Radioisotope Energy Sources

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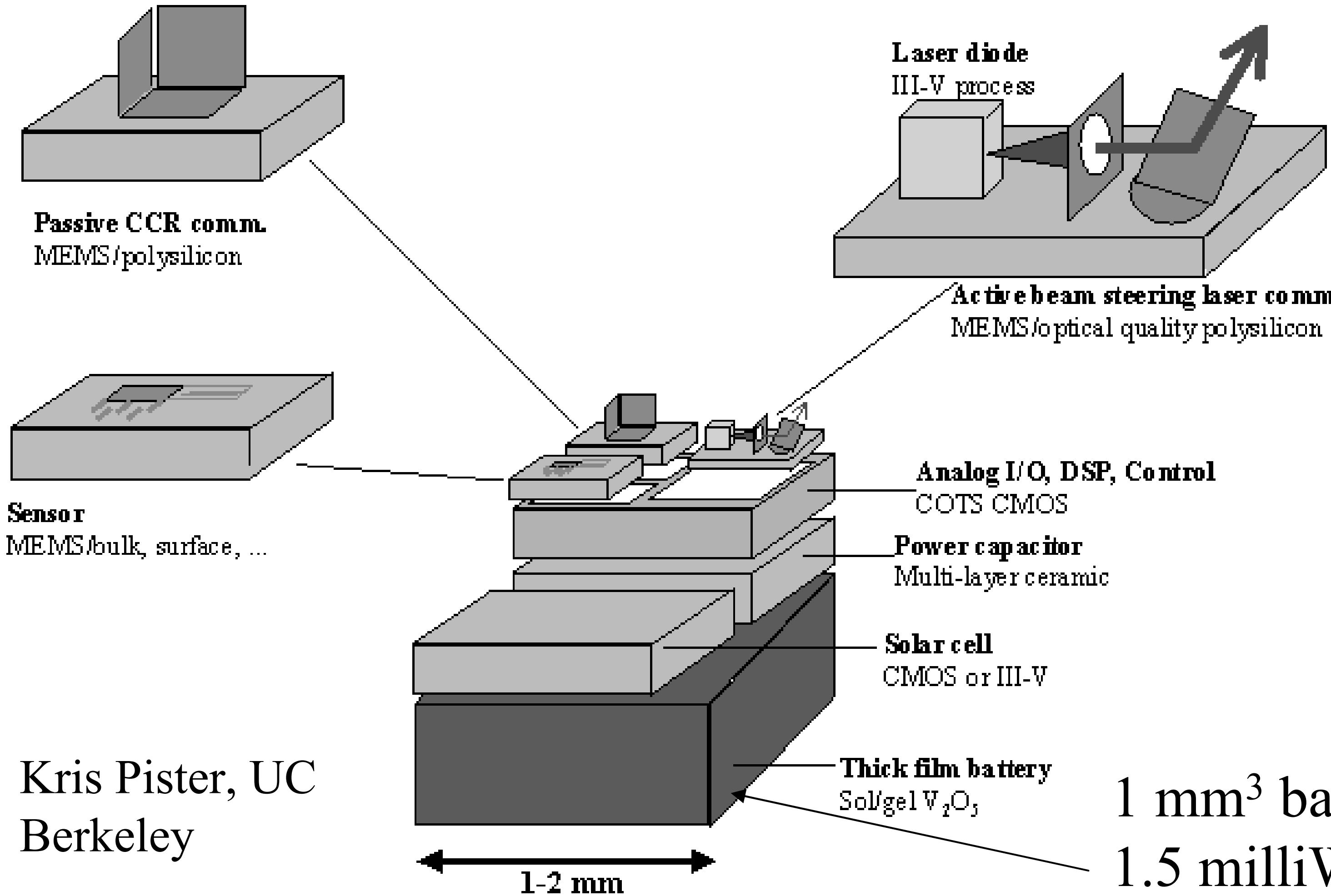
Outline

- Radioisotopes
- Self-reciprocating cantilevers
- DC-biases for sensing and electronics
- RF-pulses
- Betavoltaics

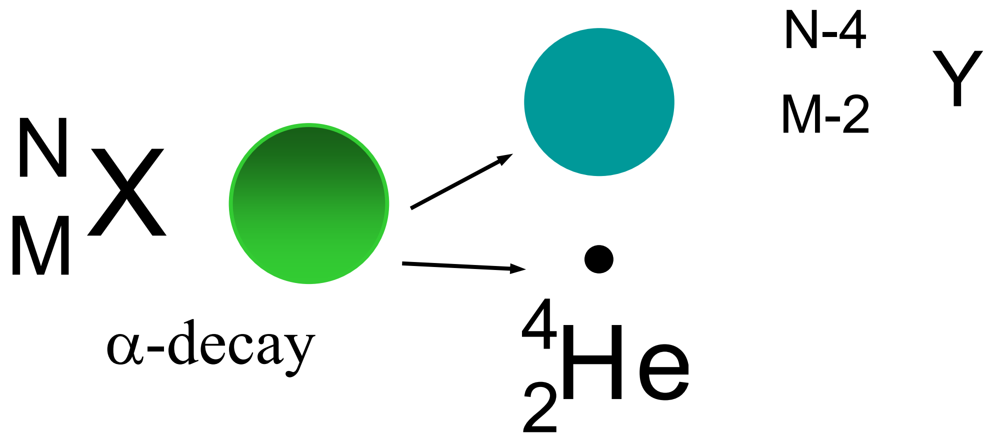
Autonomous Sensor Systems



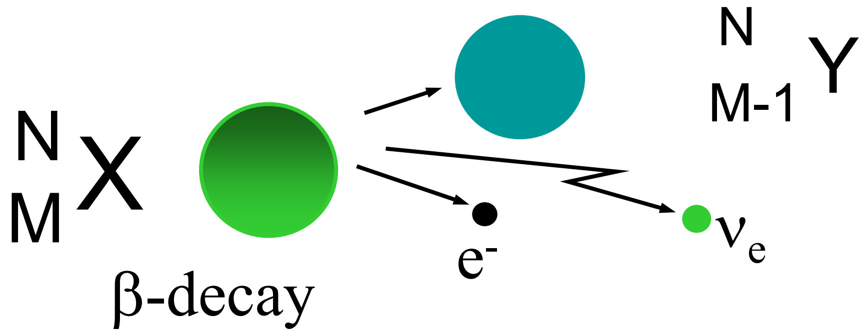
Kris Pister, UC Berkeley

1 mm^3 battery ~ 1.5 milliWatt--Hour

What is the smallest power source?



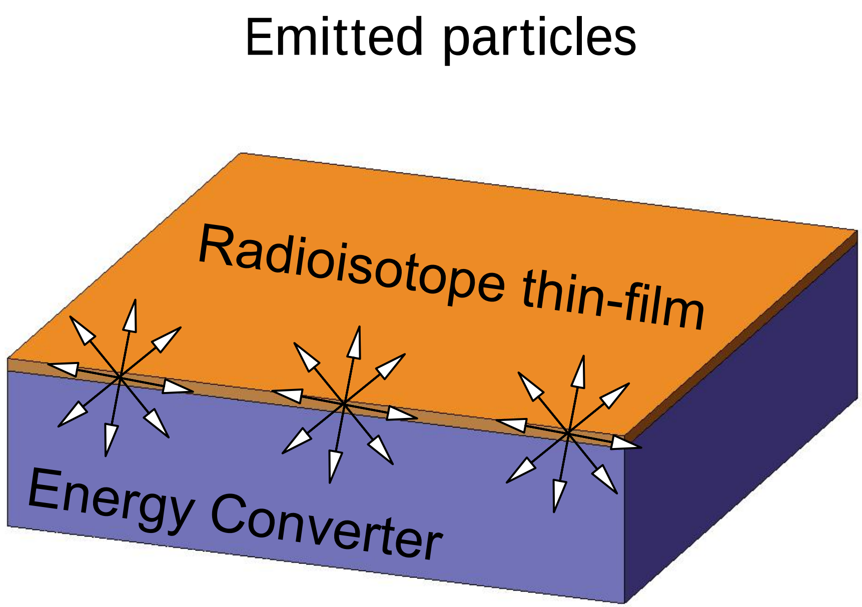
MeV Per Reaction



keV-MeV Per Reaction

- **Ultimately Scaled Power Source**
- **Conversion efficiency can in principle reach 100%**

Radioisotope **Thin Film** Energy: Emission, *not Fission or Fusion*



- **$P_{out,R} = N_{out,R} \times E_{avg}$**
- **$N_{out,Pm\text{-}147}$** : 830 Curie/g X 3.7X10^{10} emissions/s/Curie
- **$E_{avg,Pm\text{-}147}$** : 63 keV

→ **$P_{out,PM\text{-}147}$** : 0.309 W/g → **2.05 W/cc**

*H. Flicker et al., "Construction of a Pm-147 Atomic Battery," IEEE Trans. Electron Devices, 1964.

Why Radioisotope Thin-films?

Microsystems
- Compact
- Long lifetime

Microbatteries
- Compact
- High energy capacity

Sensors and Wireless signal generators
- Low power

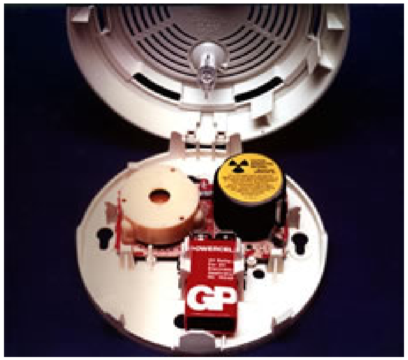
High energy density fuel

Radiation effects

Fuel	Energy Density
Electrochemical (Li-ion)	~10 kJ/cc
Hydrocarbon (Methanol)	~20 kJ/cc
Radioisotope (^{147}Pm, over 5.2 yrs)	170000 kJ/cc

Reliability: A radioisotope decays exponentially in time at a rate independent of ambient conditions like temperature, humidity

Safety: Radioisotopes Around Us



Americium-241 in Domestic Smoke Alarms

Tritium in Exit Signs

30% of Pacemakers implanted from 1971-75 were radioisotope powered

- NASA's RHU
- 33 Ci
- 1 Watt output
- 1.4 oz.
- 1 cubic inch
- 2.7 g of Pu-238 (oxide form)
- Rugged, reliable

Radioisotope Comparison

Low energy beta- easy to integrate

Isotope	Average energy	Half life	Specific Power	Estimated Range in Si (Max.)
	(KeV)	(year)	(W/g)	(microns)
63-Ni	17	100.2	0.0067	21
3-H	5.7	12	0.33	2
147-Pm	67	2.6	~0.2	55
210-Po	5300	0.38	140	26
238-Pu	5500	88	0.56	27
244-Cm	5810	18	2.8	28

Low energy beta- hard to integrate

Higher energy beta

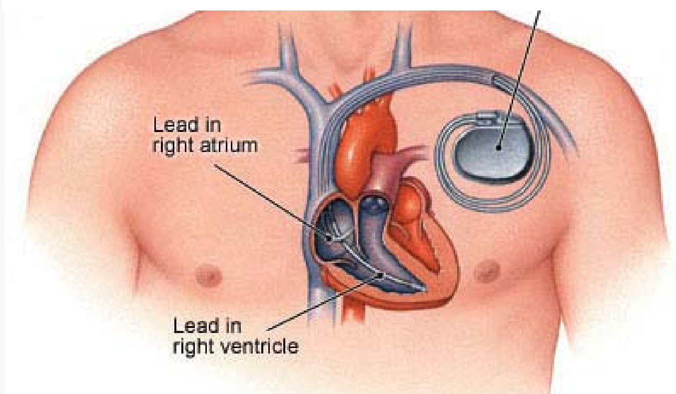
Alpha sources:

- **Chemical toxicity**
- **Damage**

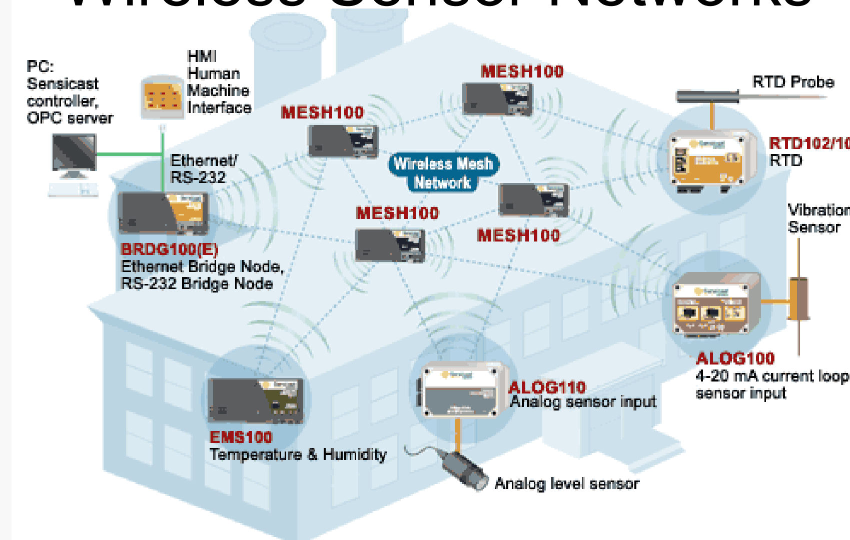
Radioisotope Thin-film Powered Autonomous Microsystems

Enabling compact, long-lifetime, inexpensive, & safe

Implantable Medical Devices such as Pacemakers



Wireless Sensor Networks



100'µW continuously

10-100µW pulsed for sensing, 1-100mW for communication

Nickel-63 (^{63}Ni)

Safety

- Penetration range of
  - primary radiation: <50 μm in most solids
  - secondary radiation: None
- Effusivity: No effusion from thin-film sources even @ 400C
- Chemical toxicity: OSHA regulations permit work without any shielding, 2 millicurie annual intake limit*

Power generation characteristics

- Half-lifetime: 100.3 years
- Specific activity: ~10 curie/g
- $E_{rad,avg}$: 17.3 keV → $P_{out,dens}$: 0.1-1 μW/cm^2

Human Health Fact Sheet, Argonne National Laboratory, August 2005

Williams, D. F., “Recovery and purification of nickel-63 from hfir-irradiated targets," Oak Ridge National Laboratories, Tech. Rep., 1993

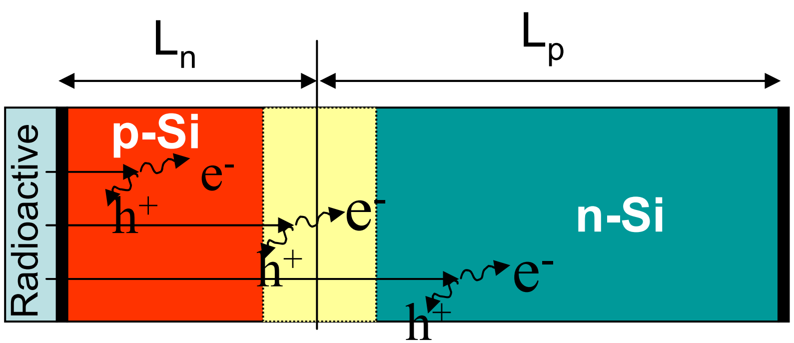
Classical Categories of Radioisotope Power Sources

Kinetic energy

Charge

Thermionic, Thermoelectric

•Thermal to electric conversion



Betavoltaic

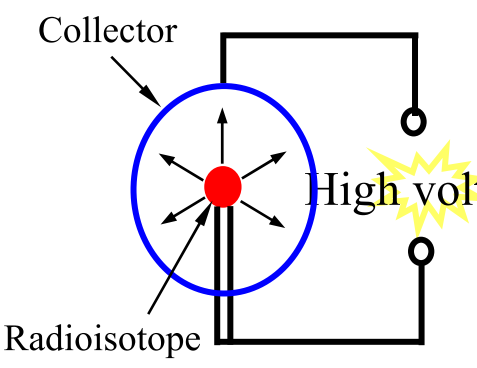
Ionization

- Liquids – photon creation – liquid scintillation
- Gases – ion-electron generation

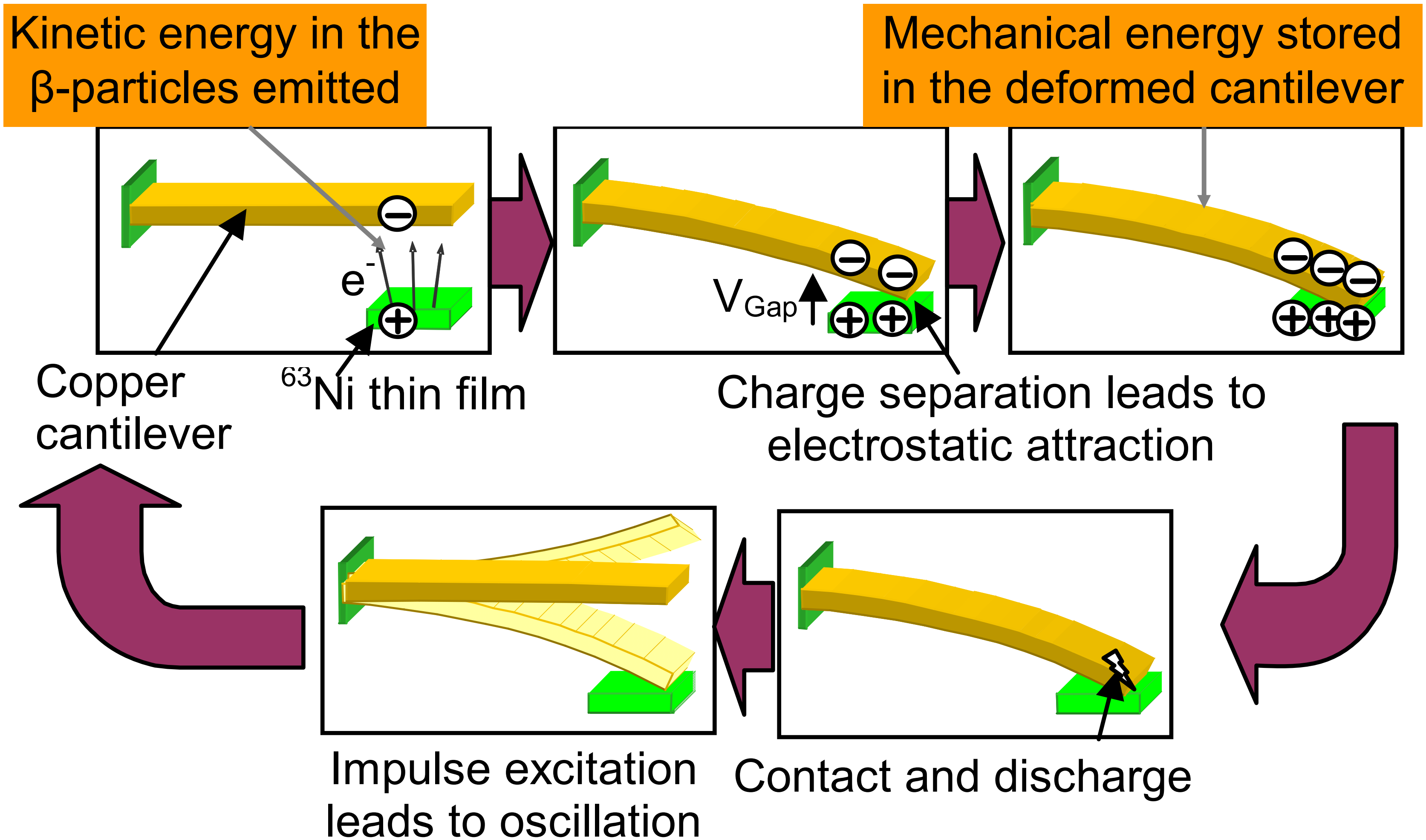
Semiconductors: e-h+ creation – damage to lattice

