config.



10 µW≈1g requirement

Si: 430 mm³ (8.6 cm²)

W: 52 mm³ (1.4 cm²)

OUTCOMES

- Wireless sensors in vehicle evaluated for non-critical, low data throughput functions
- Linear resonant device compatible with several identified sources
- Approx. 1g requirement for ≈10 μW
  - Not possible with Si-based MEMS harvester
  - MEMS scaled only with a high density material (e.g., tungsten)

Conference paper:

- A. Dompierre, M. Traore, and L. Fréchette, "Measurements of car vibrations under reallife driving conditions and assessment of energy harvesting for wireless sensor nodes," in ASME 2013 International Mechanical Engineering Congress and Exposition, American Society of Mechanical Engineers. American Society of American Engineers, 2013, pp. V014T15A023–V014T15A023

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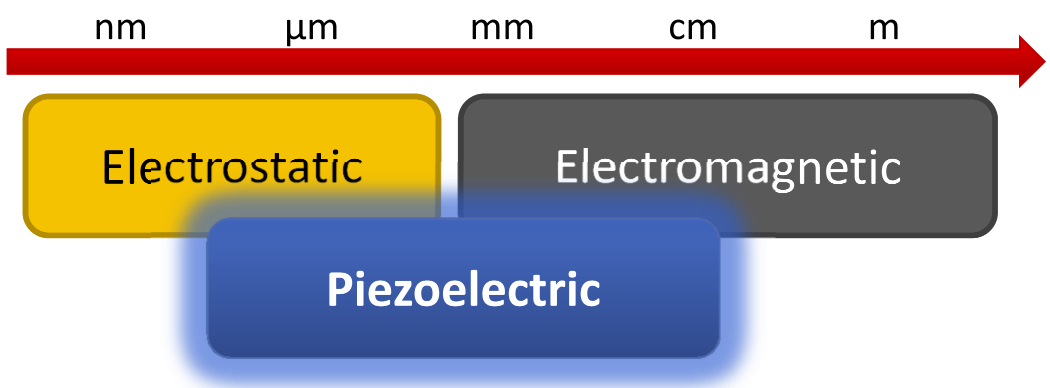
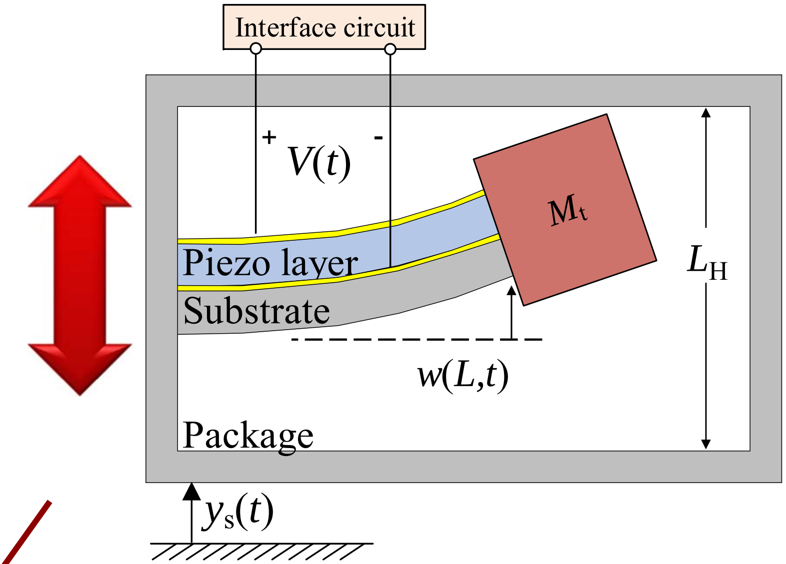
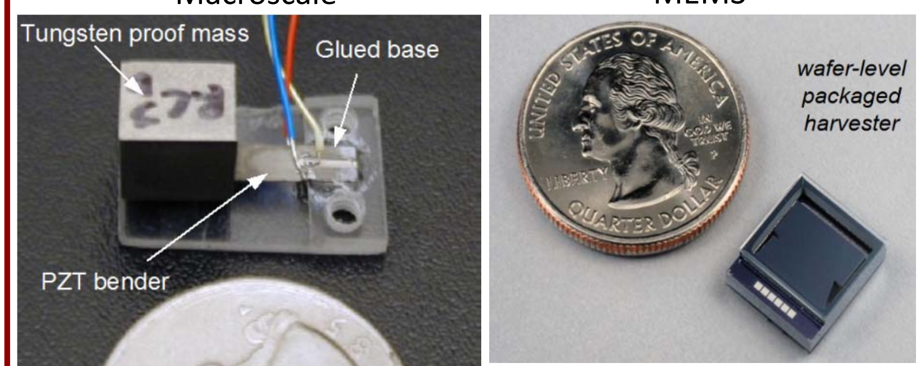
KINETIC HARVESTING: OVERVIEW

- Electromechanical conversion principles:





Macroscale | MEMS



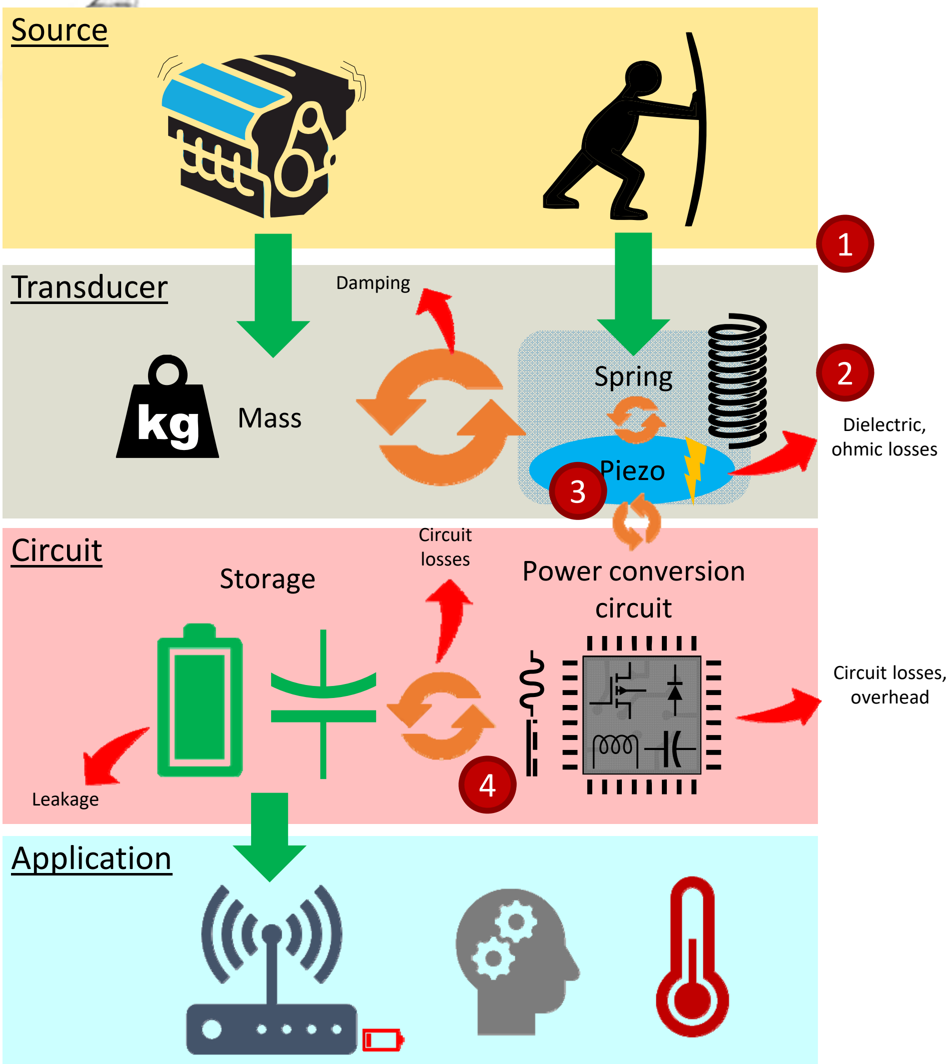
Source: Roundy (2004) | Source: Microgen (2015)

