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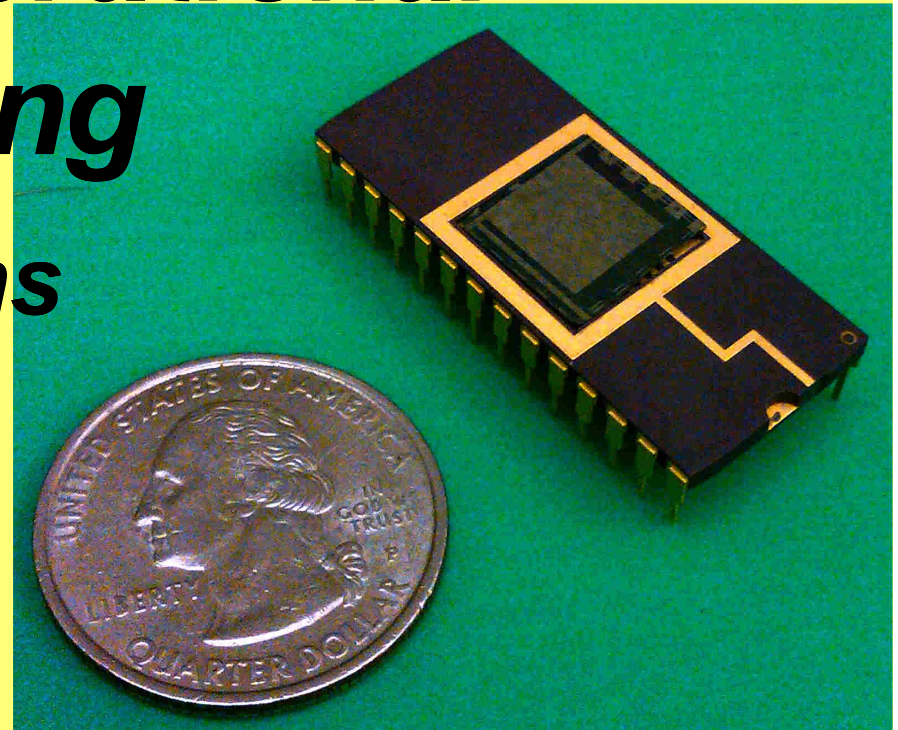
Piezoelectric Vibrational Energy Harvesting

MEMS-based solutions



Robert G. Andosca

Founder, President and CTO

Junru Wu

Founder and Technical Fellow

Cornell University

CNF
Cornell NanoScale
Science and Technology Facility

NSF

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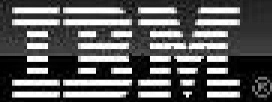
A Smarter Planet™

The planet will be instrumented, interconnected, intelligent

People want it. We can do it.



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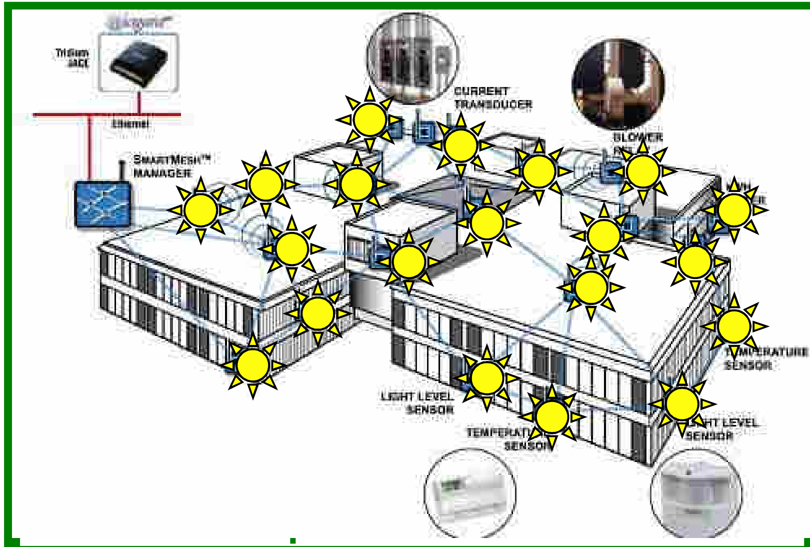
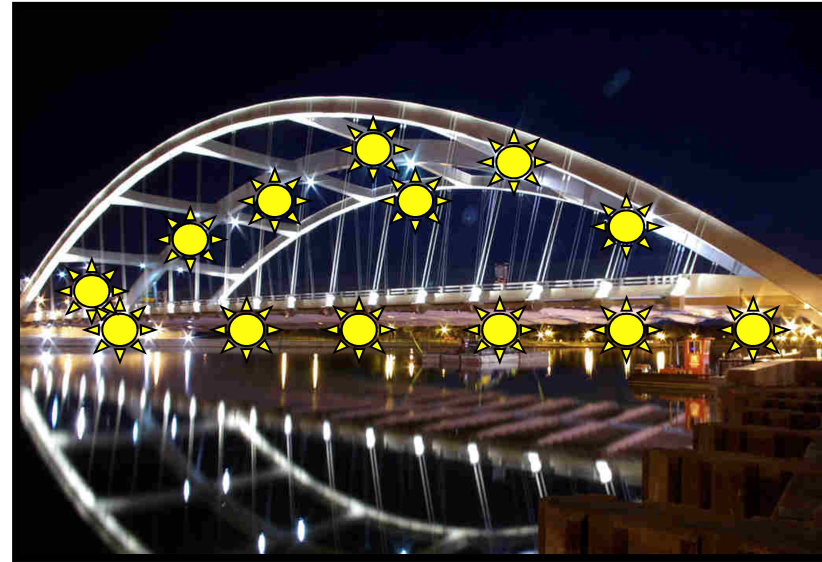
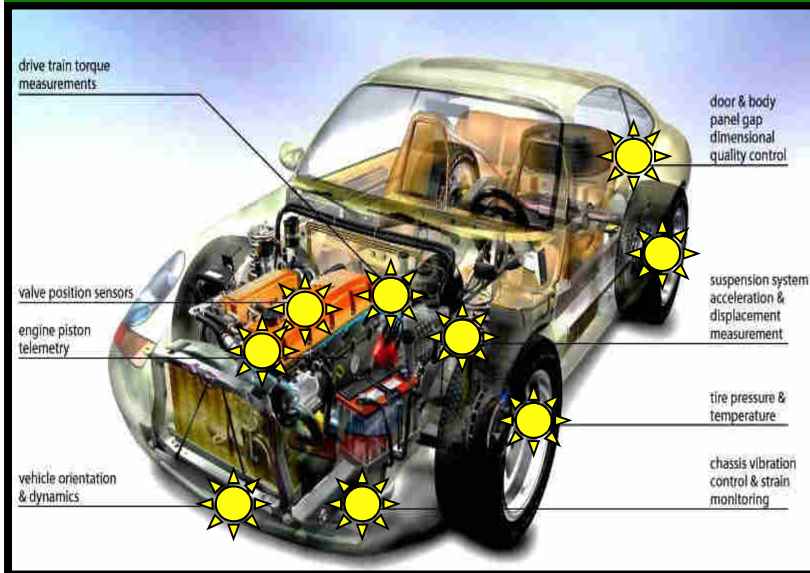
WSN Markets