Vacuum

•Direct charge collection and storage

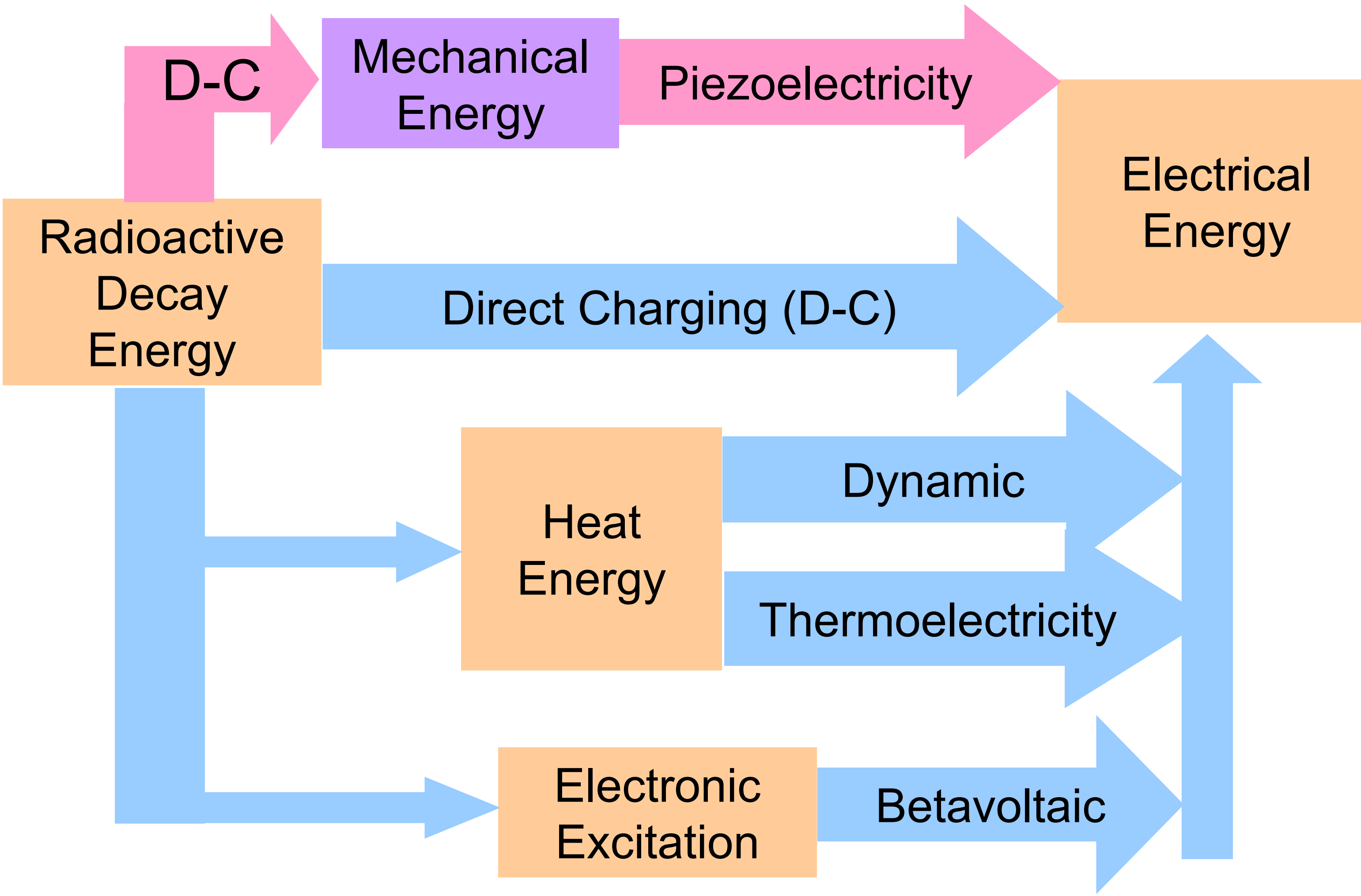


Self-Reciprocating Cantilever

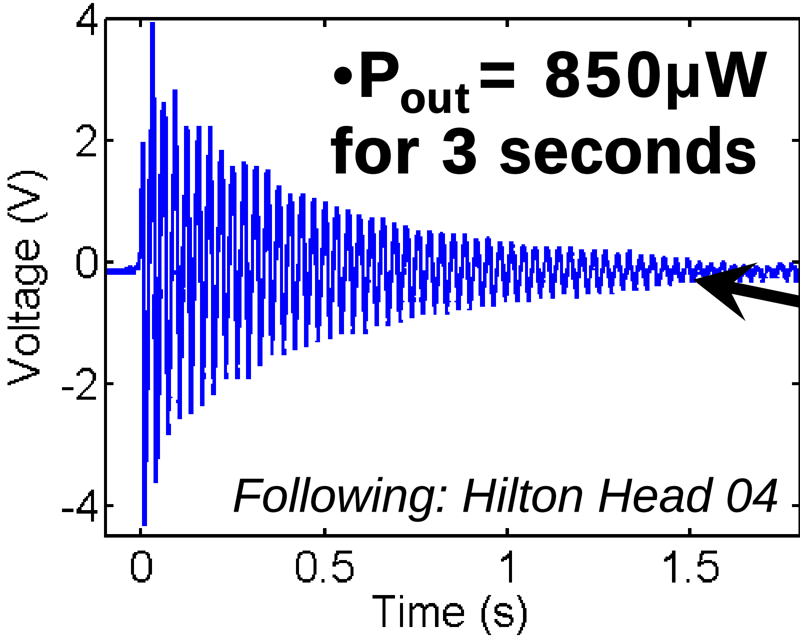


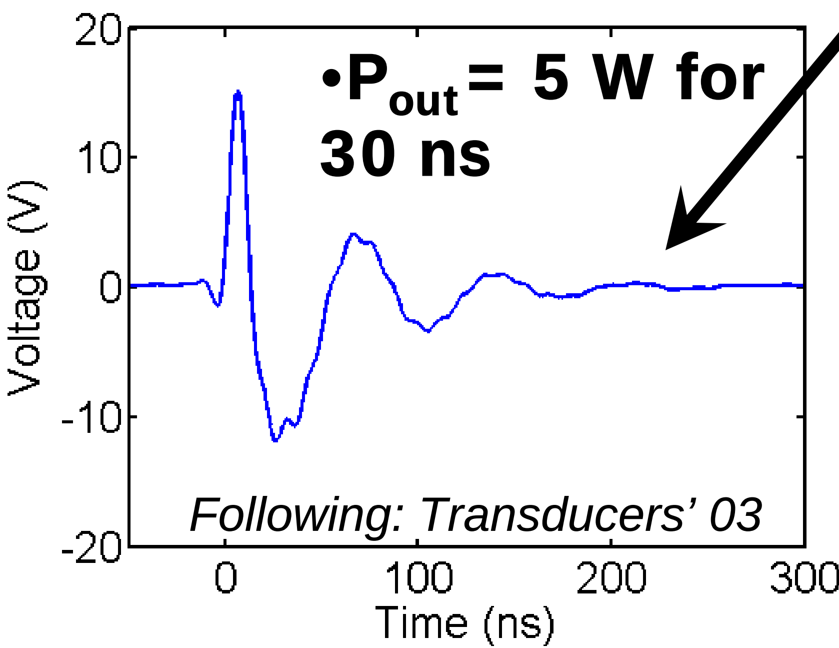
H. Li, A. Lal, J.Blanchard, D. Henderson, Journal of Applied Physics, 2002

Radioisotope-powered Electro-Mechanical Power Generator (REMPG)

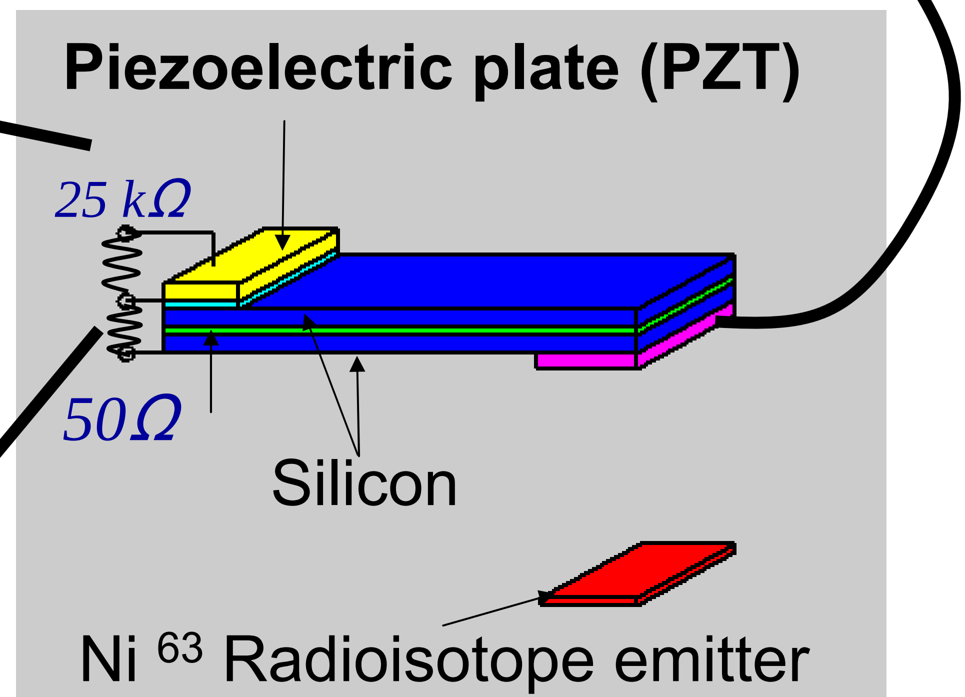


The Handbuilt Device





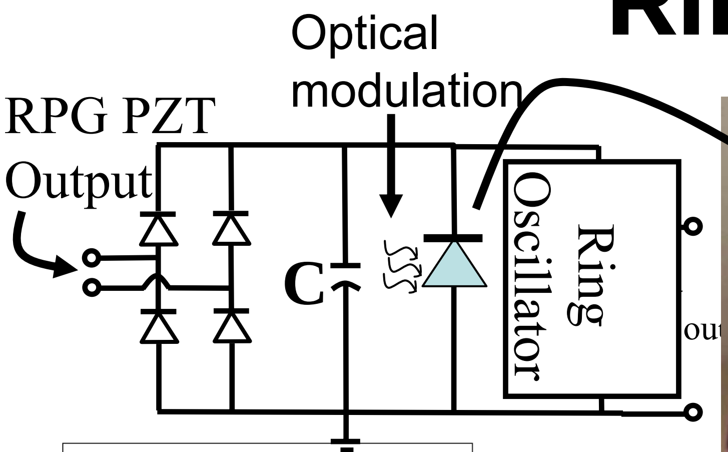
•Betavoltaic collector – 70 nW continuous

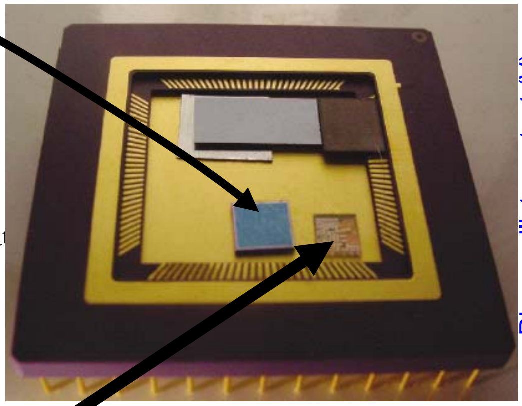


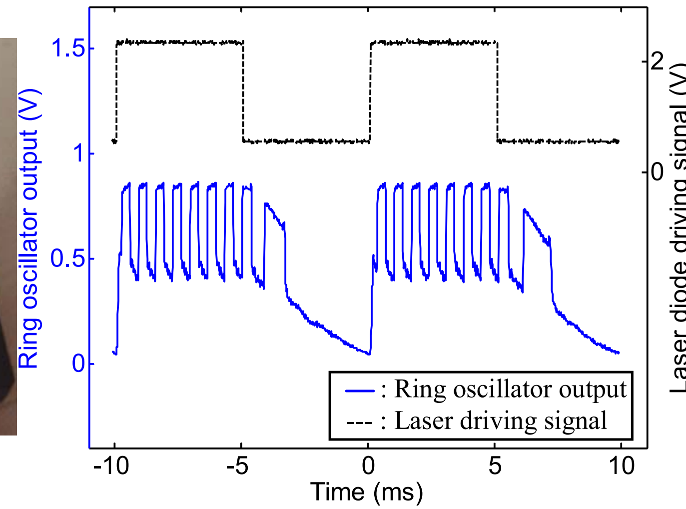
•Power output for 10 mCi source

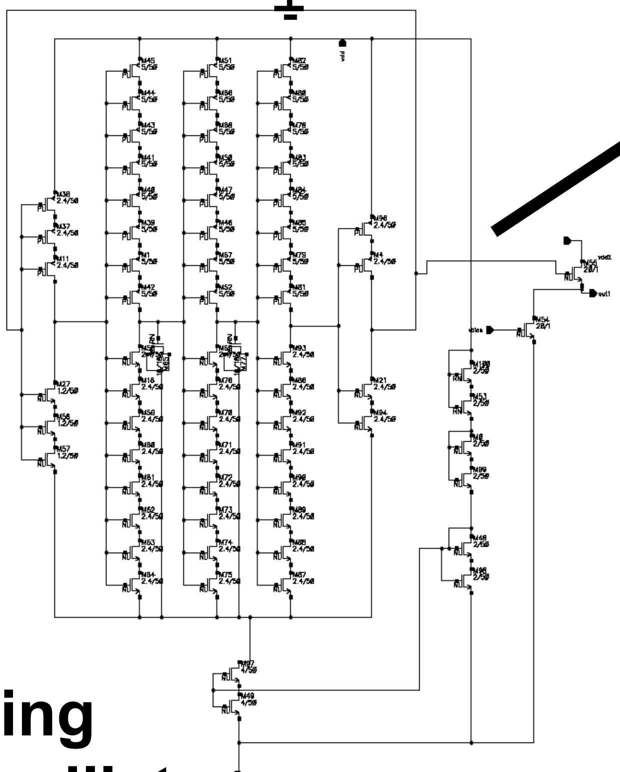
•Three power types produced from same device