Problematics

- Harvester design needs to be tailored to the application considering:
  - Sensor average power consumption
  - Vibration source characteristics
  - Overall size allowed
- Macroscale solutions costly and bulky
- MEMS solution power density must be increased to be competitive

How should cost effective and high power density piezoelectric vibration energy harvesters be designed and fabricated to power a wireless sensor node from ambient vibrations?

General Energy Chain of a Vibration Energy Harvesting (VEH) Device



Fundamental limits:

1) How much energy is transmitted to the device?
2) How much mechanical energy can the device collect/store/support?
3) How much mechanical energy can be converted to electricity?
4) How much electrical energy can be extracted from the transducer and stored externally?

Power Limit Due to Energy Absorption

$$\bar{P}_{el}(\Omega_r) = \left(\frac{M_{eq}|A|^2}{4\omega_n(\zeta_m + \zeta_{el})} \right) \left(\frac{\zeta_{el}}{\zeta_m + \zeta_{el}} \right)$$

$$\underbrace{F_{in,RMS} \times \dot{W}_{RMS}}_{\text{Power Input, } \bar{P}_{in}} \times \underbrace{\eta}_{\text{Efficiency}}$$

$$\bar{P}_{lim} = \frac{M_{eq}|A|^2}{8\omega_n} Q_m$$

- Power limited by
  - Mechanical damping
  - Mass size
  - Vibration characteristics

- Trade-off between power input and efficiency
- Optimal condition: $\zeta_{el,opt} = \zeta_m$
- Since $\zeta_{el,max} \approx \kappa^2/4$, can be achieved if

$$Q = \frac{1}{2\zeta}$$

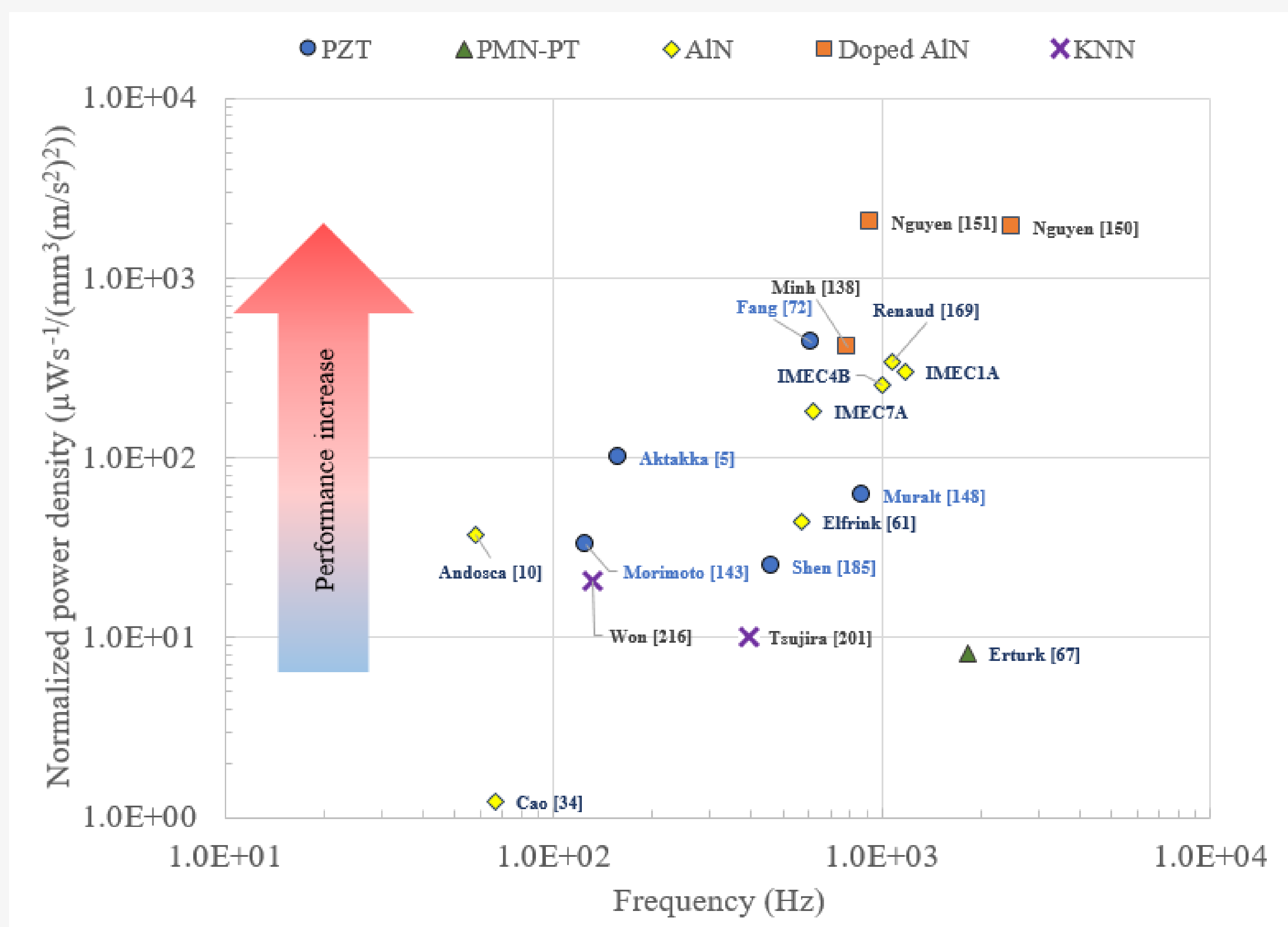
$$\kappa^2 Q_m \geq 2$$

Resonator FOM

Normalized Power Density:

$$P_\rho = \frac{\text{Electrical Power} \times \text{Frequency}}{\text{Acceleration}^2 \times \text{Active Volume}} \propto \rho Q_{tot} \eta$$

PVEH State of the Art Assessment



Outcomes

- Ideal harvester characteristics:
  - **High density proof mass**, sized to fill 50% space of device package
  - Minimize mechanical damping – **maximize Q_m** (crucial for MEMS resonant devices)
  - Provide sufficient coupling ($\kappa^2 Q_m > 2$) – AlN thin film adequate
  - Tuned and sized properly for source characteristics (resonant frequency and mass travel range)
- For MEMS resonant harvester, main limit is power absorption from the source
  - ρQ_m should be maximized.
  - Source characteristics, application must be considered for useful design!