Markets – Mar. 2015







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Market Problem

WSN market

- **Cost** of **changing batteries** is **holding back** the **market**

Two (2) AA batteries →

wireless sensor node

Meso to *micro*-scale

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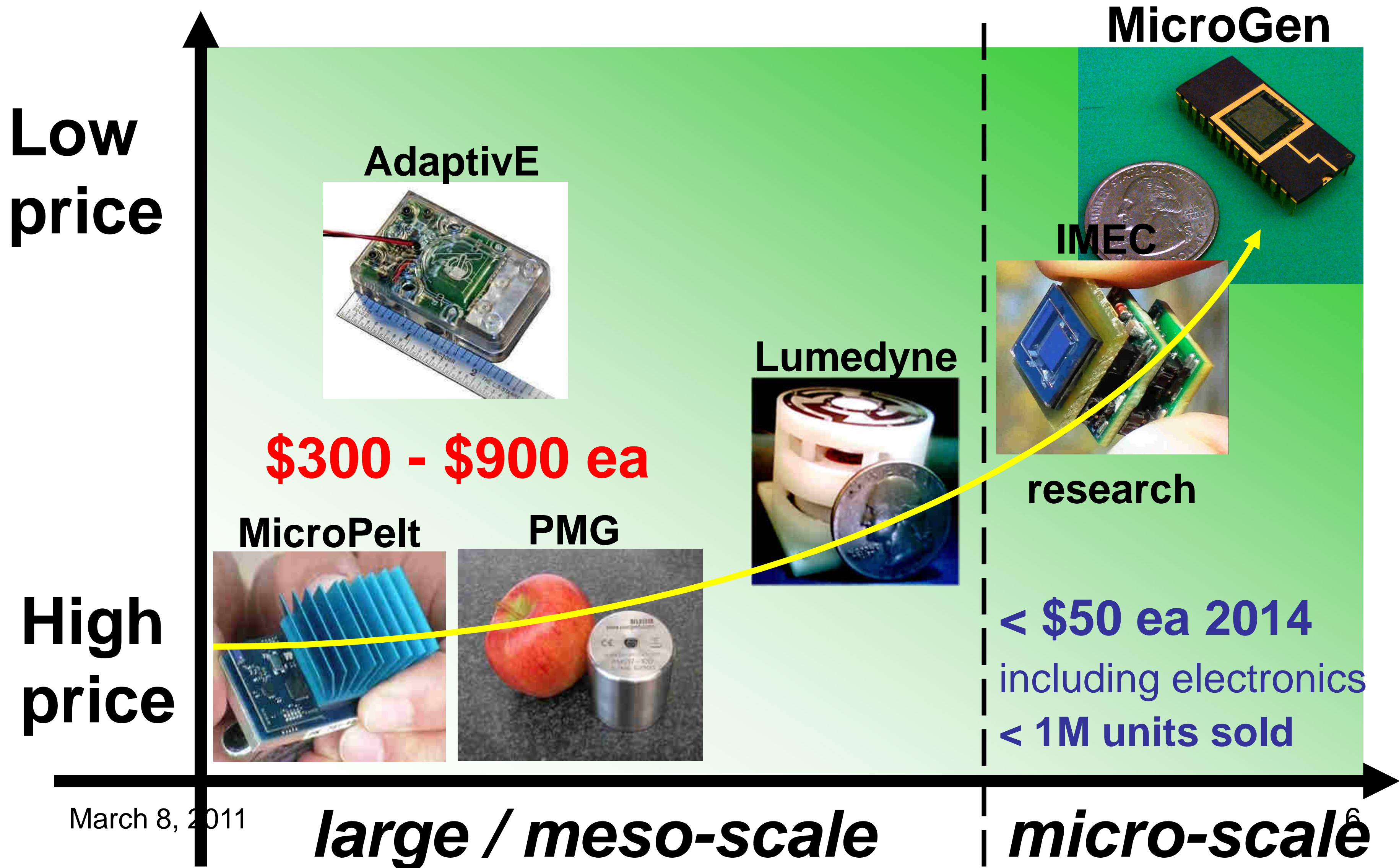

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Scaling of VEH devices

10X reduction in size

- Electrostatic force ➔ 10^2 reduction
- Electromagnetic force ➔ 10^4 reduction
- **Resistive power loss ➔** 100X greater loss
  - Due to higher electrical resistance
  - $P = V^2/R$
- **Manufacturing cost** of **MEMS coils**

MEMS-based PZEH devices overcomes these **issues** and has the **highest effective power density**

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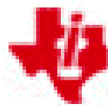
EH-Boards on Market

Energy Harvesting "*plug-n-play*" boards

- Able to accept multiple EH inputs (solar, thermal, vibrational)
- Voltage rectifying and regulating electronics
- Power storage with efficient power management
  - Advanced thin-film rechargeable batteries; and/or
  - ultra-capacitors.
- Most integrated with sensors and/or wireless radios

EH-Link®

Advanced batteries, TI wireless radios



Ultra-cap, no radio

Both storage, wireless radio

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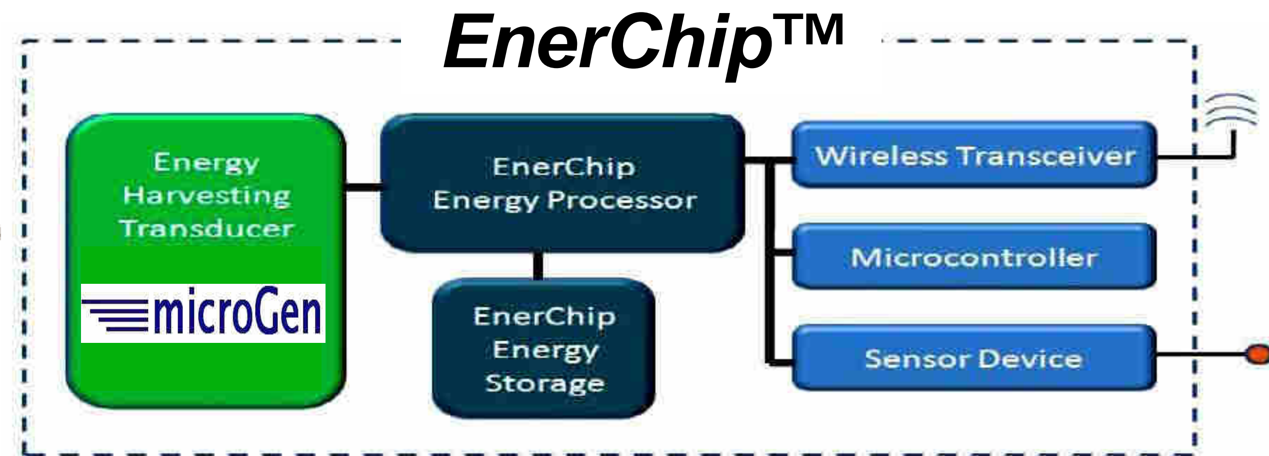
Example EH-Board



"Integrating **MicroGen's *BOLT120A*** micro-power generator **producing a minimum of 100 μWatts** (120 Hz and 1.0 g acceleration) will be more than enough power to charge **Cymbet's *Enerchip* Energy Processor board** with advanced energy processing and storage (thin-film batteries), and will power a sensor device, microcontroller and allow the **Texas Instruments wireless radio** to **transmit and receive** every **20-30 seconds**"

Jeff Sather, VP Customer Solutions

Piezoelectric Vibrational Energy Harvester (PZEH)

1-axis and standard "bandwidth" PZEH device

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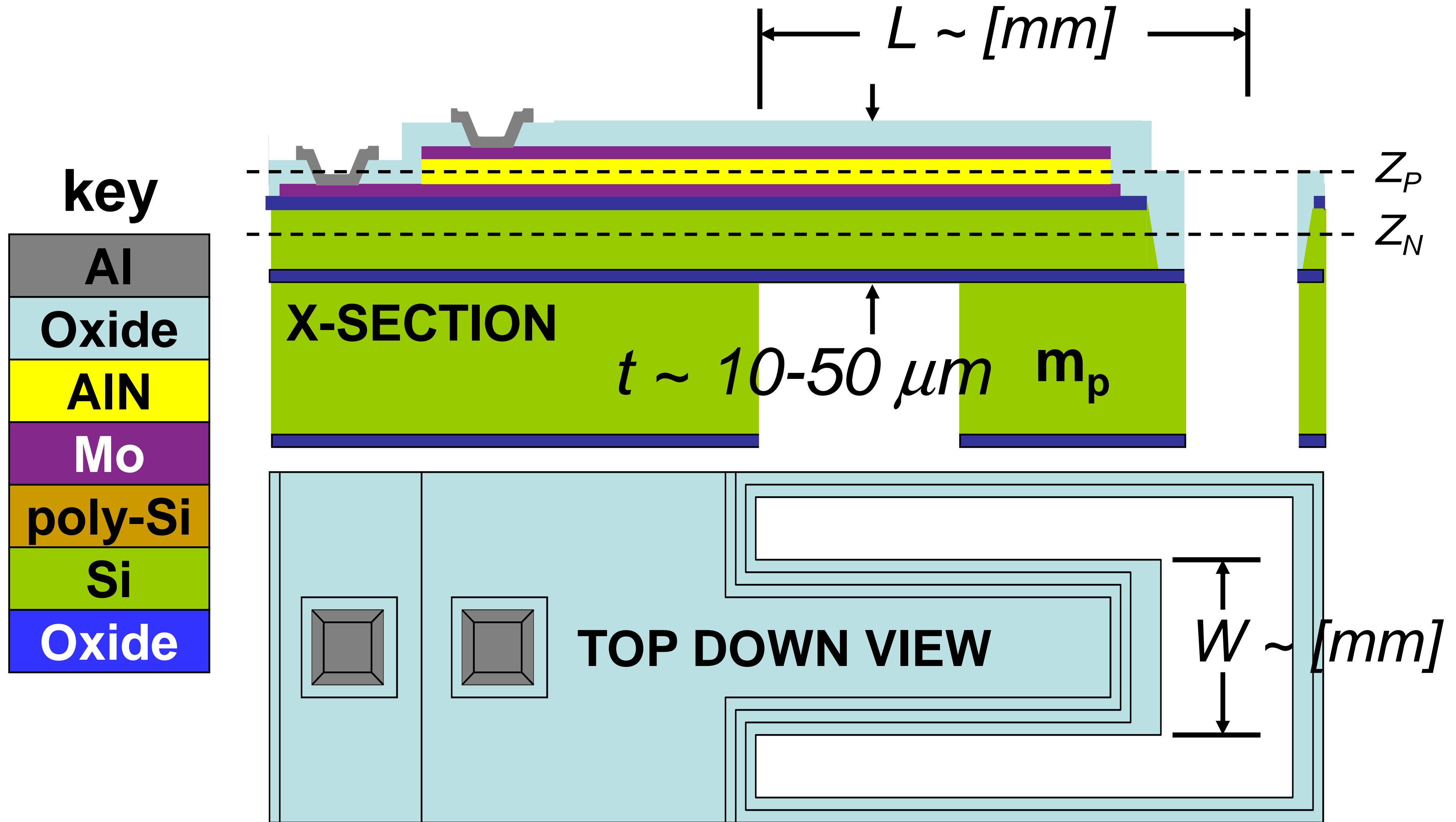
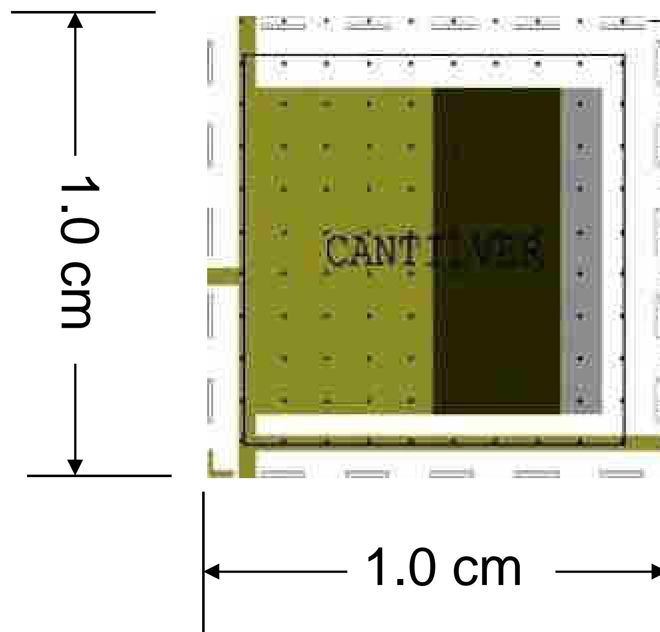
MEMS PZEH