RPG Powered Photodiode / Ring Oscillator





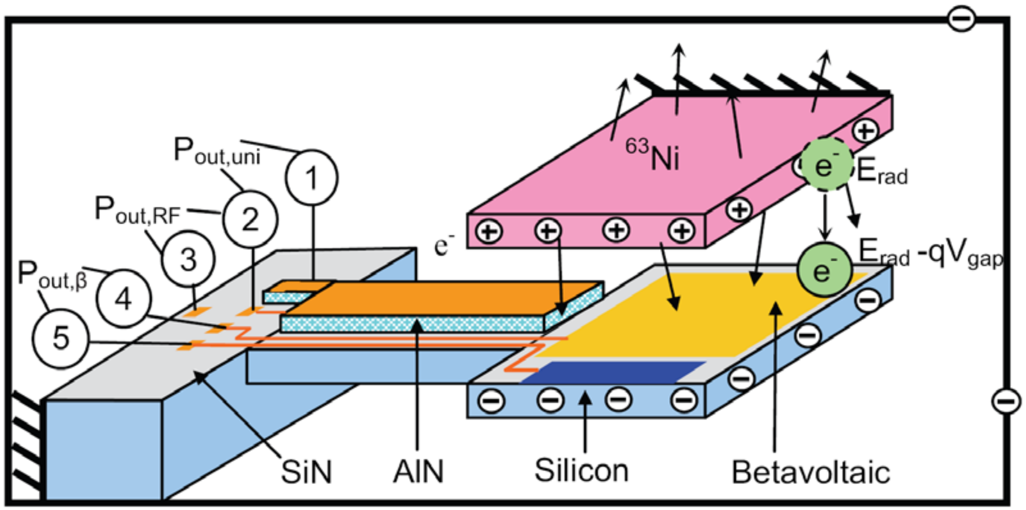




Ring oscillator

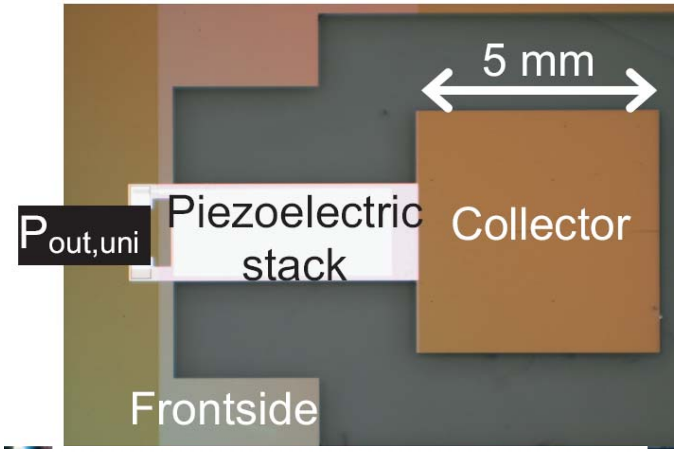
- **A photodiode and a rectifier and ring-oscillator are powered by RPG**
- **Ring oscillator frequency is controlled by signal from photodiode**

IRPG (Integrated Radioactive Power Generator)

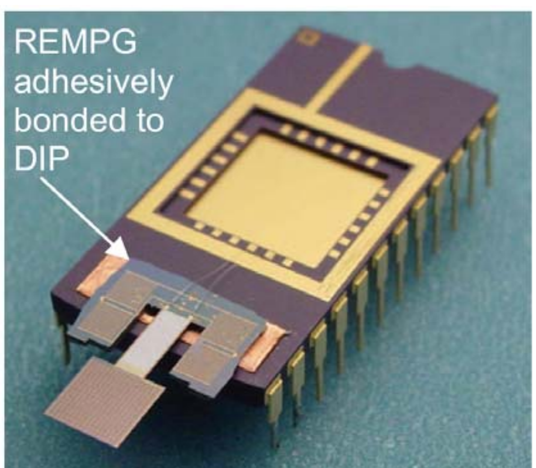


Vacuum chamber

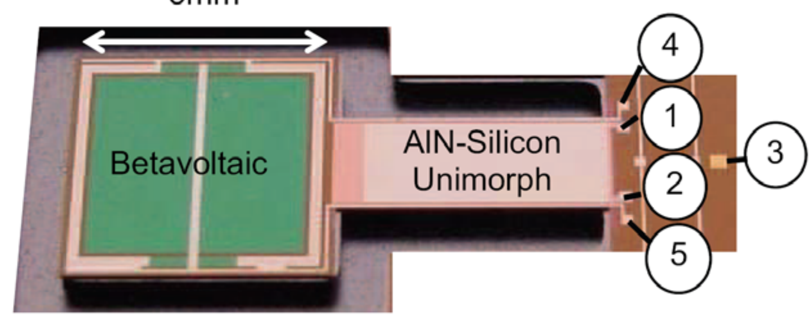
1. PZT top electrode
2. PZT bottom electrode
3. Silicon cantilever
4. Betavoltaic p$^+$
5. Betavoltaic n$^+$



$l_{cant} = 10mm,\ l_{piezo} = 4.5mm,$ $w_{cant} = w_{piezo} = 2mm,\ t_{cant} = 42.5\mu m,\ t_{piezo} = 1\mu m$



5mm



1. PZT top electrode
2. PZT bottom electrode
3. Silicon cantilever
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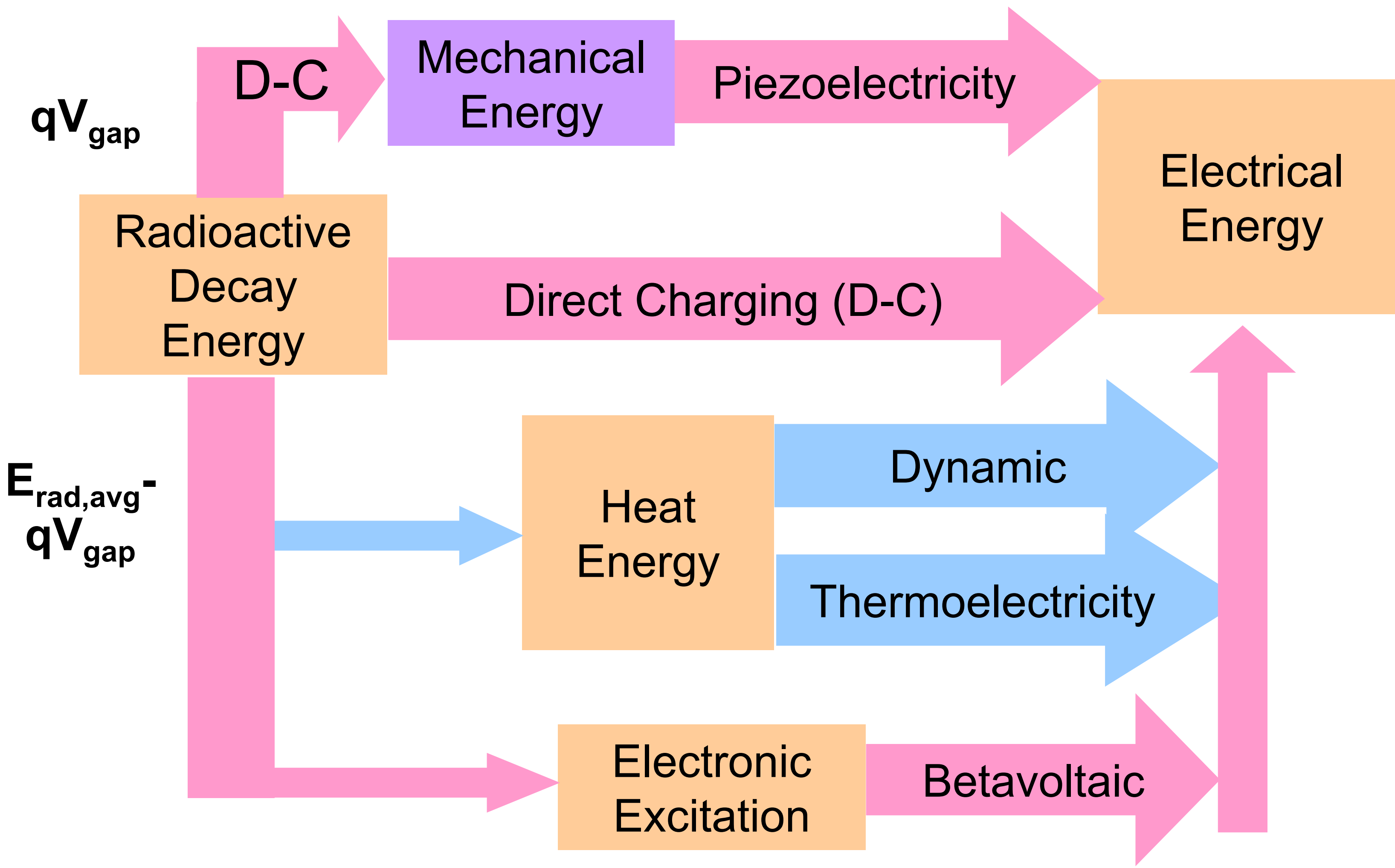
*Sonic***MEMS** Laboratory, Cornell University

Integrated Radioisotope-powered Electro-Mechanical Power Generator (IRPG)