Conference paper:

- A. Dompierre, S. Vengallatore, and L. G. Fréchette, "Theoretical and practical limits of power density for piezoelectric vibration energy harvesters," in Proceedings of Power-MEMS 2011, Seoul, South Korea. KAIST, 2011

Book chapters:

- A. Dompierre, S. Vengallatore, and L. Fréchette, "Power density limits and benchmarking of resonant piezoelectric vibration energy harvesters," in Novel Advances in Microsystems Technologies and Their Applications. CRC Press, 2013, pp. 293–333
- A. Dompierre, S. Vengallatore, and L. G. Fréchette, "Piezoelectric vibration energy harvesters: Modeling, design, limits and benchmarking," in Energy Harvesting with Functional Materials, M. Bhaskaran, S. Srira, and K. Iniewski, Eds. CRC Press, 2013, ch. 9, pp. 215–264

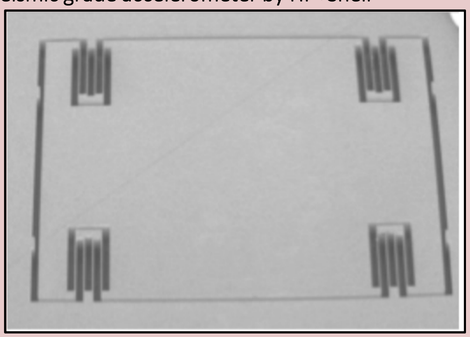
SOLUTIONS TO ENHANCE HARVESTER SENSITIVITY

Current solution	Potential solutions

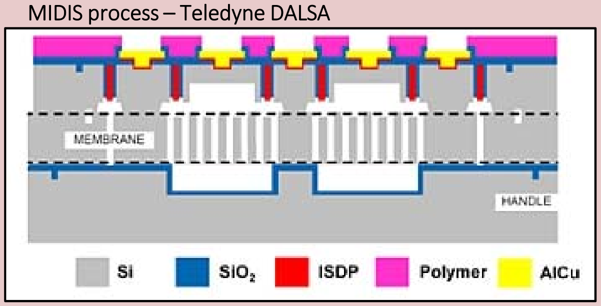
Current solution

1. Large Si mass
- Bulk micromachining
- Wafer bonding

Seismic grade accelerometer by HP+Shell



MIDIS process – Teledyne DALSA



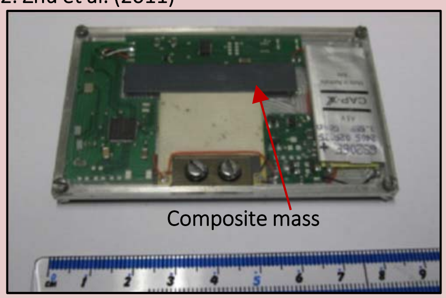
Potential solutions

Change mass composition (improve density)

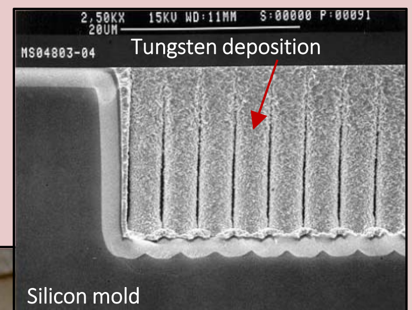
2. Screen printing (polymer + tungsten particles composite)
3. Electrodeposition (gold or other metals)
4. Thin film deposition (tungsten)
   A. Without mold
   B. With mold
5. Machining and bonding of tungsten pieces
6. Micromachining/bonding of tungsten wafers

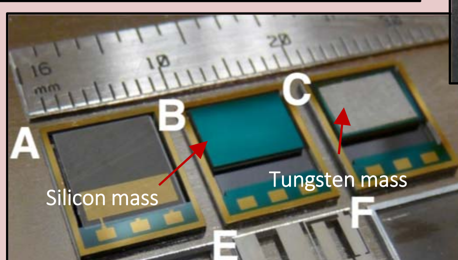
$$\frac{\rho_W}{\rho_{Si}} = 8.3$$

2. Zhu et al. (2011)



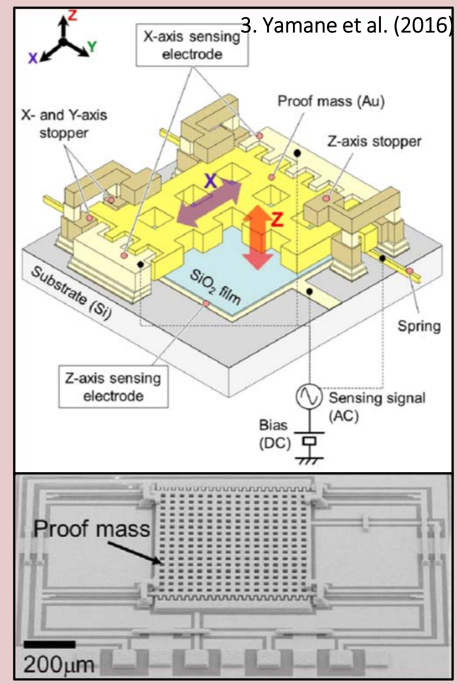
4 b). Sniegowski (1999)