“Single-chip”



- 1.0 x 1.0 cm die
- 1 cantilever
  - $W = W_i$ ~ *[mm]’s*
  - $L = L_i$ ~ *[mm]’s*
- Au proof (end) mass
- 2 electrical connections

Top down view

"Quad-chip"

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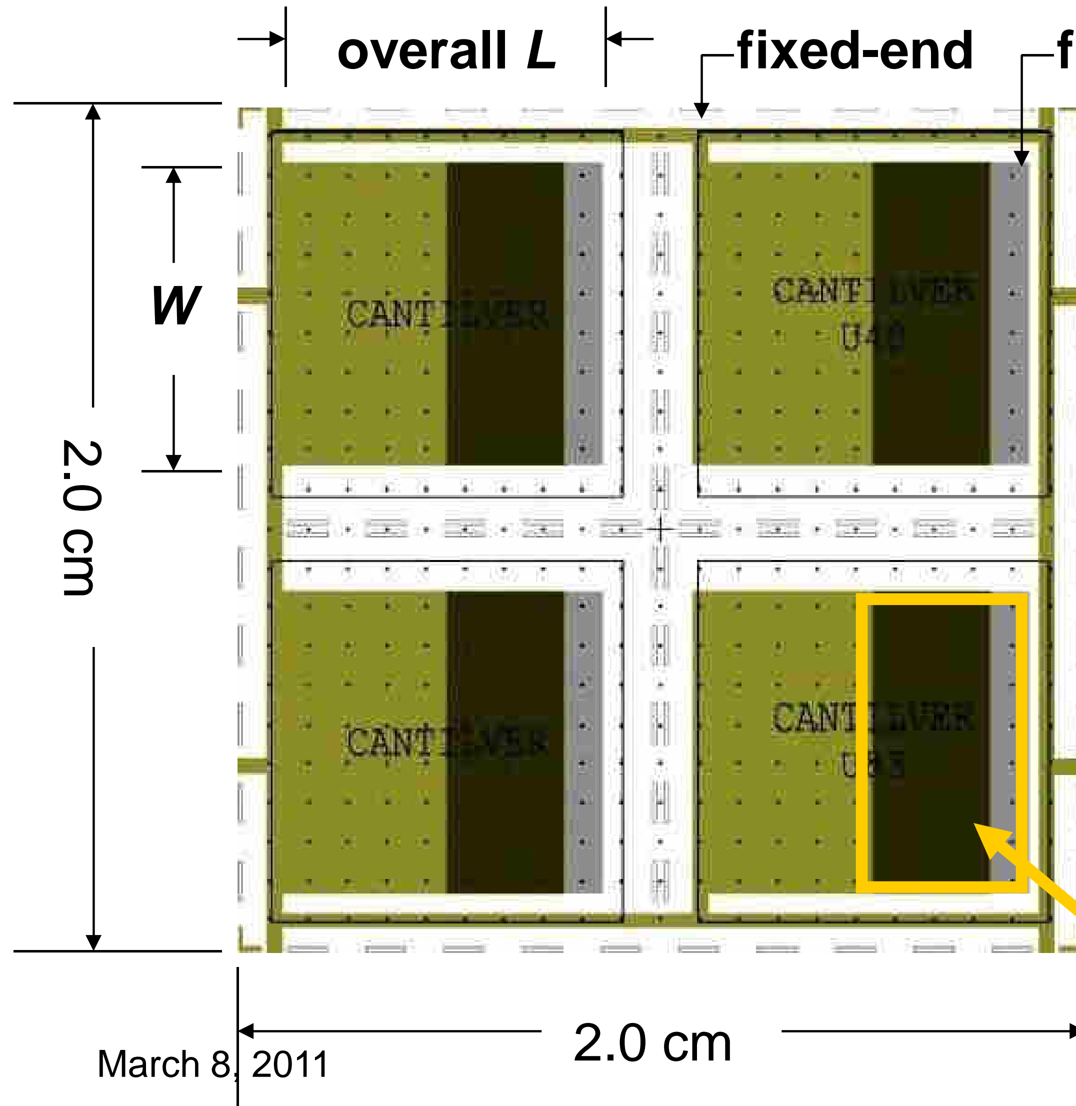

- 2.0 x 2.0 cm die
- 4 cantilevers
  - $W = W_i$ ~ [mm]'s
  - $L = L_i$ ~ [mm]'s
- End mass
- 2 electrical connections
  - All four (4) cantilevers in parallel

End (proof) mass

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Analytical modeling - Voltage

$$V = \frac{Q_T}{C_p} \qquad C_p = \varepsilon_o K_p \left(\frac{LW}{t_p} \right)$$

$$V_{z,\max} = \frac{1}{2\pi} \left(\frac{d_{31} E_p}{K_p} \rho \right) \left(\frac{t_p}{L} \right) \left(z_N - z_p \right) \left(\frac{G}{\varepsilon_o \zeta \nu_1} \right) \left(\frac{k_{z,1} F_{z,1}(L)}{D_{z,1}(L)} \right)$$

Voltage is linear with ($z_N - z_p$)

Voltage is independent of *W*

Voltage is inversely proportional to *L*

Analytical modeling - Power

$$P = \frac{1}{2} C_p V^2 = \frac{1}{2} \frac{Q_T^2}{C_p} \qquad C_p = \varepsilon_o K_p \left(\frac{LW}{t_p} \right)$$

$$P = \frac{1}{8\pi^2} \boxed{\left(\frac{d_{31}^2 E_p^2}{K_p} \rho^2 \right)} \left(\frac{W t_p}{L^2} \right) \left(z_N - z_p \right)^2 \left(\frac{A^2 G^2}{\varepsilon_o \zeta^2 v_1^2} \right) \left(\frac{k_{z,1}^2 F_{z,1}^2(L)}{D_{z,1}^2(L)} \right)$$