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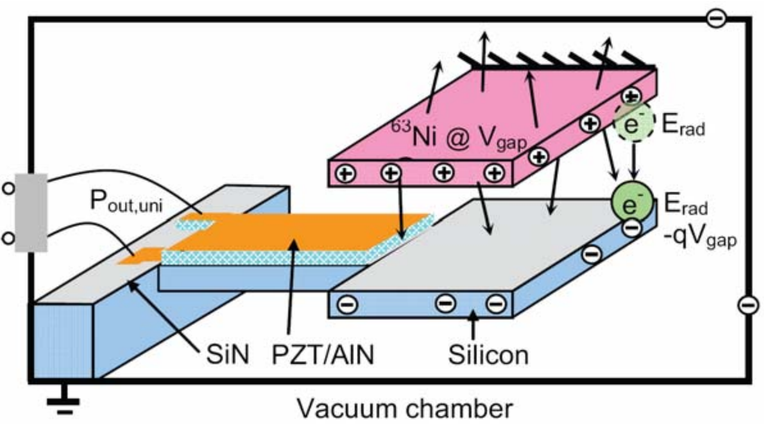
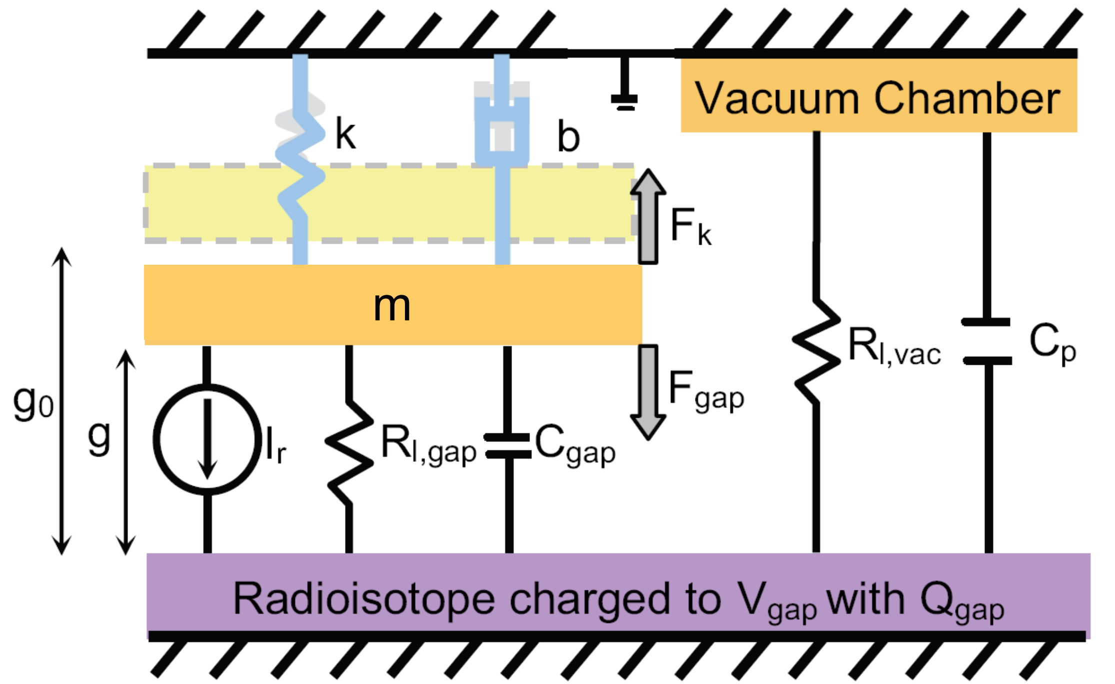
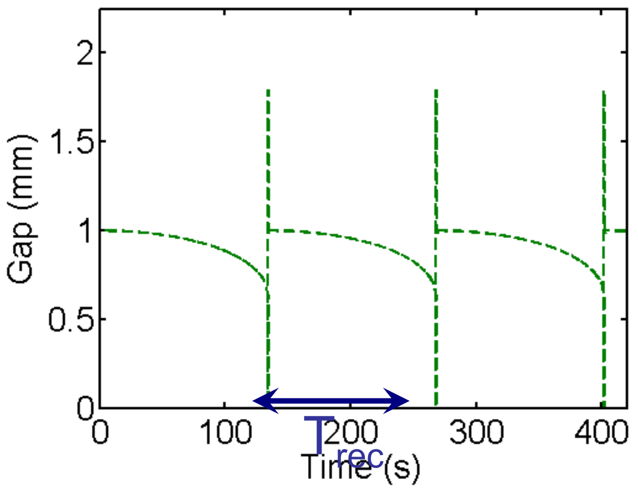
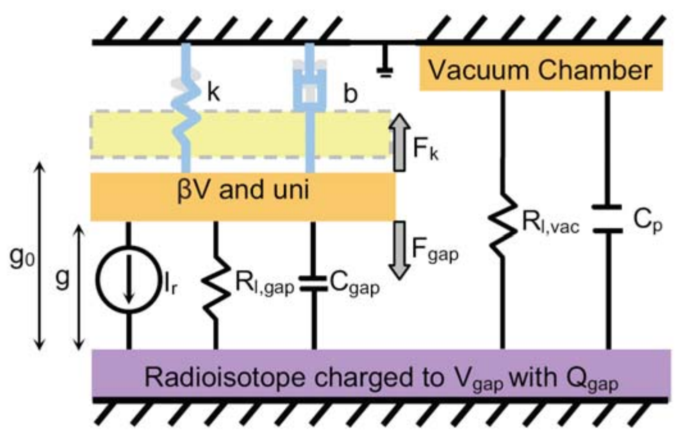
REMPG Modeling

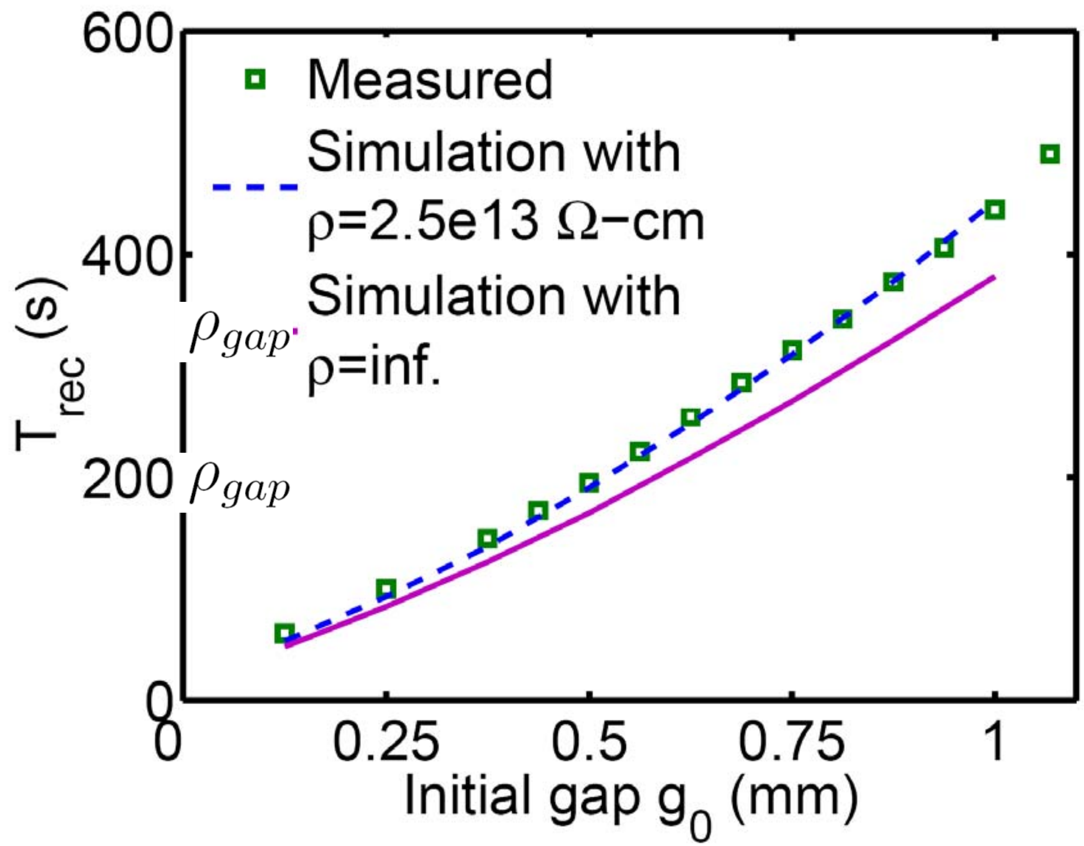




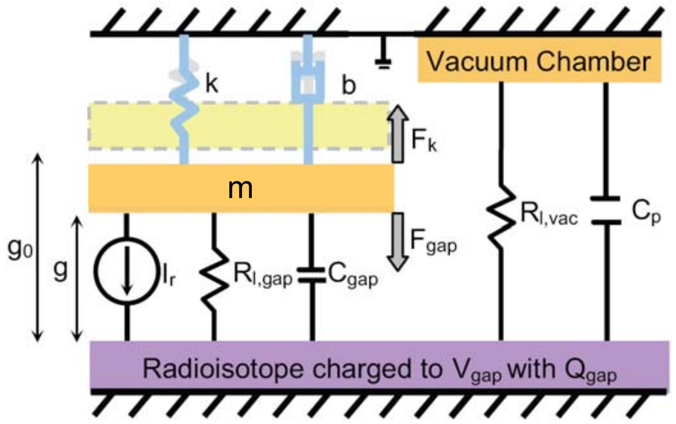
Measured REMPG Reciprocation Period (T_{rec})