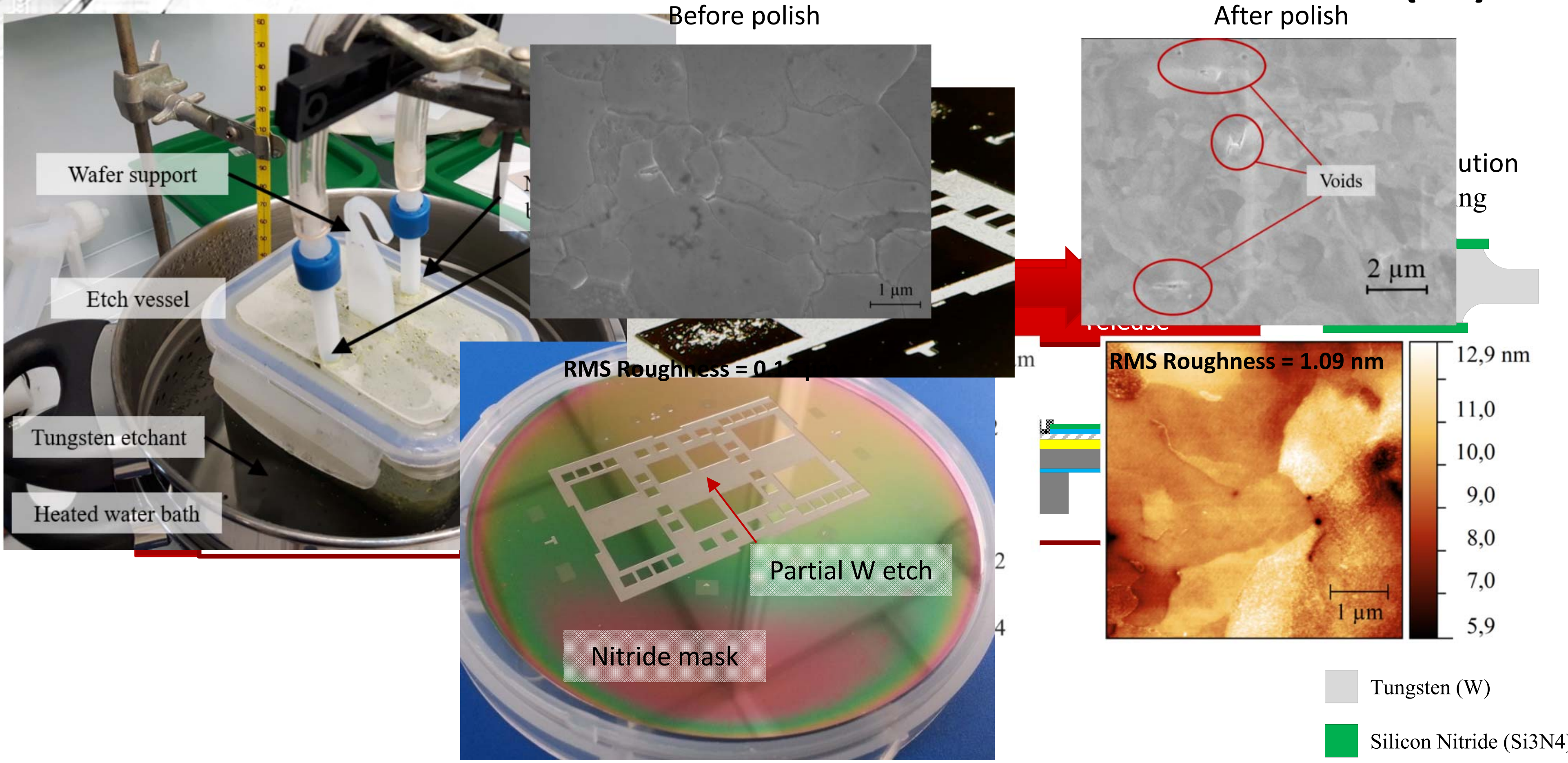


5. Aktakka et al. (2011)

3. Yamane et al. (2016)

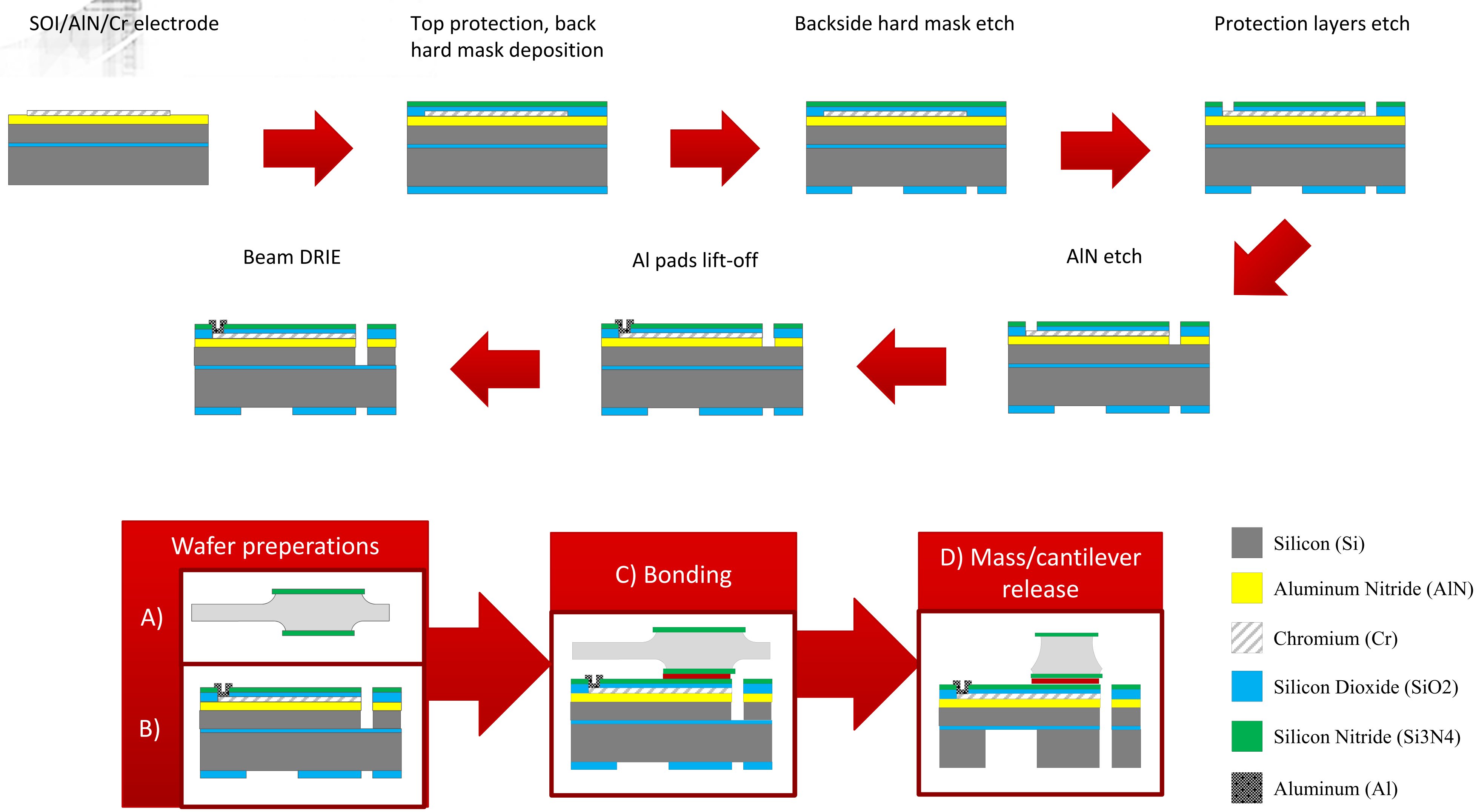


FABRICATION PROCESS FLOW – MASS WAFER (A)