Power increases as $(z_N - z_p)^2$

Power is proportional to W

Power is inversely proportional to L^2

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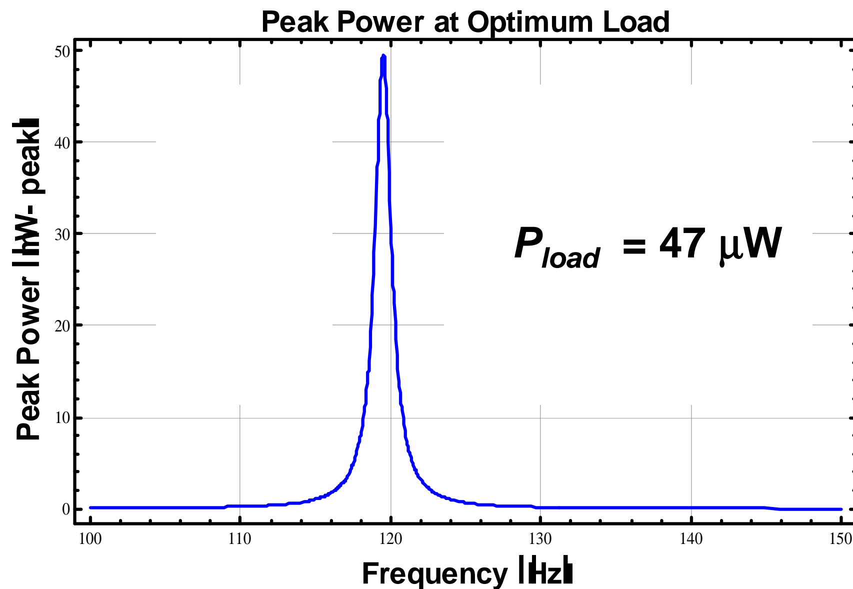
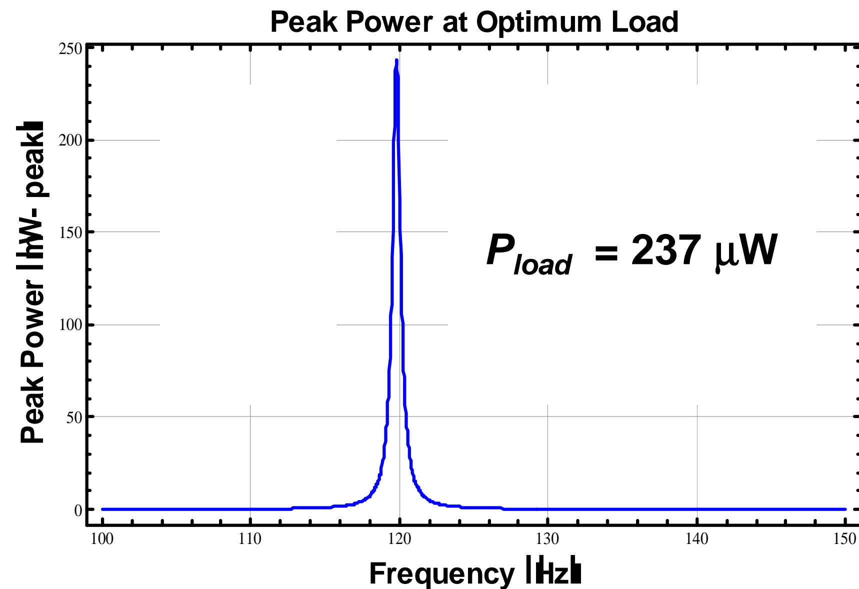
Analytical modeling P_{load}

P_{load} @ ν_1 = 120 Hz and G = 1 g





SOI device layer = t_{low}

$(z_N - z_p) \approx Z_{low}$

s.f. ≈ 2.75 *

SOI device layer = t_{high}

$(z_N - z_p) \approx Z_{high}$

s.f. ≈ 0.34 *

** Relative to AlN bulk yield strength*

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AlN -vs- other piezos

Common piezoelectric materials.

Material	coupling coefficient d_{31} (pC/N)	Young's modulus E_p (GPa)	Dielectric constant K_p	Density ρ (g/cc)	Voltage material coefficients * $\left[\frac{d_{31}E_p}{K_p}\rho\right]$	Power material coefficients * $\left[\frac{d_{31}^2 E_p^2}{K_p}\rho^2\right]$
AlN	**-2**	340	**9**	3.26	**12.55**	**0.83**
$LiNbO_3$	-0.85, -1	181.6	29, 85	4.644	0.43 - 1.49	0.01 - 0.04
$BaTiO_3$	-34.5	67	1250 - 10,000	6.02	0.07 - 0.57	0.03 - 0.24
PVDF	20	3	12	1.78	0.46	0.00
Sol-gel PZT	**-44.2**	100	**1700**	7.55	1.00	1.00

* *values normalized to PZT*

AlN is much more manufacturable as well

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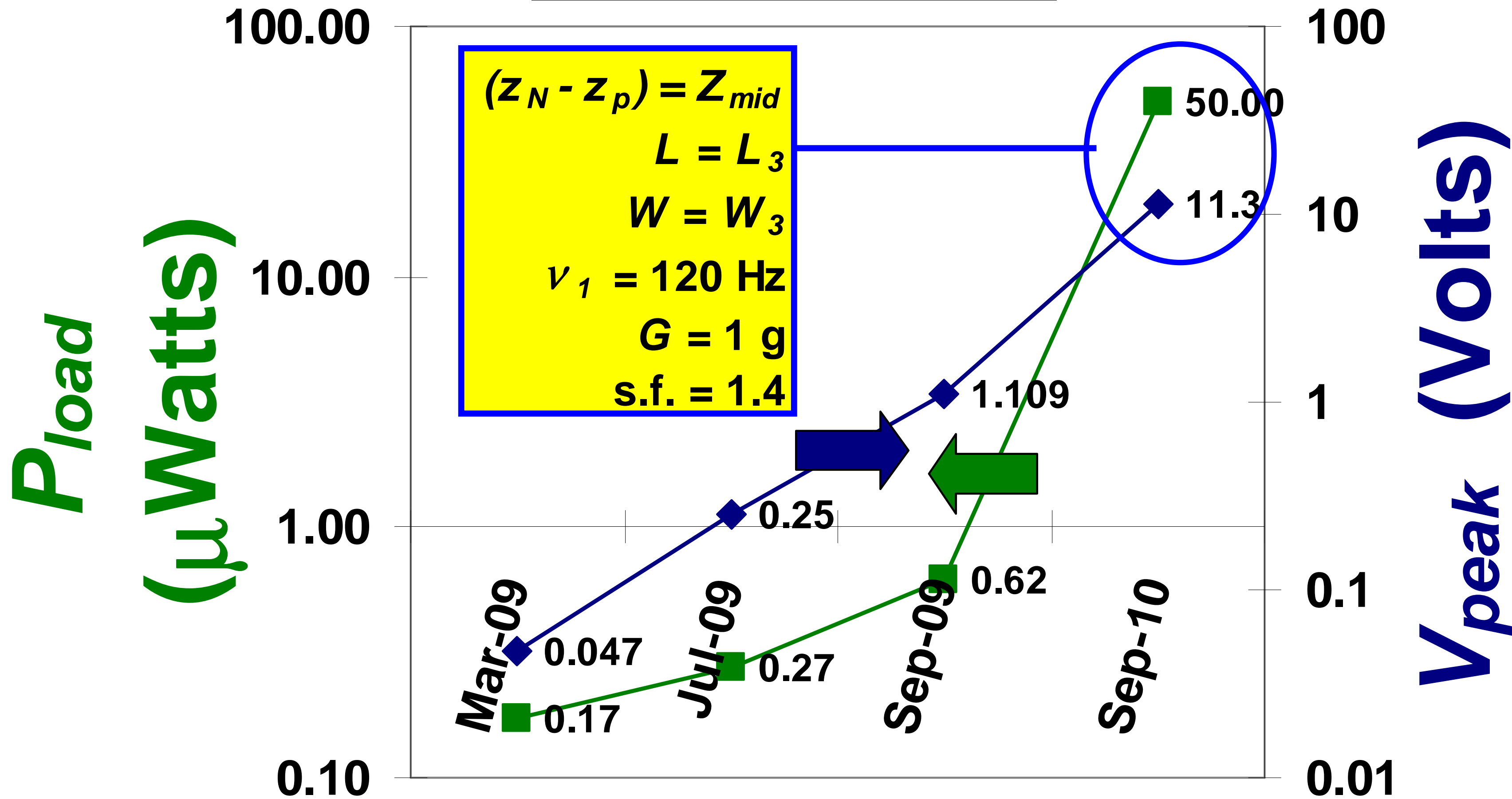
Predicted *V* & *P*

Single-chip



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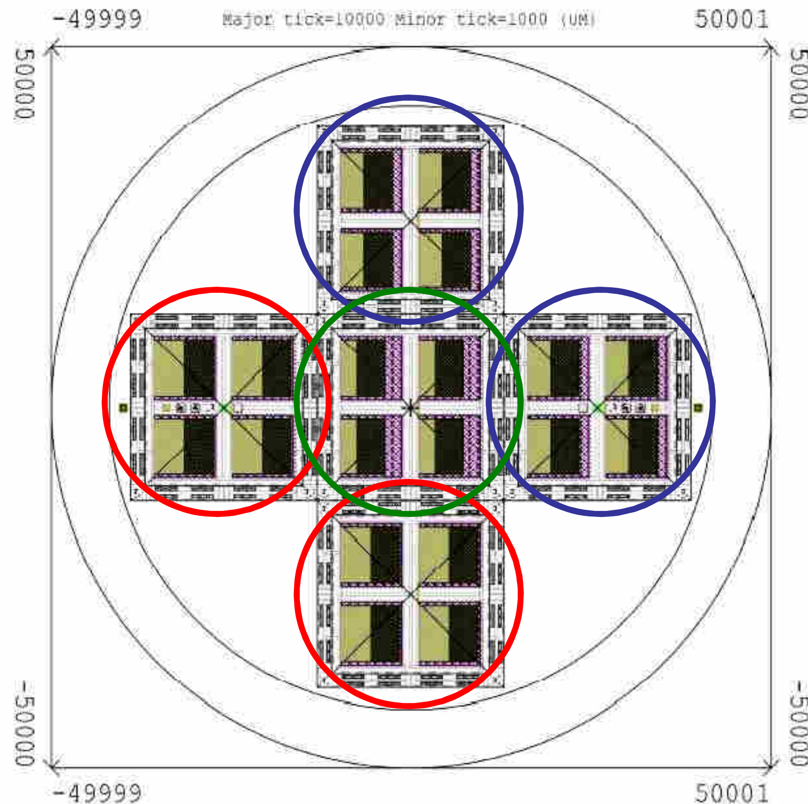
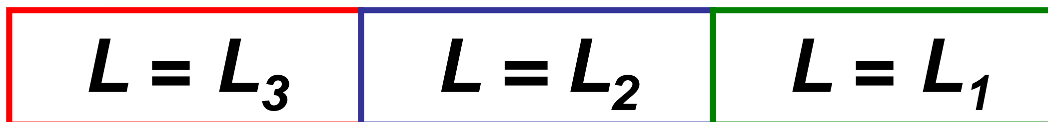
Reliability testing