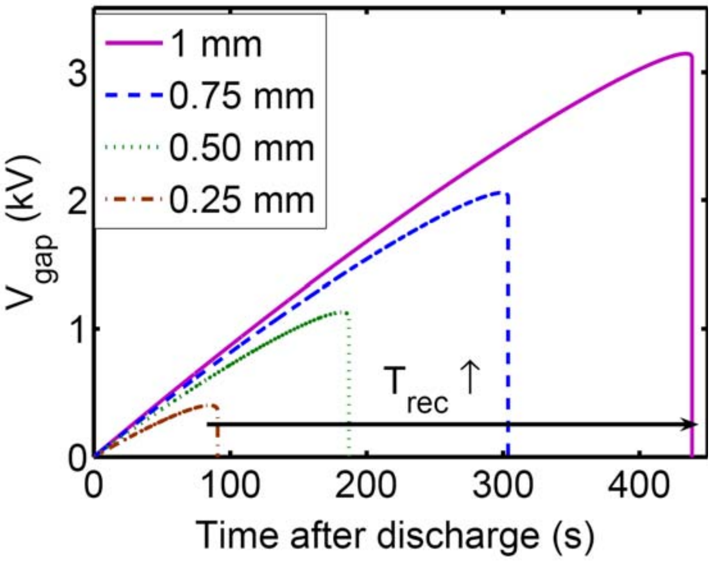




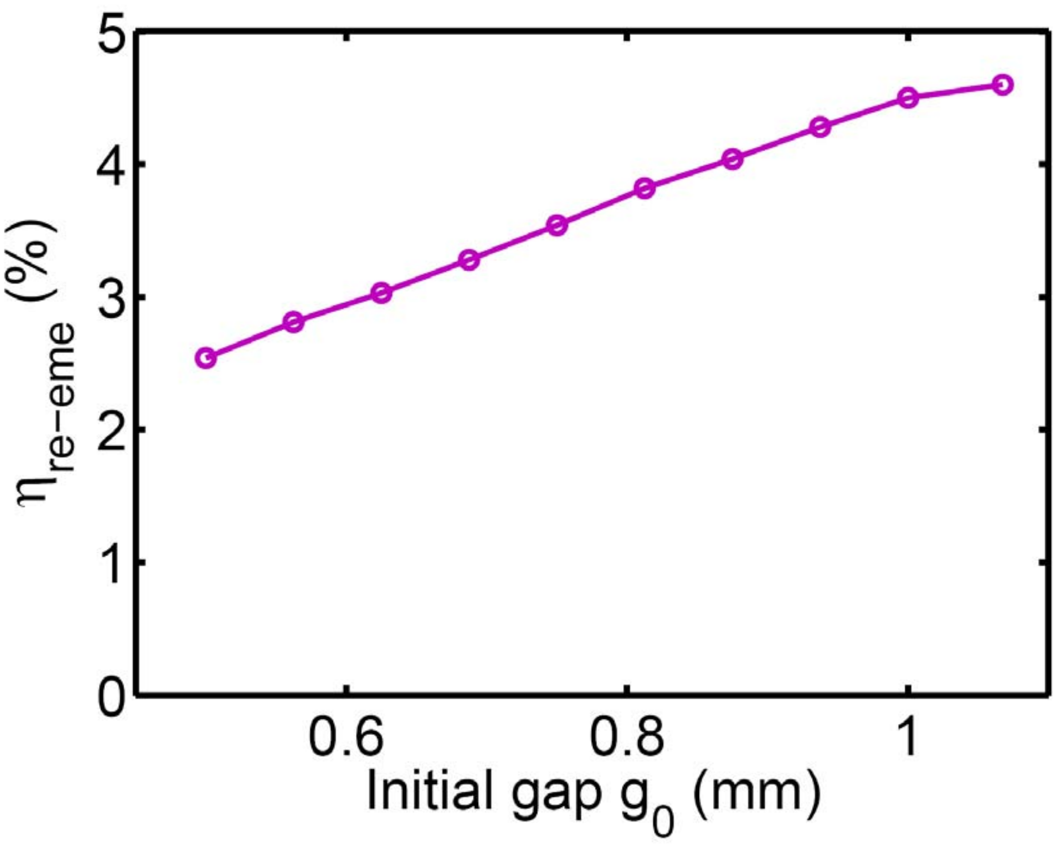


Measured Radioisotope-Electromechanical Energy Conversion Efficiency

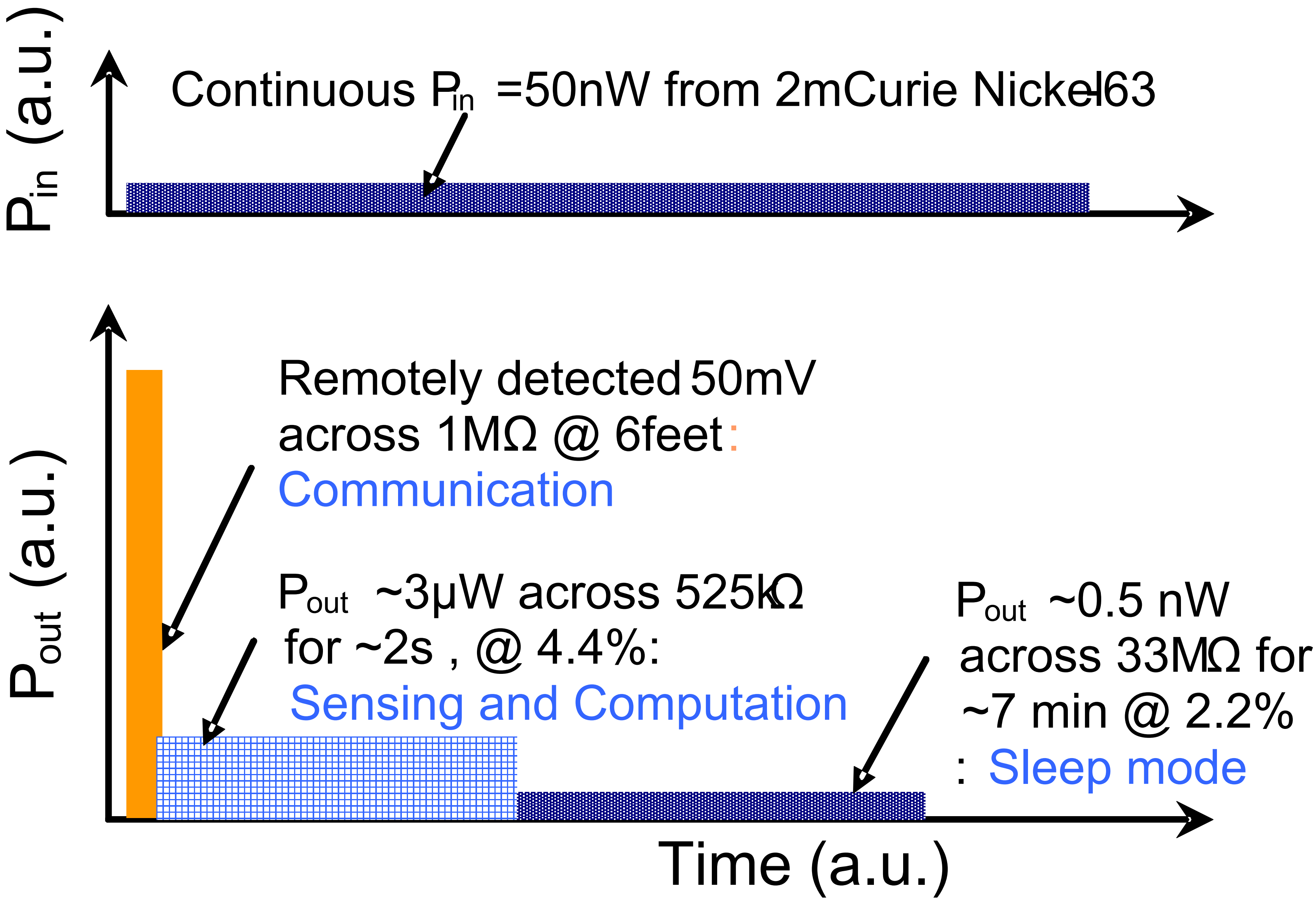




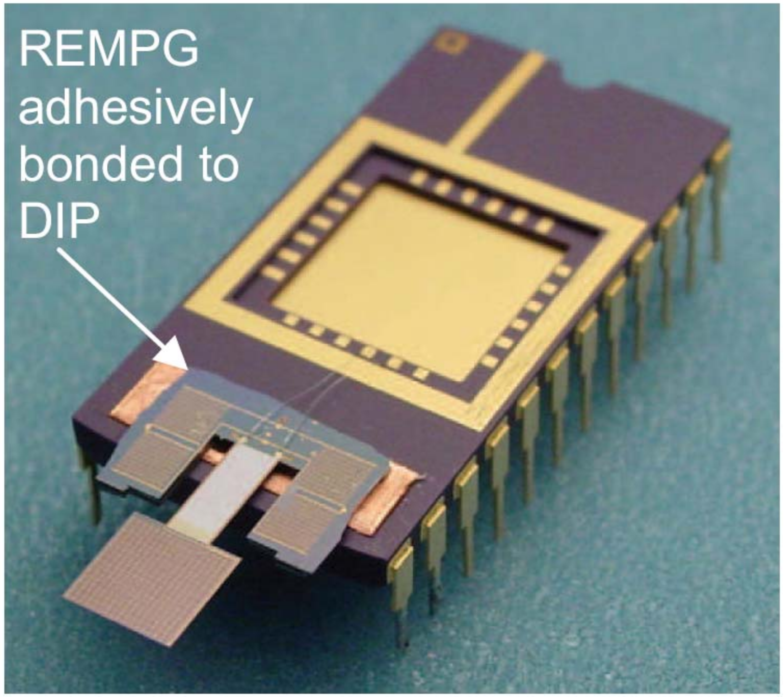
$$\eta_{re-eme} = \frac{E_{eme,rempg}|_{t=T_{rec}-\delta t}}{E_{in,rempg}}$$



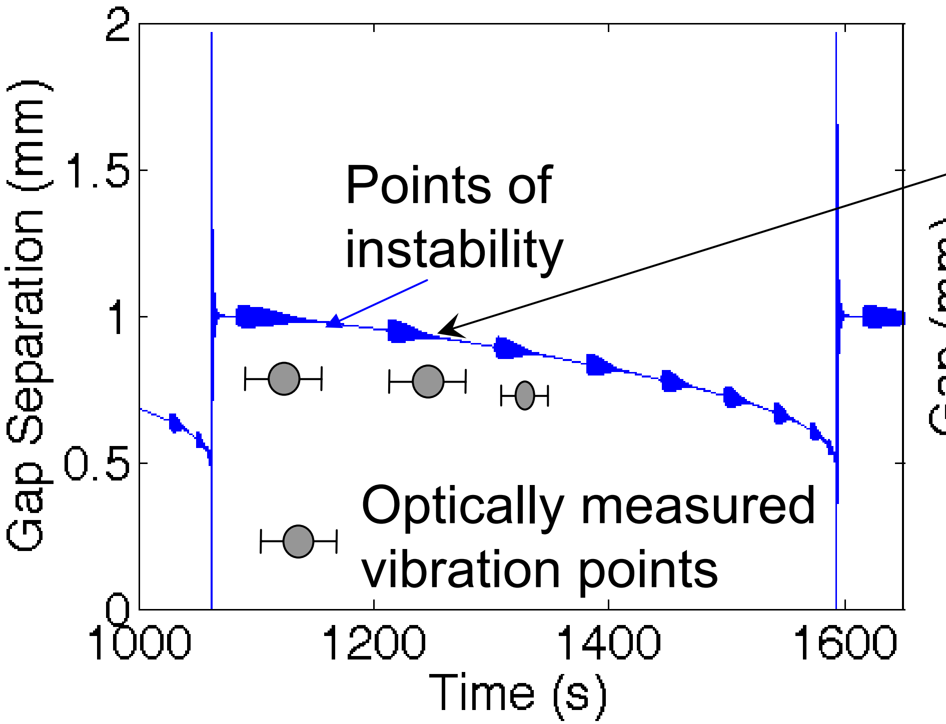
IRPG Power Supply Model

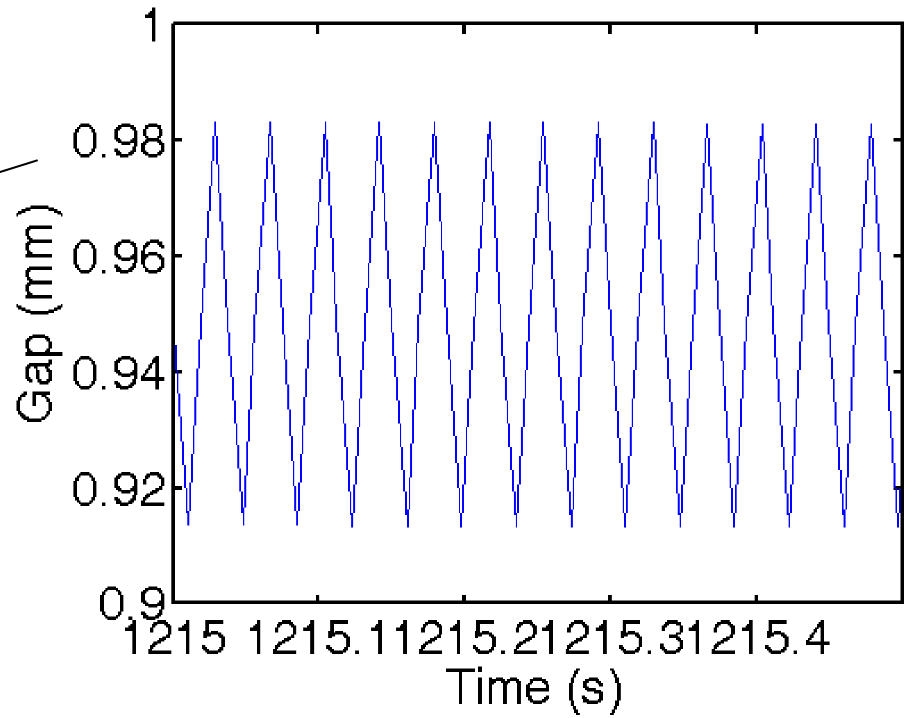


What About Vibration Scavenging From RPG?