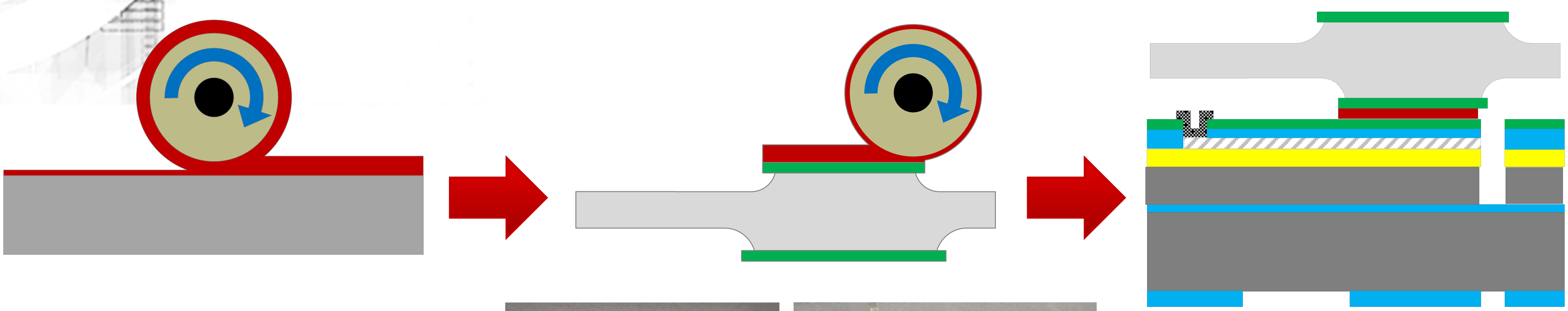
- A. Dompierre and L. G. Fréchette, “A wafer-level process for bulk tungsten integration in MEMS vibration energy harvesters and inertial sensors,” in TRANSDUCERS 2017, IEEE, 2017
- A. Dompierre and L. Fréchette, PCT Patent WO2 018 227 308, 2018

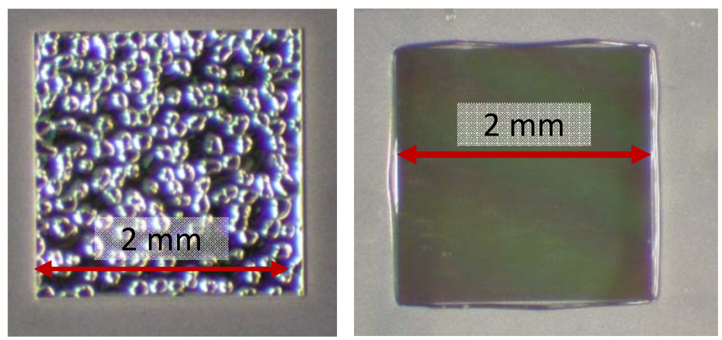
FABRICATION PROCESS FLOW – DEVICE WAFER (B)

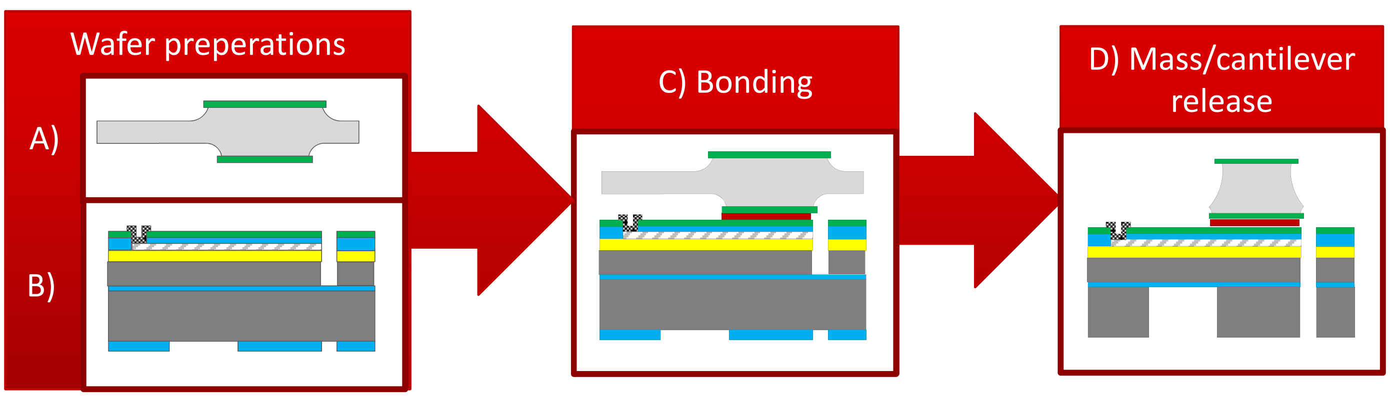


FABRICATION PROCESS FLOW – BONDING (C)