L and **end-mass** varied to **optimize power** and evaluate cantilever **reliability**

(in progress)





$L_3 > L_2 > L_1$

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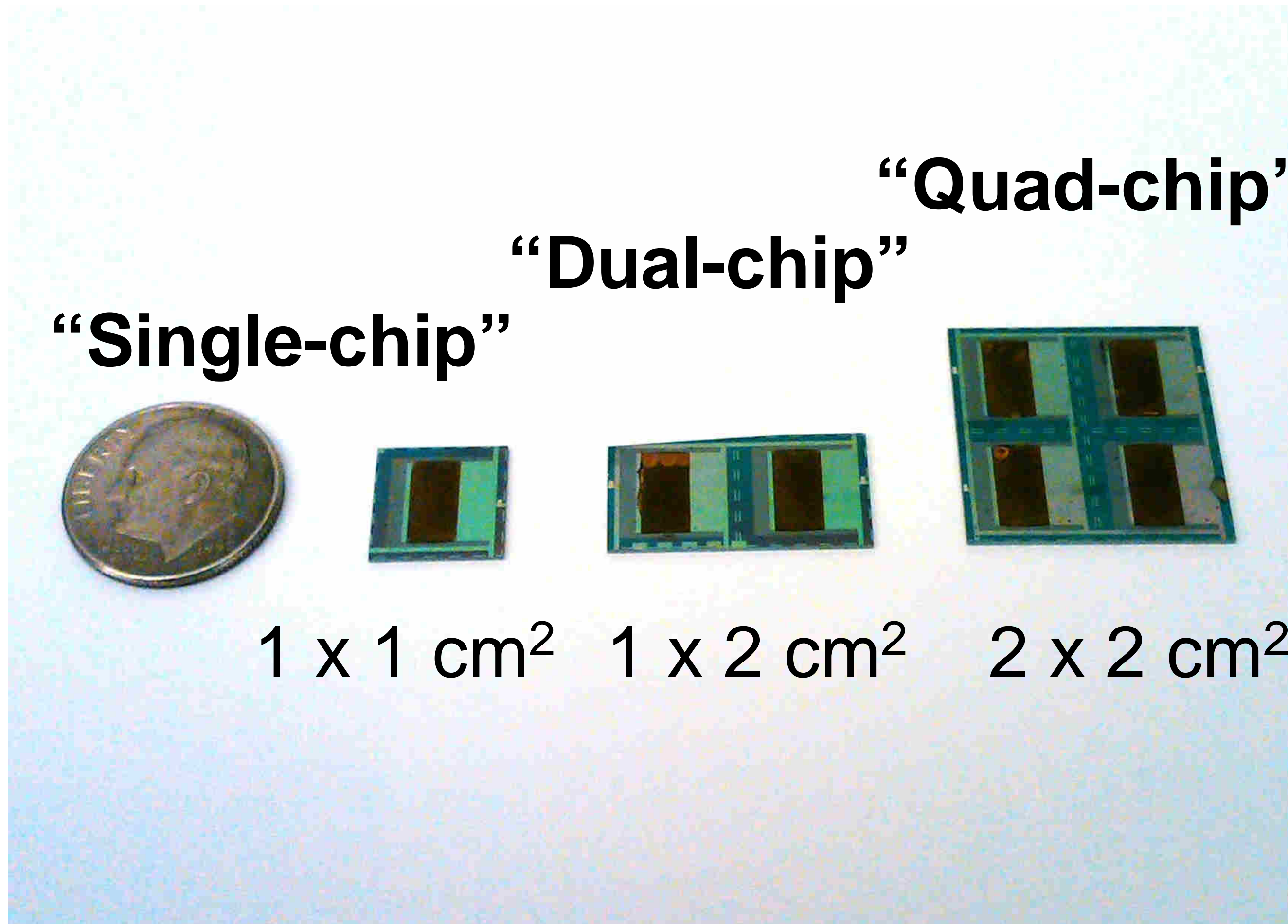
BOLT™ chips



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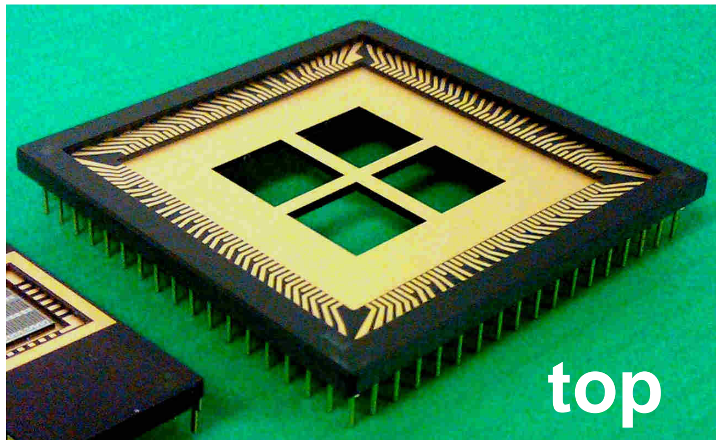
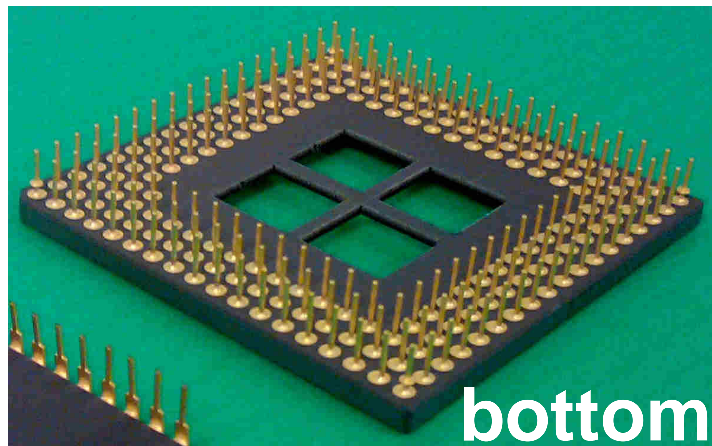
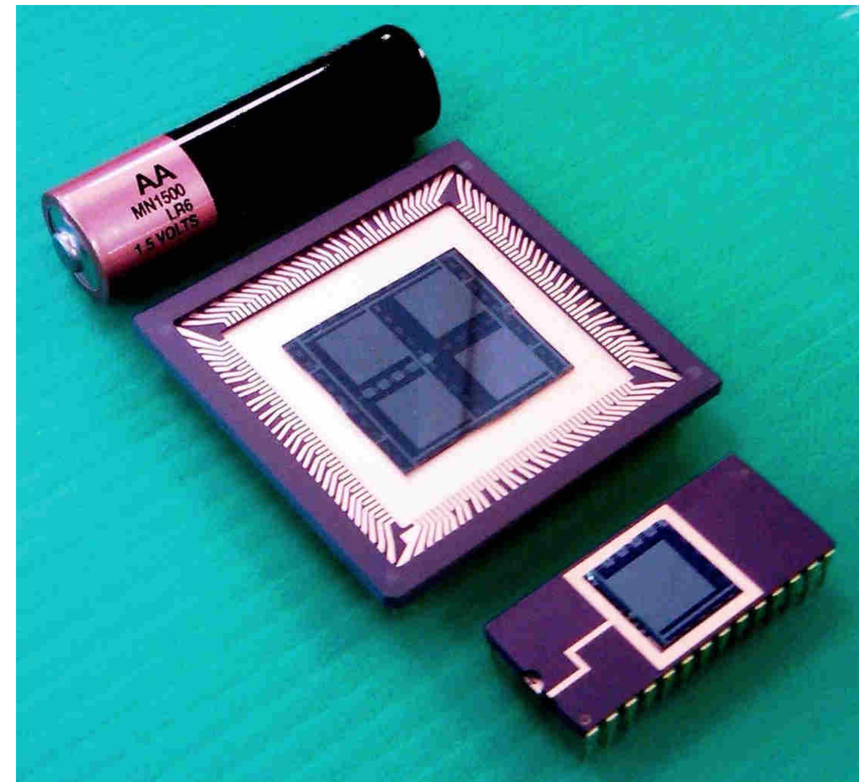
Initial packaging

milled demo package





Packaged Quad-chip and Single-chip demo units



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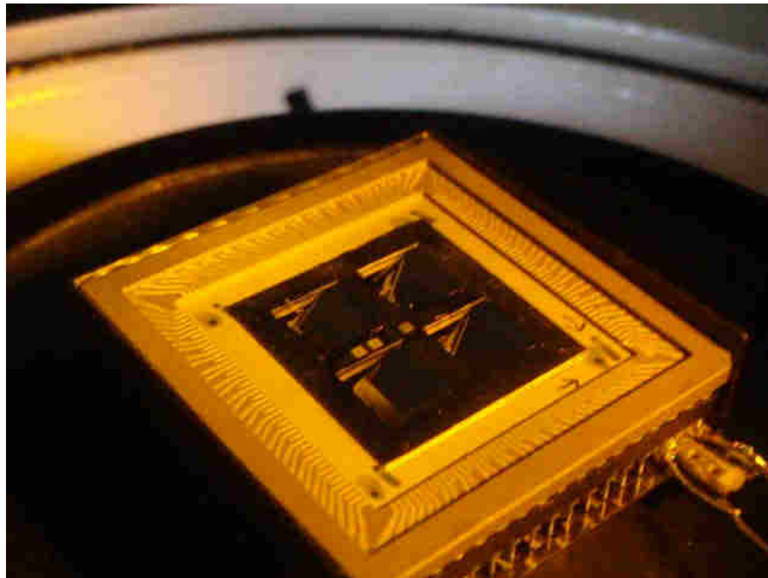
BOLT0609™ demonstration