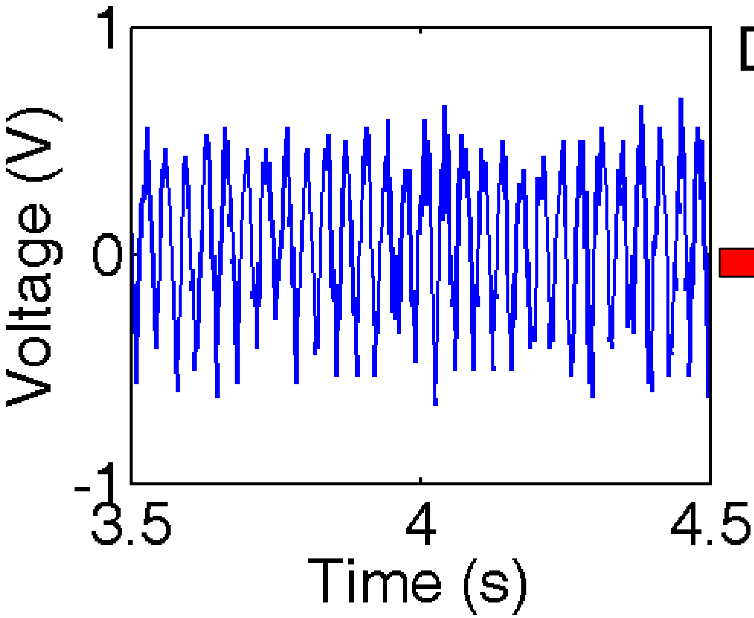
Simulation and verification of continuous vibration modes



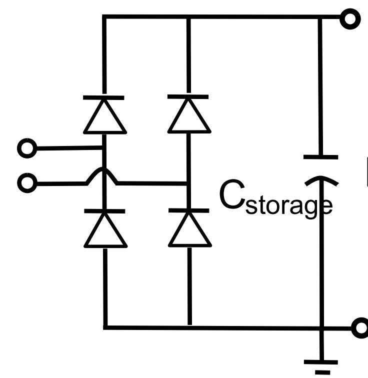


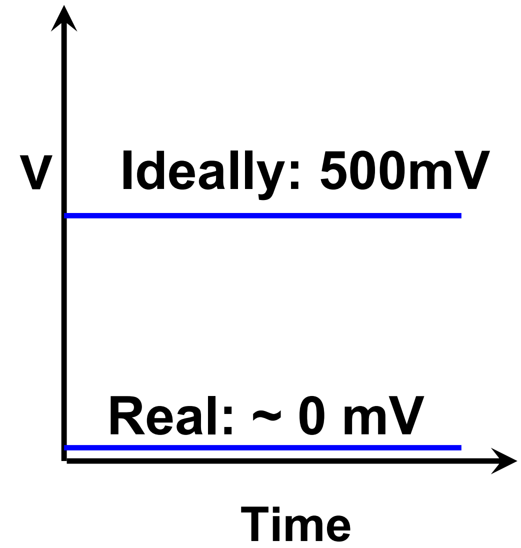
•Simulink simulation and experimental observation proving continuous reciprocation in the RPG for high efficiency (23%)

The Bridge-Rectifier Problem



Voltage drop = 150mV
Due to diode drop

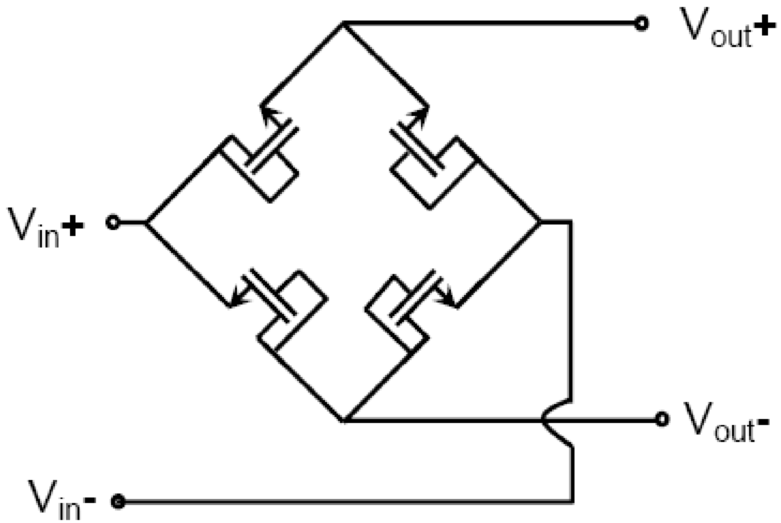


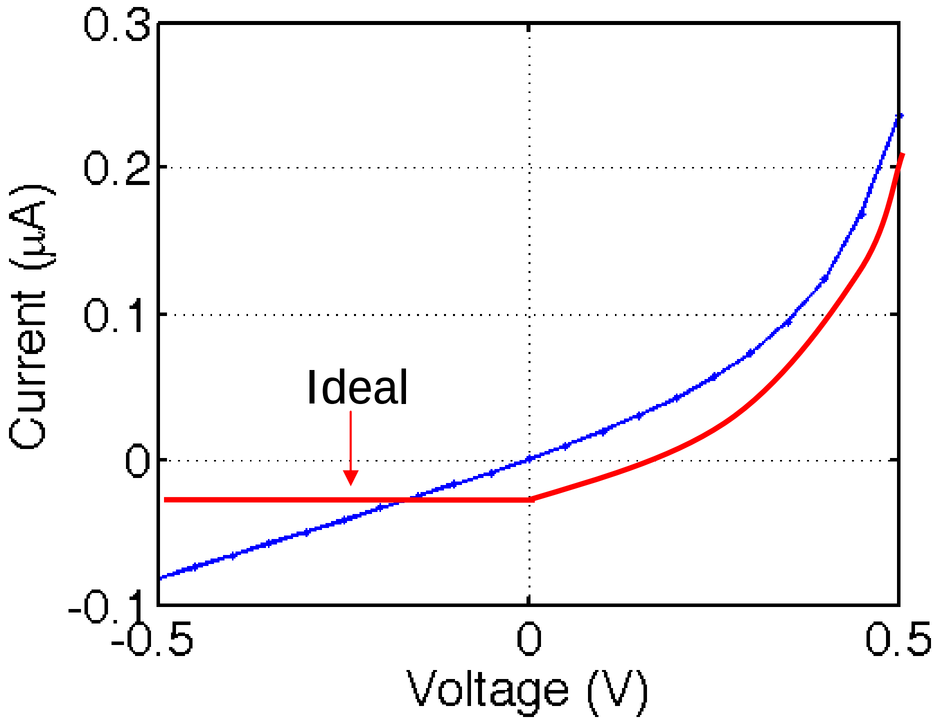


- 70 nW continuous output, at a conversion efficiency of <u>**23%,**</u> **but output voltages can be low**

- Loss of voltage headroom kills efficiency
- Need low-voltage drop rectifier to improve efficiency

Zero-threshold voltage MOSFET Bridge Rectifier ?

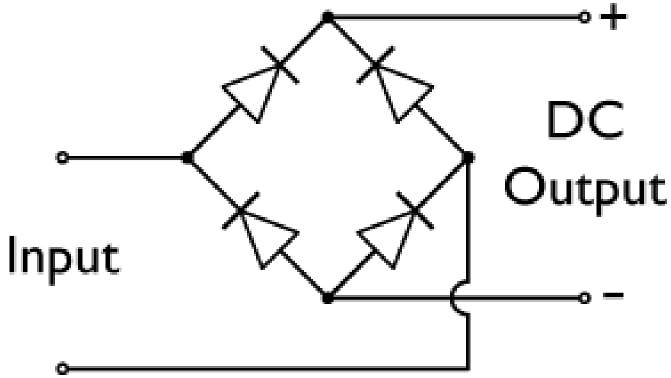


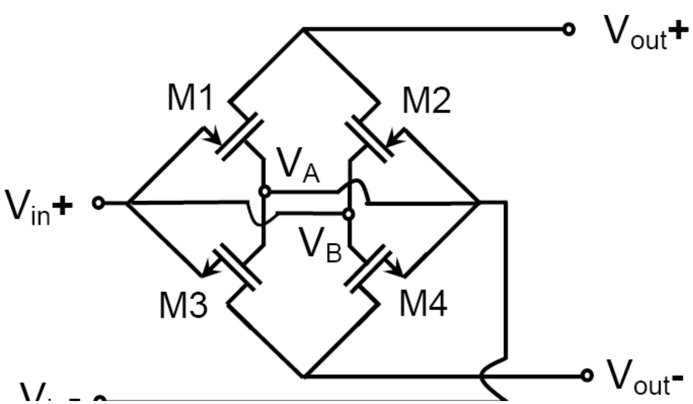


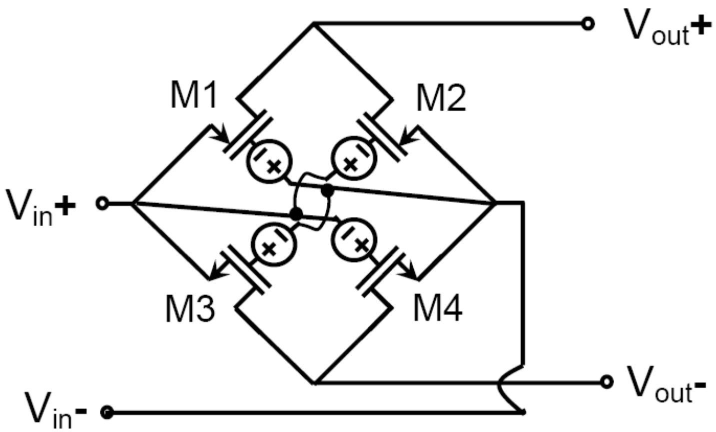
- Voltage drop = 450mV (measured in SoS 0.5 µm) for V_{th} = 0.455 V
- Zero threshold MOS could minimize voltage dropout

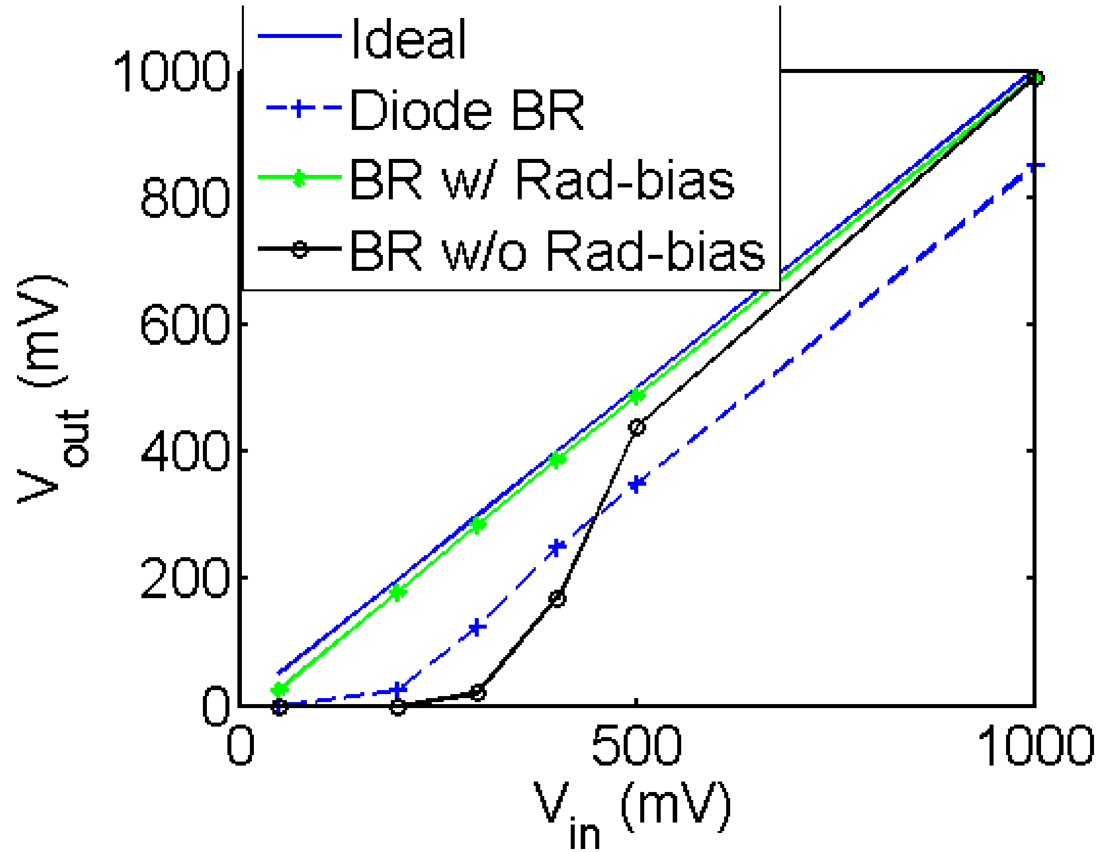
- I-V characteristics of a diode connected zero threshold voltage n-MOSFET fabricated in the 0.5 µm SoS technology