Dummy wafer coating, roller transfer — Adhesive transfer — Bonding

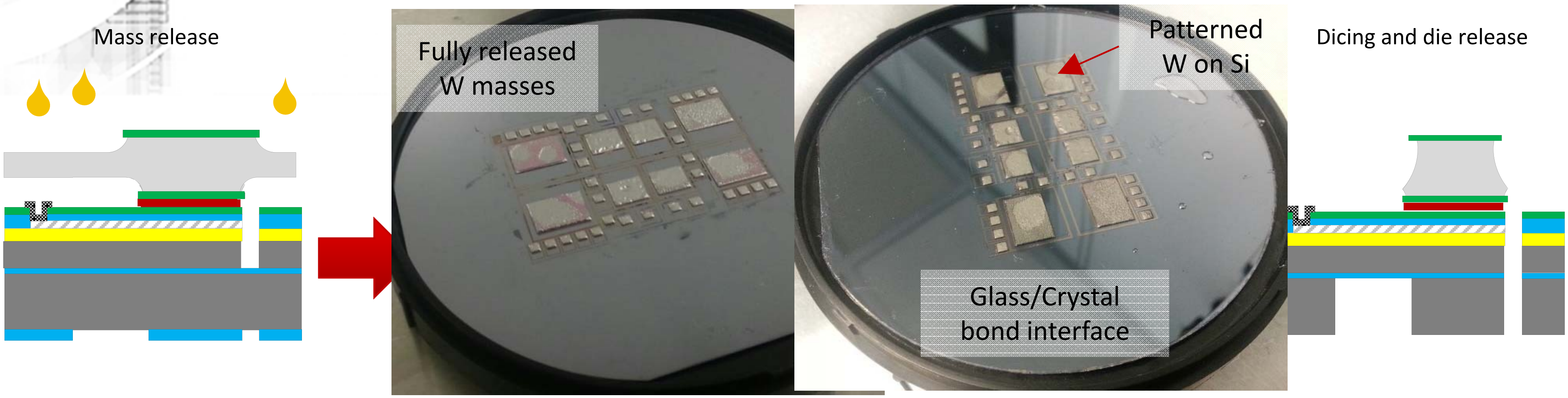


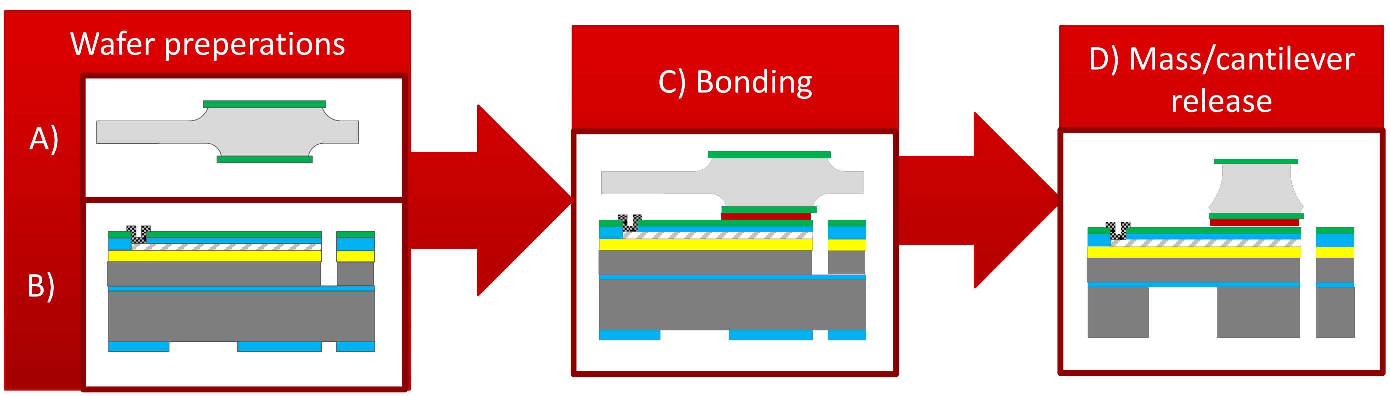




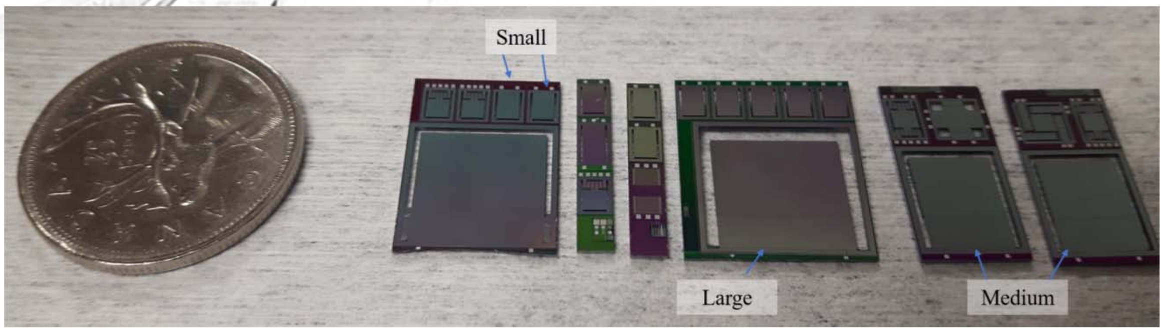
- SU-8
- Tungsten (W)
- Silicon (Si)
- Aluminum Nitride (AlN)
- Chromium (Cr)
- Silicon Dioxide (SiO2)
- Silicon Nitride (Si3N4)
- Aluminum (Al)

FABRICATION PROCESS FLOW – RELEASE STEPS (D)

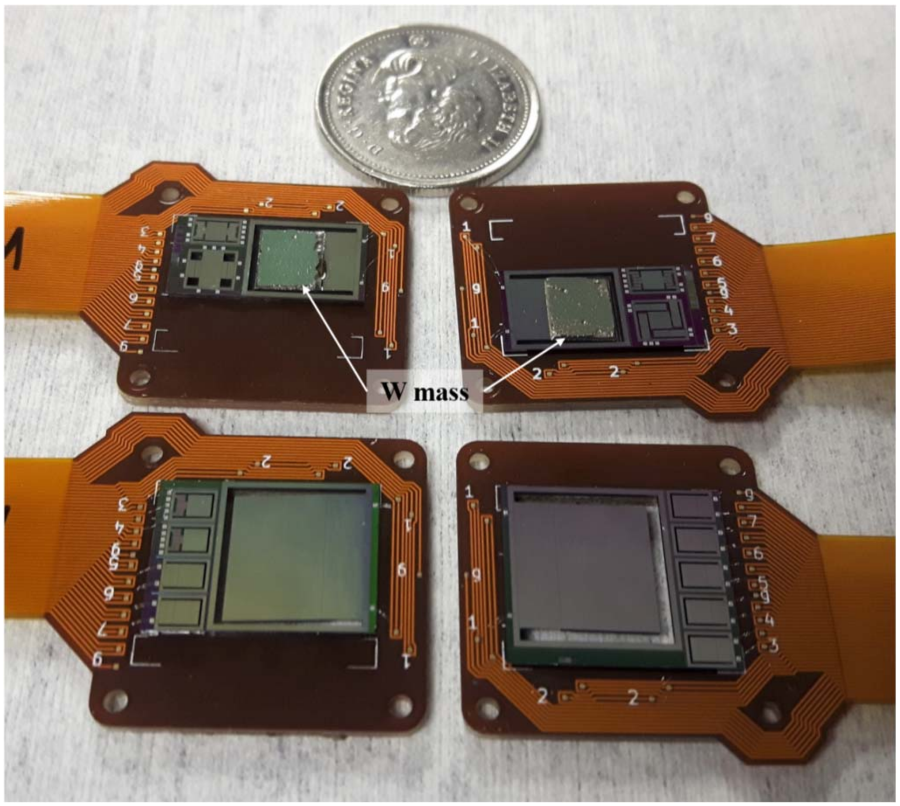


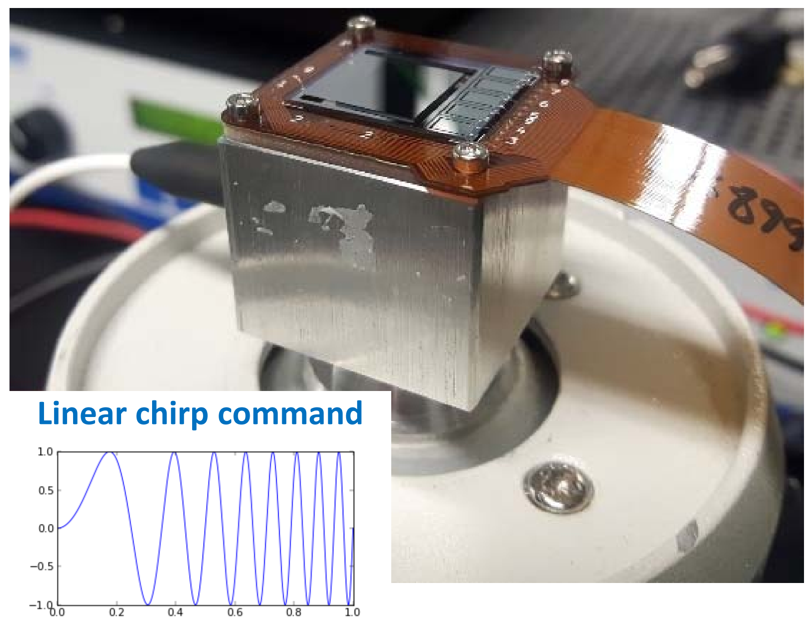


TESTED DESIGNS



- Devices tested before and after tungsten (W) integration
- Characterized in lab on electrodynamic shaker
- Low amplitude chirp signals used to extract FRF