Resonant frequency

- Cantilever to cantilever =
  = 60 ± 0 Hz
- FWHM < 4 Hz (as shown)

G-acceleration (as shown)

- **G = 0.5 g**
- δ_{max} = deflection > ± 2 mm
- **Single-chip** (R_{load} < 20 kΩ)
  - **P_{load} > 50 μWatts**
- **Quad-chip** (R_{load} < 5 kΩ)
  - **P_{load} > 200 μWatts**

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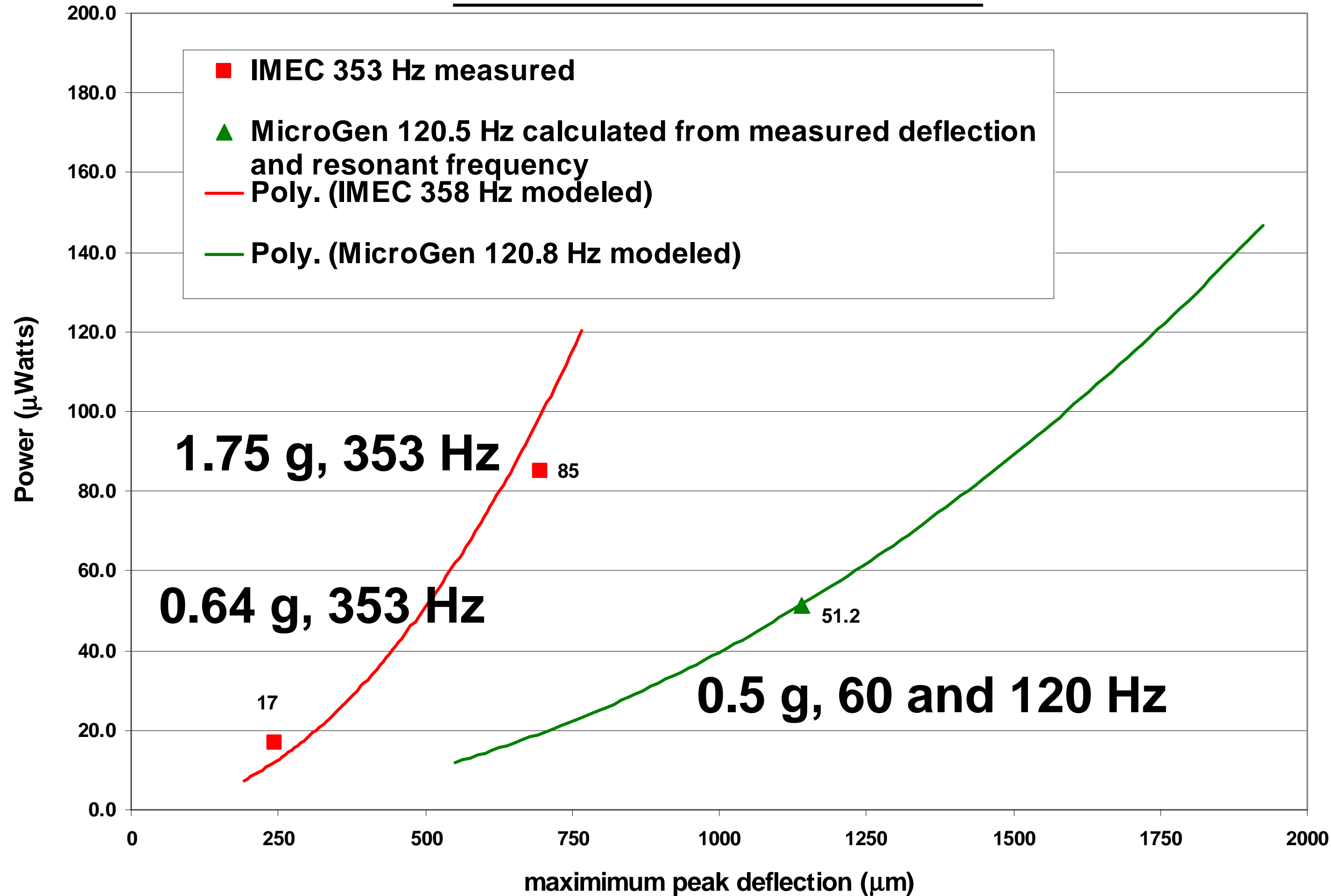
Power



$P \propto G^2$

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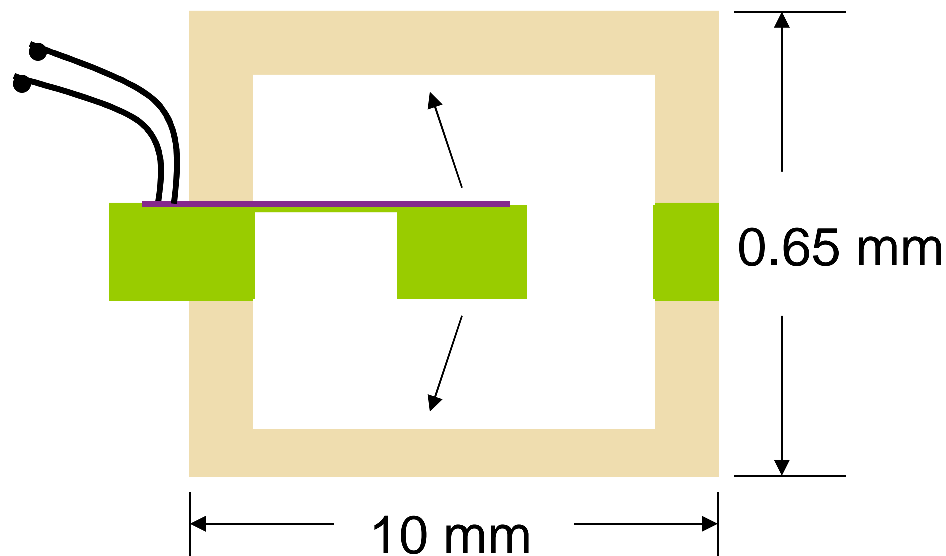
Alpha-level Packaging



Wafer / chip-scale packaging

- hermetically sealed

- **Single-chip package**
- New Director, Packaging and Test
  - **T. Gus McDonald**
    - TI's DMD DLP technology
    - Corning optical switch technology
    - **Major focuses**
      - Efficient packaging
      - Reliability testing

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Alpha *BOLT*™

BOLT™ Family of Products

*generating **100 μWatts** minimum*
*at **constant G-level***

ν (Hz)	1.00 g	0.75 g	0.50 g	0.25 g	0.10 g
50 ± 2	*BOLT050A*	*BOLT050B*	*BOLT050C*	*BOLT050D*	*BOLT050E*
60 ± 2	*BOLT060A*	*BOLT060B*	*BOLT060C*	*BOLT060D*	*BOLT120E*
100 ± 2	*BOLT100A*	*BOLT100B*	*BOLT100C*	*BOLT100D*	*BOLT100E*
120 ± 2	*BOLT120A*	*BOLT120B*	*BOLT120C*	*BOLT120D*	*BOLT120E*

BOLT050, BOLT060, BOLT100 and BOLT120 will be released as ***Alpha*-products summer 2011**

Important points

- **Power enables EH-boards effectively**
  - > 50 μWatts/cm^2 unpackaged; > 75 μWatts/cm^3 packaged
  - ➔ We can obtain 2-4X power density in near-term
- **Price-point drops with volume**
  - < $20 each at 1M/year
- **Reliability ➔ 20+ years**
- **Overall packaged size < 0.7 cm^3**

Parametric Mode Enabled (PME)

or

Vibration Induced Broadband Excitation *VIBE*™

Multi-axis (2 and 3) and broadband

International Patent Application Serial No. PCT/US08/57865, R.G. Andosca and J. Wu, entitled "Piezoelectric Vibrational Energy Harvesting Systems Incorporating Parametric Bending Mode Energy Harvesting," filed by UVM through DRM PLLC on March 21, 2008 (provisional March 21, 2007.)