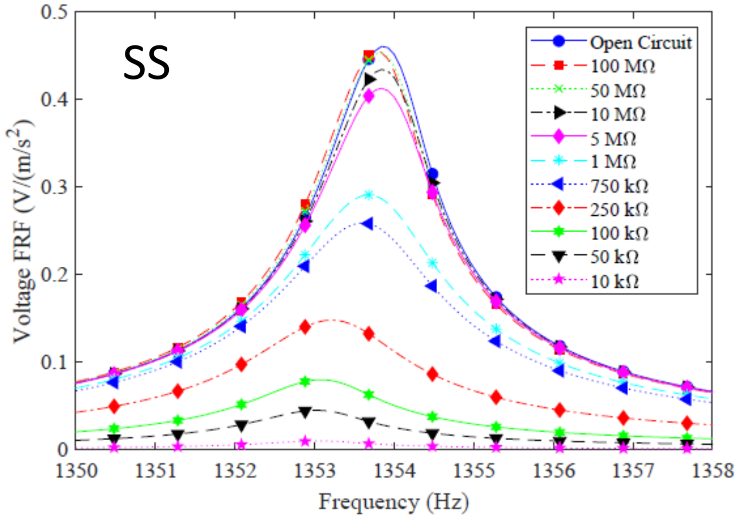


EXAMPLE OF FREQUENCY RESPONSE FUNCTIONS

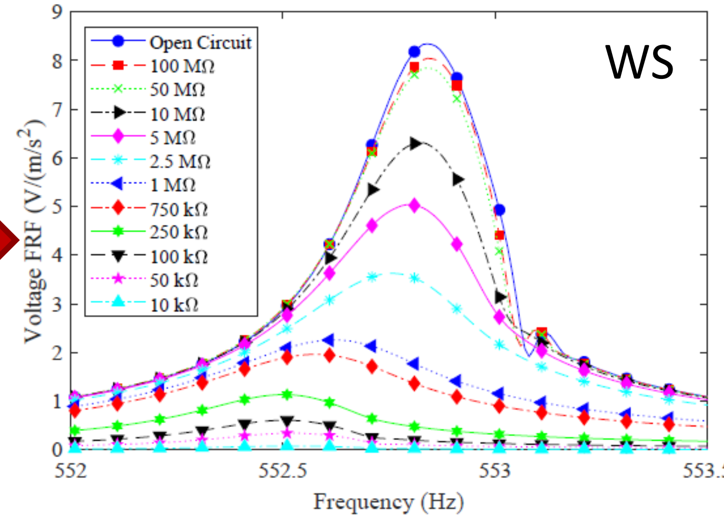
E3 (**Si-based**)
a = 5 m/s^2

E3' (**W-based**)
a = 0.5 m/s^2

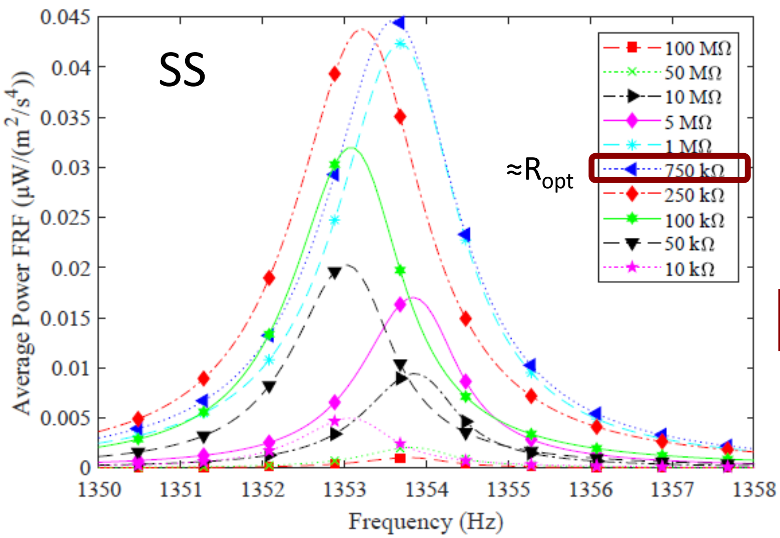
Voltage FRFs



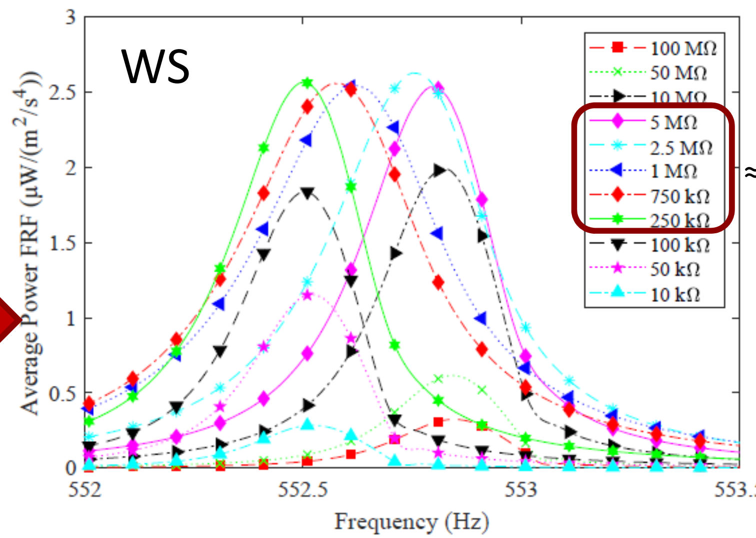
≈18X



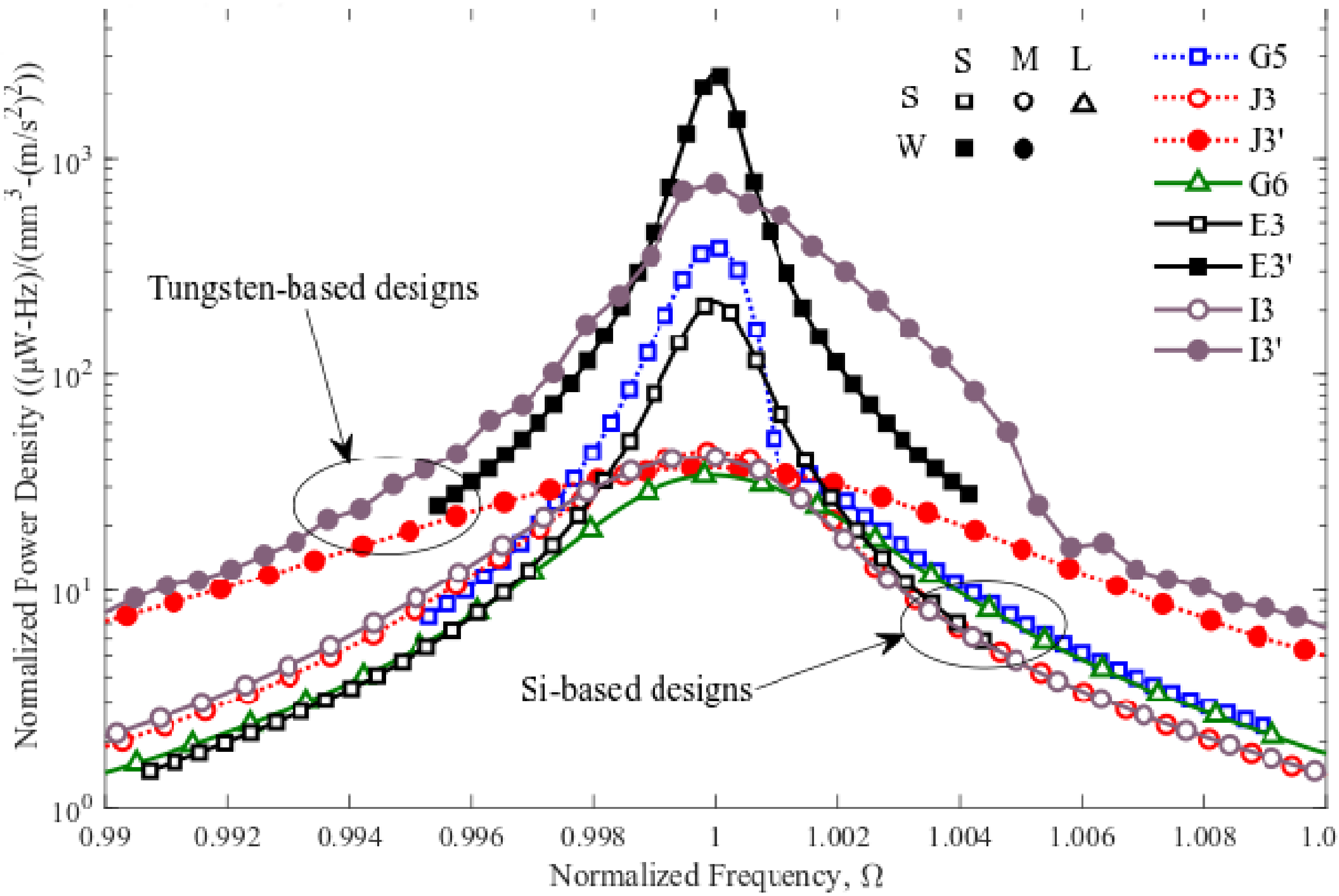
Power FRFs



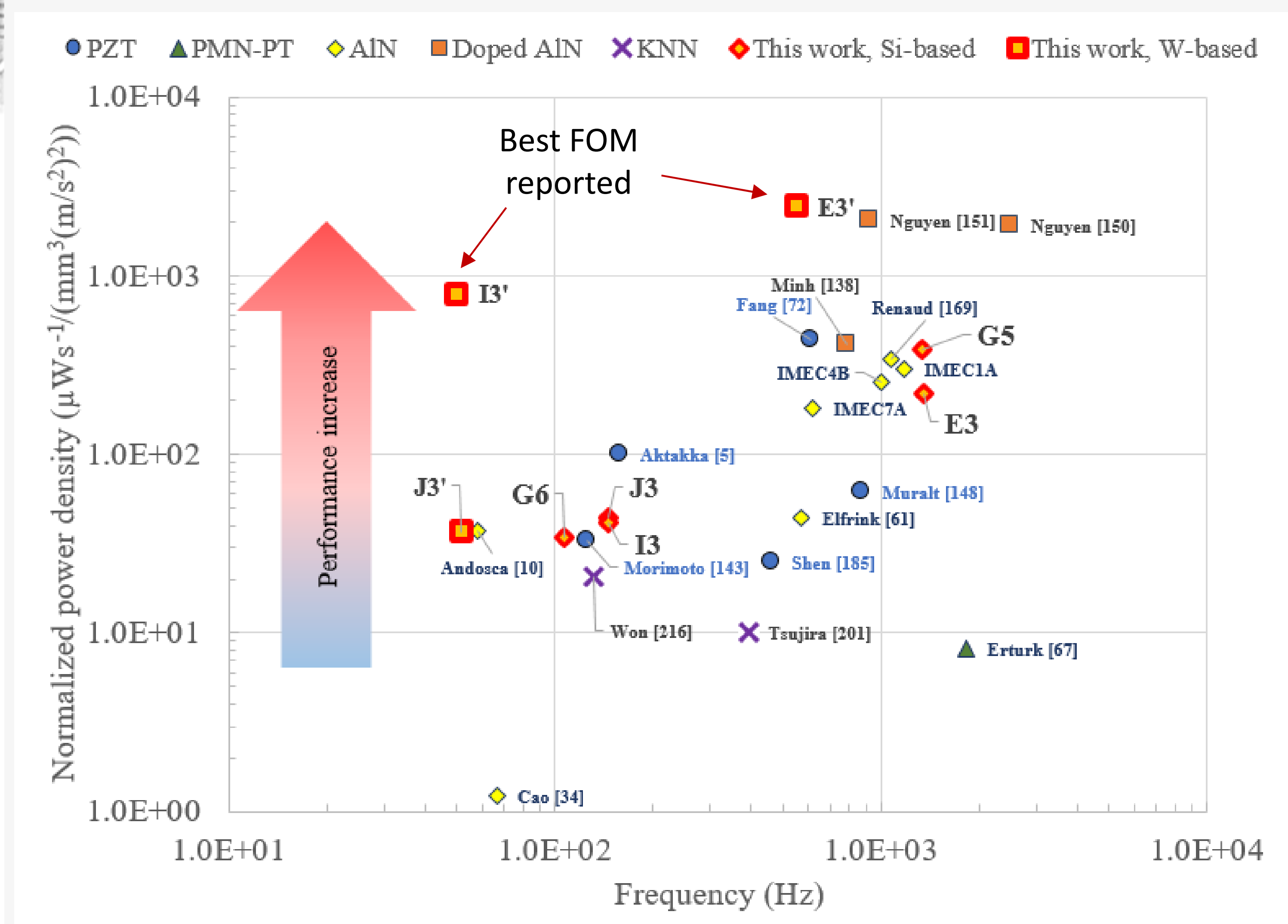
≈ 50X



COMPARISON OF NPD FOR ALL TEST DEVICES



COMPARISON TO STATE OF THE ART



CONCLUSION

- Significant opportunities to make automotive sensors wireless, using energy harvesting from vibrations, for:
  - Non-critical sensors
  - Periodic measurements

- Methodology for source and application assessment with VEH applied to cars and found that:
  - Linear resonant VEH is well adapted, with best range in sub-150 Hz range

- High power density MEMS piezoelectric VEH demonstrated with tungsten proof mass:
  - High Q factor achieved in ambiant air
  - Wafer-level W integration process (patent pending)
  - Best reported Normalized Power Density FOM below 100 Hz

NEXT STEPS

- Test matching of harvester with harvesting circuit and wireless sensor in real vibration conditions
- Improve fabrication process
  - Dimension control
  - Packaging strategy
  - Explore alternative metal etching methods (e.g., plasma etching)
- Evaluation of fatigue and stress degradation for harvesting application
- Demonstrate by implementing with real application

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TESTED DESIGNS

Config. Device ID	SL G6	SM I3, J3	SS G5,E3	WM I3', J3'	WS E3'
Beam width (mm)	11	7	2	7	2
Beam length (mm)	3,2	3,23	1	3,23	1
Si beam thick. (µm)			30		
AlN thick. (µm)			1		
SiO_2 protection thick. (µm)			0,1		
Cr elect. Thick. (µm)			0,1		
SiO_2 pass. Thick. (µm)			2		
SI3N4 thick. (µm)			0,1		
Mass width (mm)	11	7	2	7	2
Mass length (mm)	7,8	6	2	6	2
Si mass thickness (µm)			430		
W mass thickness (µm)	0			440	AD28