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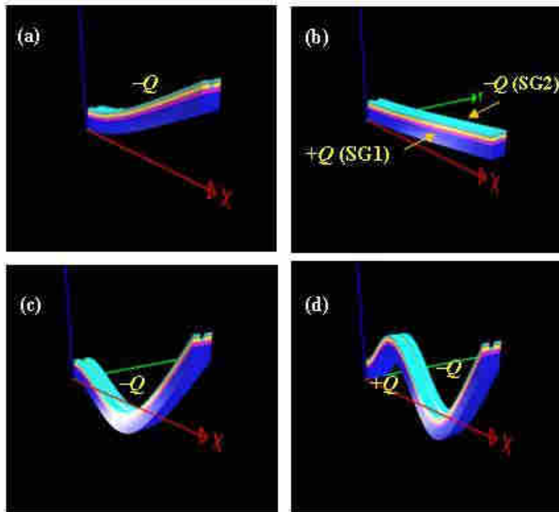
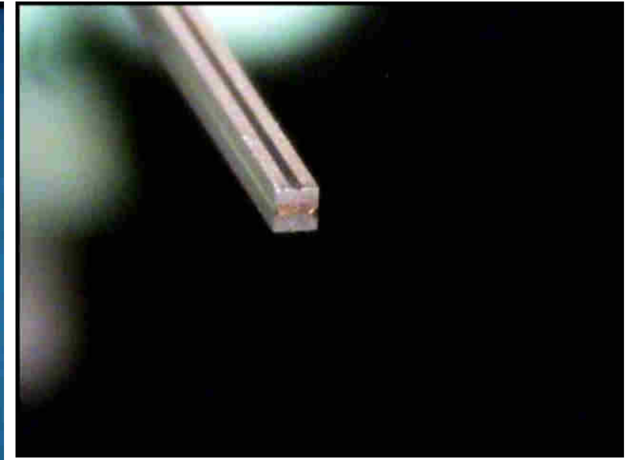
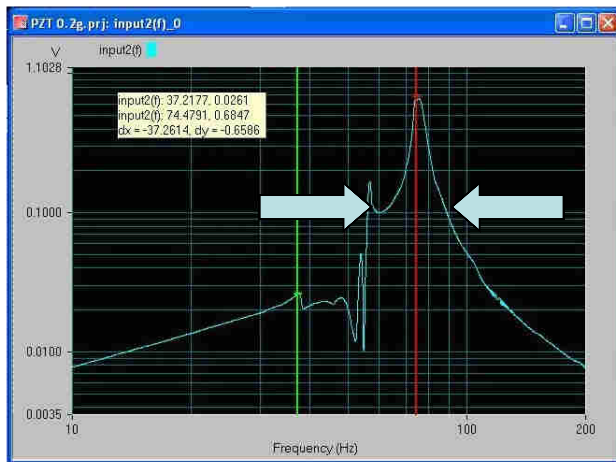
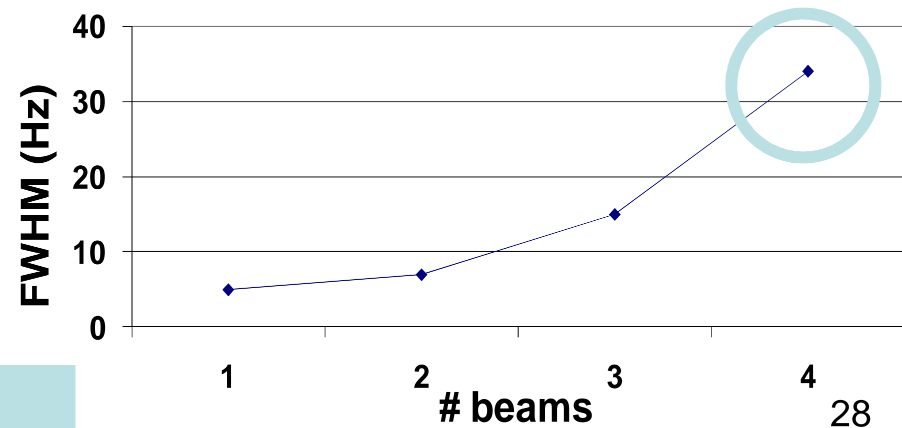
Meso *VIBE*™







Meso-scale PME-PVEH Bandwidth Broadening



ν_1 = 75 +/- 17 Hz

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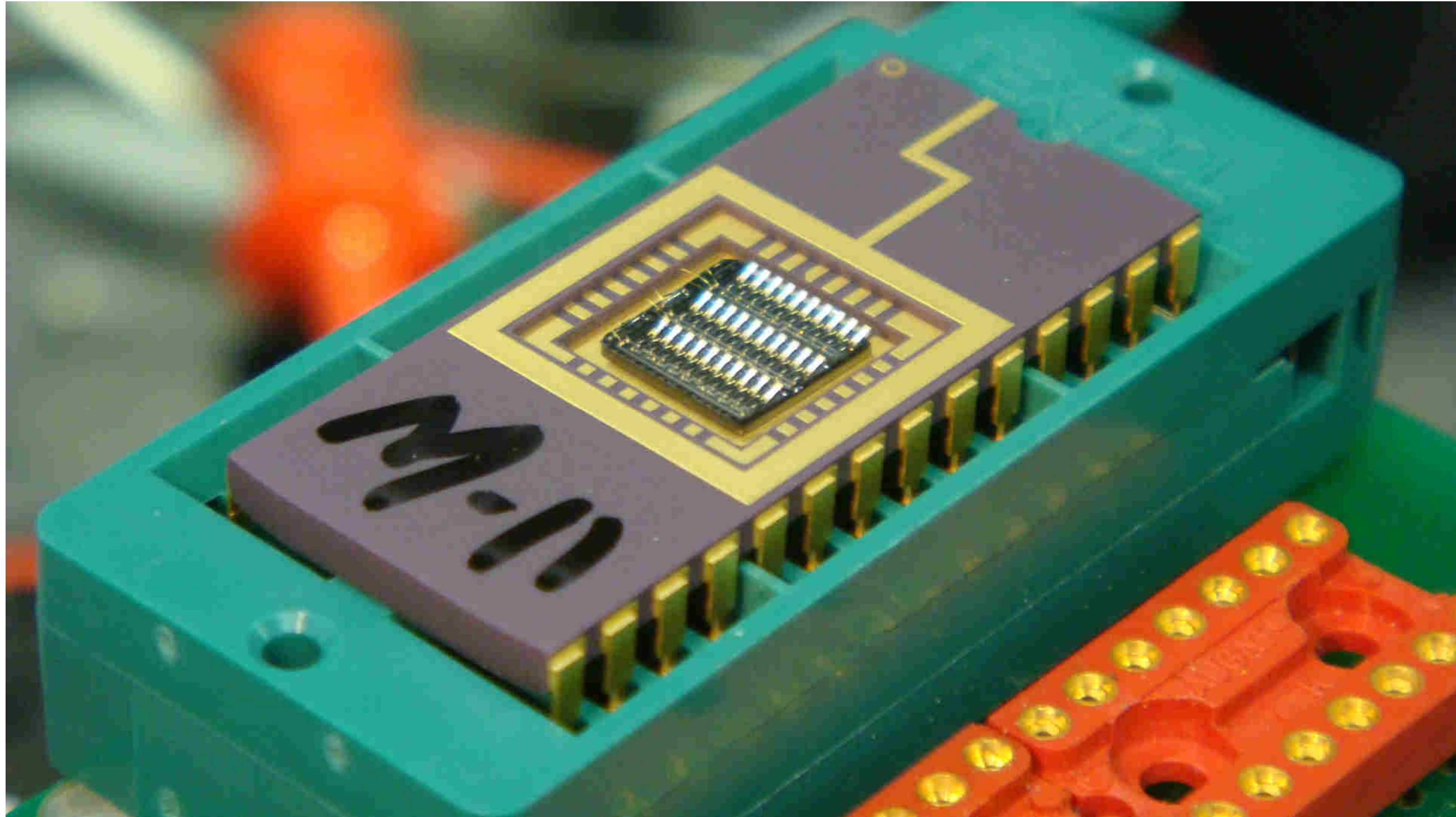
MEMS *VIBE*™



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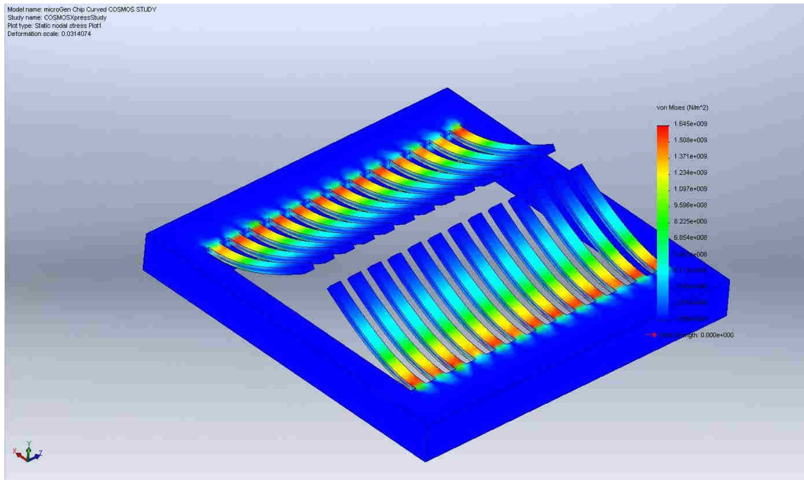
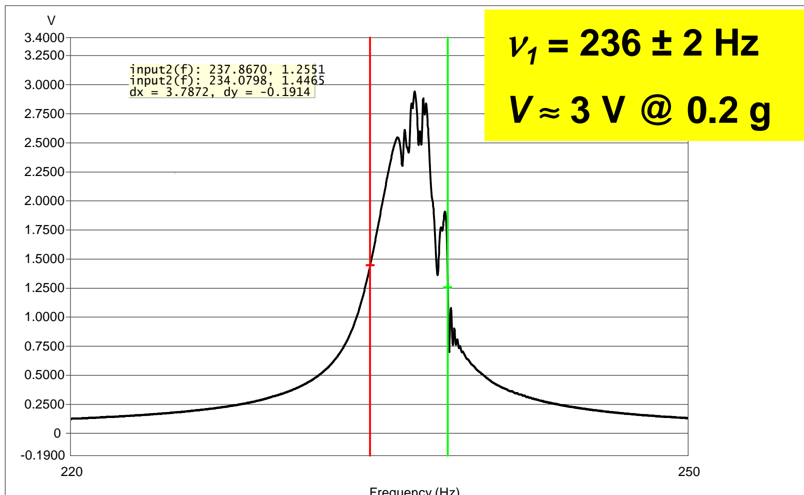
MEMS PME-PZEH

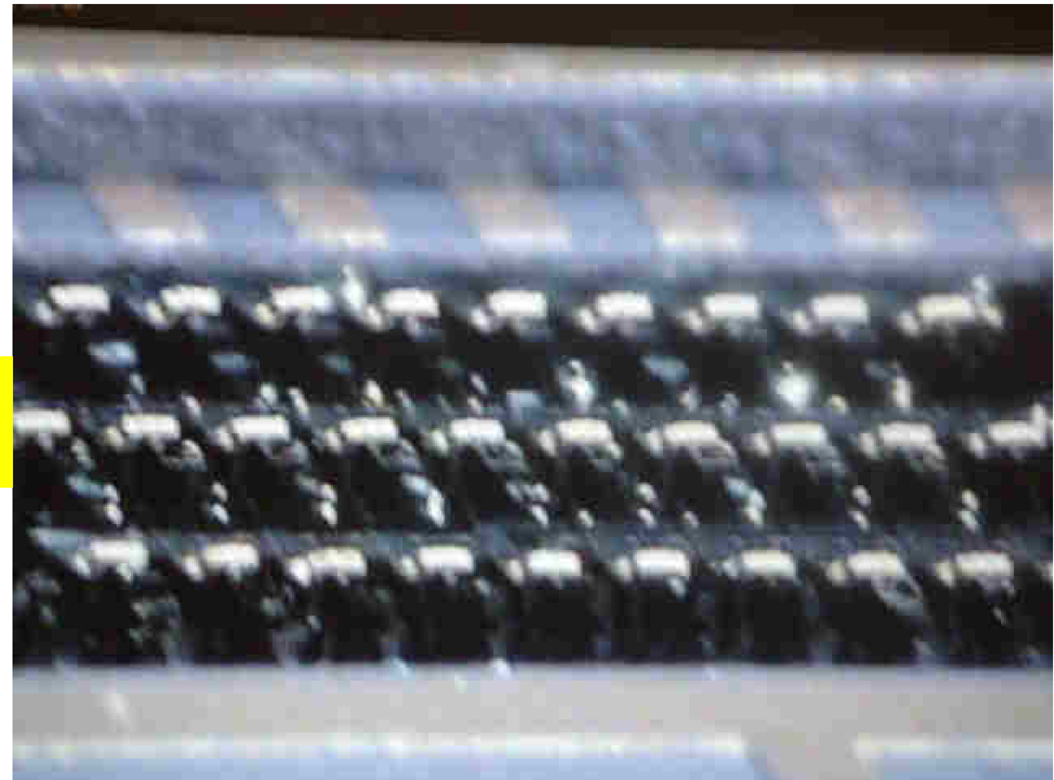




ν_1 = 236 ± 2 Hz

$V \approx$ 3 V @ 0.2 g

CANTILEVER END-VIEW



ν_1 = 240 ± 2 Hz within-die,
± 5 Hz die-to-die

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Important points

- **Monolithically multi-axis power generation**
- **Broad bandwidth – up to ± 50 Hz**
  - Random or shifting frequencies
  - Temperature compensation
- **Reliability ➔ 20+ years**
- **Overall packaged size < 0.7 cm^3**

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7/12/10 Press release

"MicroGen signs MOU with Cornell's Energy Materials Center EMC2 / NYSTAR"

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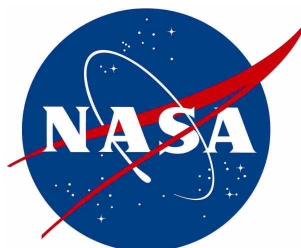
Acknowledgements

This work was funded in part by the following organizations



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Management Team

Over 100 years combined experience

~ Balanced team with core skill sets

~ Management / Product Development roles

~ 18 startups to large companies

~ $17 M capital raised ~ 20 product launches

Robert Andosca, **Founder, CTO –** 20+ yr MEMS Expert; MS/PhD (ABD) UVM

David Hessler **CEO –** Xerox, Serial ENT, VC; MS / MBA UMICH

Michael Perrotta **CFO/COO –** Kodak, Serial ENT; BS Eng, MBA Simon

Junru Wu, **Founder, Tech Fellow –** Vibration Expert; MS/PhD UCLA

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Advisory board

MEMS and Semiconductor

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- **Roger Grace**, President, **Roger Grace Associates** (marketing), FL
- **Dr. Les Fritzemeier,** CEO, **Wakonda Technology** (photovoltaic), MA
- **Andrew Tucker**, VP North American Field Operations, **SPP Process Technology Systems** (semiconductor/MEMS equipment manufacturer), MA, USA & Wales, UK

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- **Skip Ashton**, Sr. VP Engineering, **Ember Corporation** (WSN), MA
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- **Steve Grady,** VP Marketing, **Cymbet Corporation** (advanced batteries), MN
- **Peter Tsepellef**, CEO, **Grape Networks** (WSN), CA

Vibration and piezoelectrics

- **Dave Henderson,** CEO, **NewScale Technologies**, NY
- **Dr. Junru Wu**, Technical Fellow, **MicroGen**; Professor Physics, **UVM**, VT

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References

[1] R. Andosca, and J. Wu, "Energy Harvesting: Meso to Micro-scale Technologies", **invited speaker to "Extreme Electronics/MEMS – Energy" Session of SEMICON West**, San Francisco, CA, July 13, 2010.

[2] R.G. Andosca and J. Wu, "Efficient vibrational power harvesting – Analytical solutions and design concepts", **Journal Acoustical Society of America**, submitted for publication June 2010.

[3] **MicroGen internal patent disclosure**, "MEMS-based Piezoelectric Vibrational Energy Harvester and Highly-Manufacturable Method of Manufacture", R.G. Andosca inventor (filed January 2010, and provisional patent application to be filed in 2010).

[4] **MicroGen internal patent disclosure**, "MEMS-based Parametric-Mode-Enabled Piezoelectric Vibrational Energy Harvester and Method of Manufacture", R.G. Andosca inventor (filed January 2010, and provisional patent application to be filed in 2010).

[5] R.G. Andosca, **Invited panelist** for "Energy and Environmental Sensing" Session of MEMS Executive Congress (organized by the MEMS Industry Group), Sonoma, CA, November 4-6, 2009.

[6] R. Andosca, K. Lee, N. Stoffel, J. Wu, P. Tspellef, and M. St. Germaine, "MEMS Energy Harvesting for WSN", **invited speaker** to the 2009 Sensors Expo and Conference, Rosemont, IL, June 8-10, 2009.

[7] R. Andosca, K. Lee, and J. Wu, "Efficient Vibrational Energy Harvesting for WSN", **invited speaker** to the NanoPower Forum Workshop/Darnell Group, San Jose, CA, May 18-20, 2009.

[8] International Patent Application Serial No. PCT/US08/57865, R.G. Andosca and J. Wu, entitled "Piezoelectric Vibrational Energy Harvesting Systems Incorporating Parametric Bending Mode Energy Harvesting," filed by UVM through DRM PLLC on March 21, 2008.

[9] U.S. Provisional Patent Application 60/896,077, "MEMS-Based Vibrational Power Scavenger," UVM, R.G. Andosca and J. Wu, filed March 21, 2007.