Bridge Rectifier Comparison









- Radioisotope powered bias enables super-efficient bridge rectifier

Self-powered DC bias generation

$$I_{FN} = A_G A \varepsilon_{ox}^2 \exp(\frac{-B}{\varepsilon_{ox}})$$

$$A = \frac{q^3 (m/m_{ox})}{8\pi h \Phi_B} = 1.54*10^{-6} \frac{(m/m_{ox})}{\Phi_B} [\frac{A}{V^2}]$$

$$B = \frac{8\pi \sqrt{2 m_{ox} \Phi_B^3}}{3qh} = 6.83*10^7 \sqrt{(m_{ox}/m)\Phi_B^3} [\frac{V}{cm}]$$

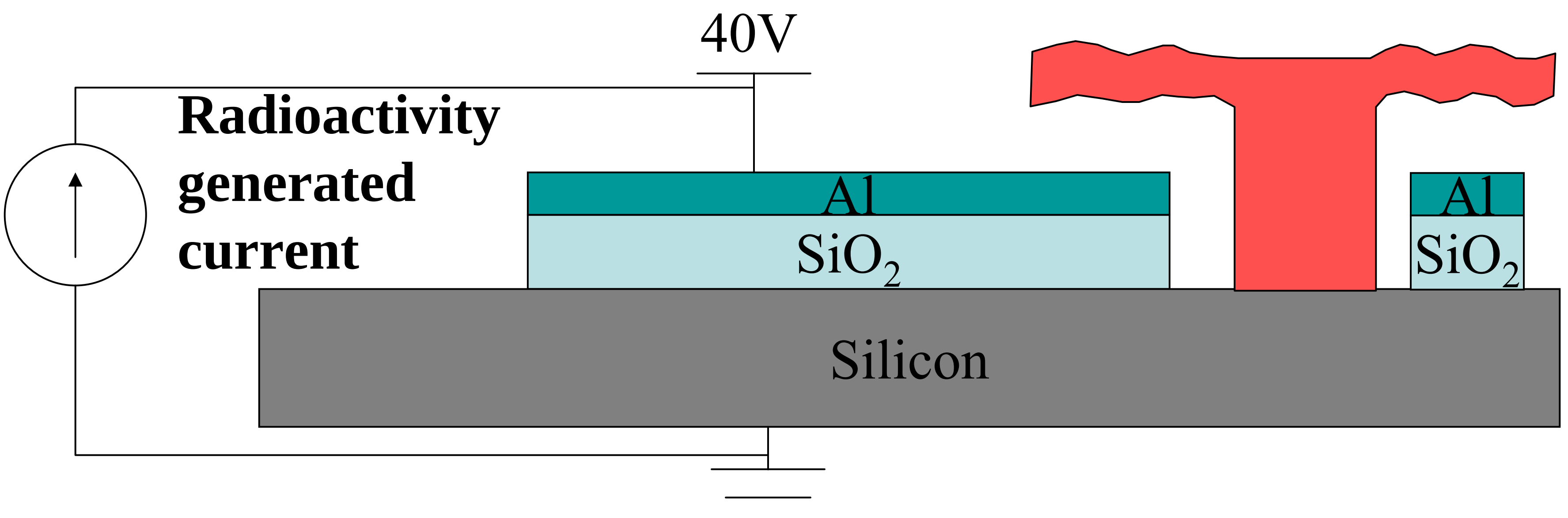
- Where

m_{ox} = Effective Electron Mass

m = Free Electron Mass

Φ_B = Barrier Height at the Interface

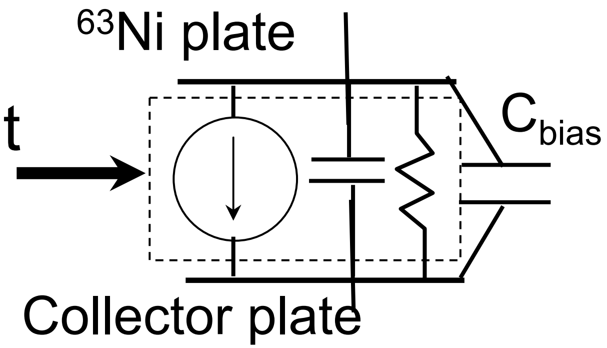
A_G = Gate Area

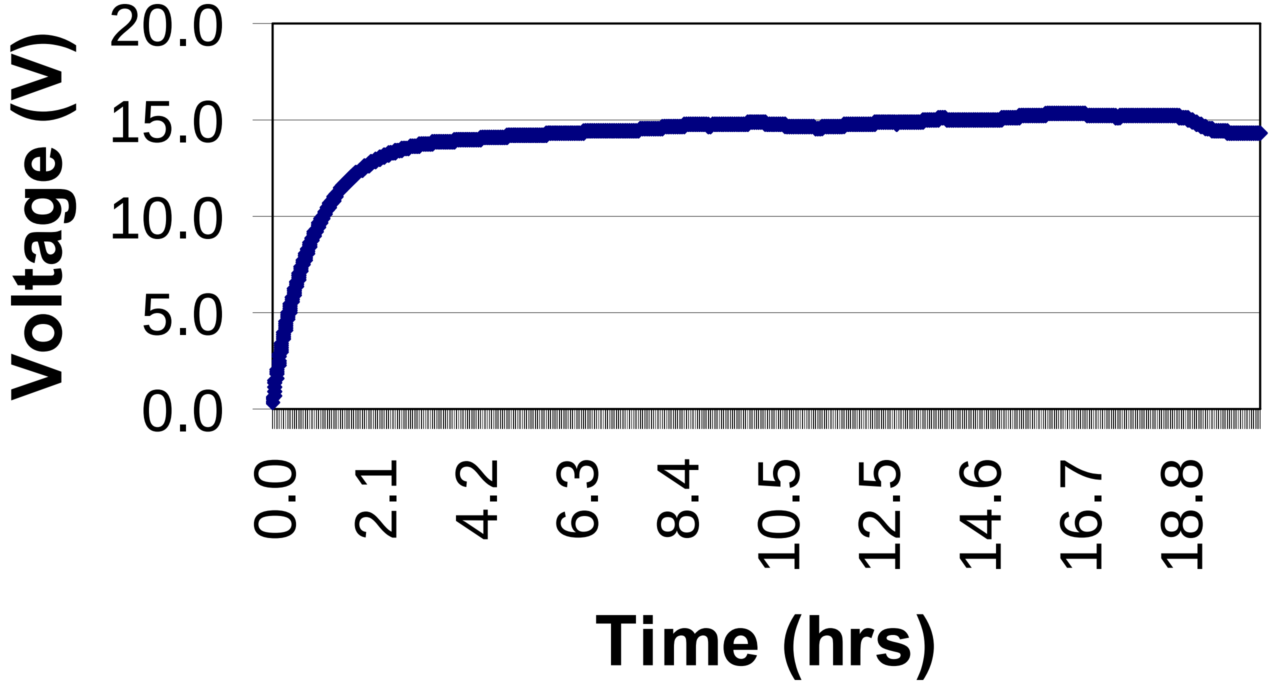


Example: 10 nm oxide with 5 pA can generate 40V

Radioisotope-enabled 15 V source

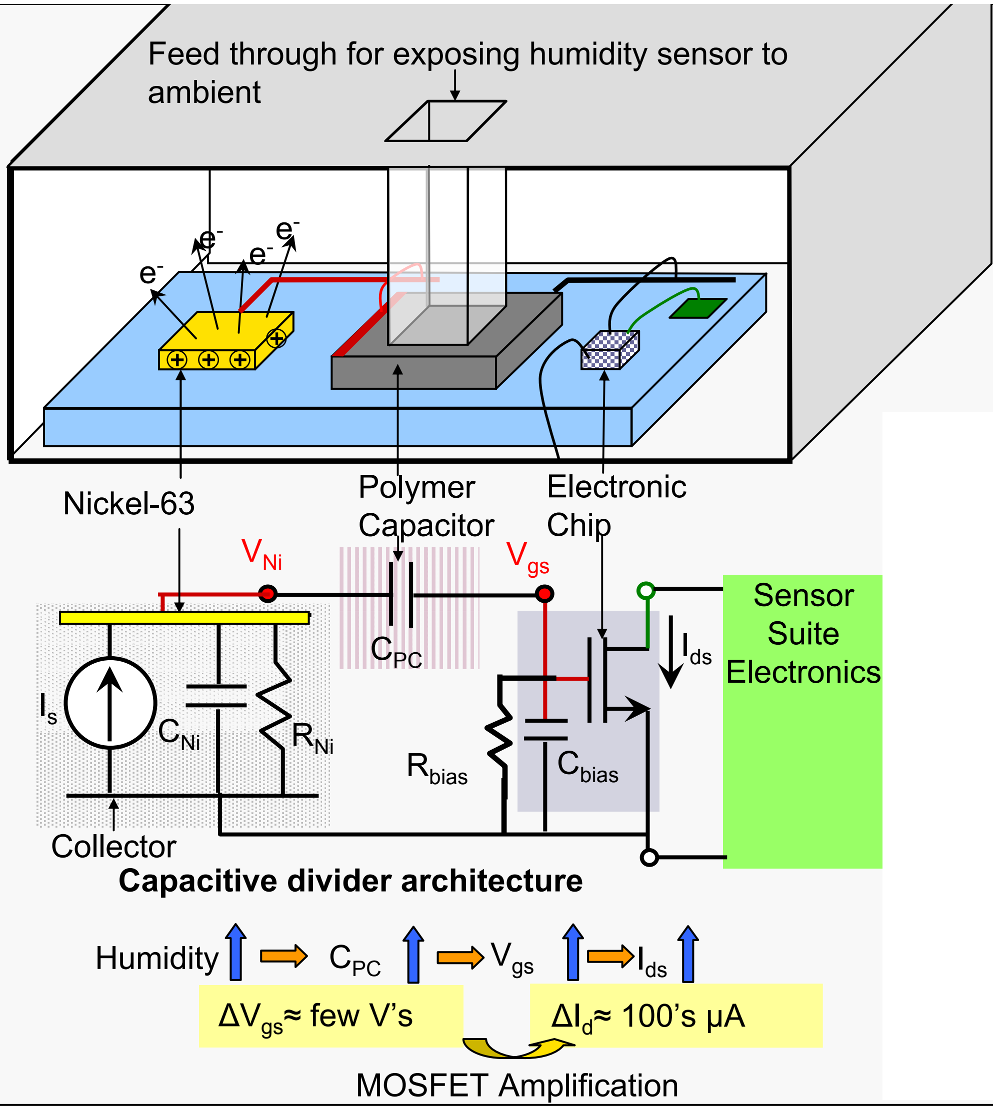
Electrical Equivalent circuit for source-collector



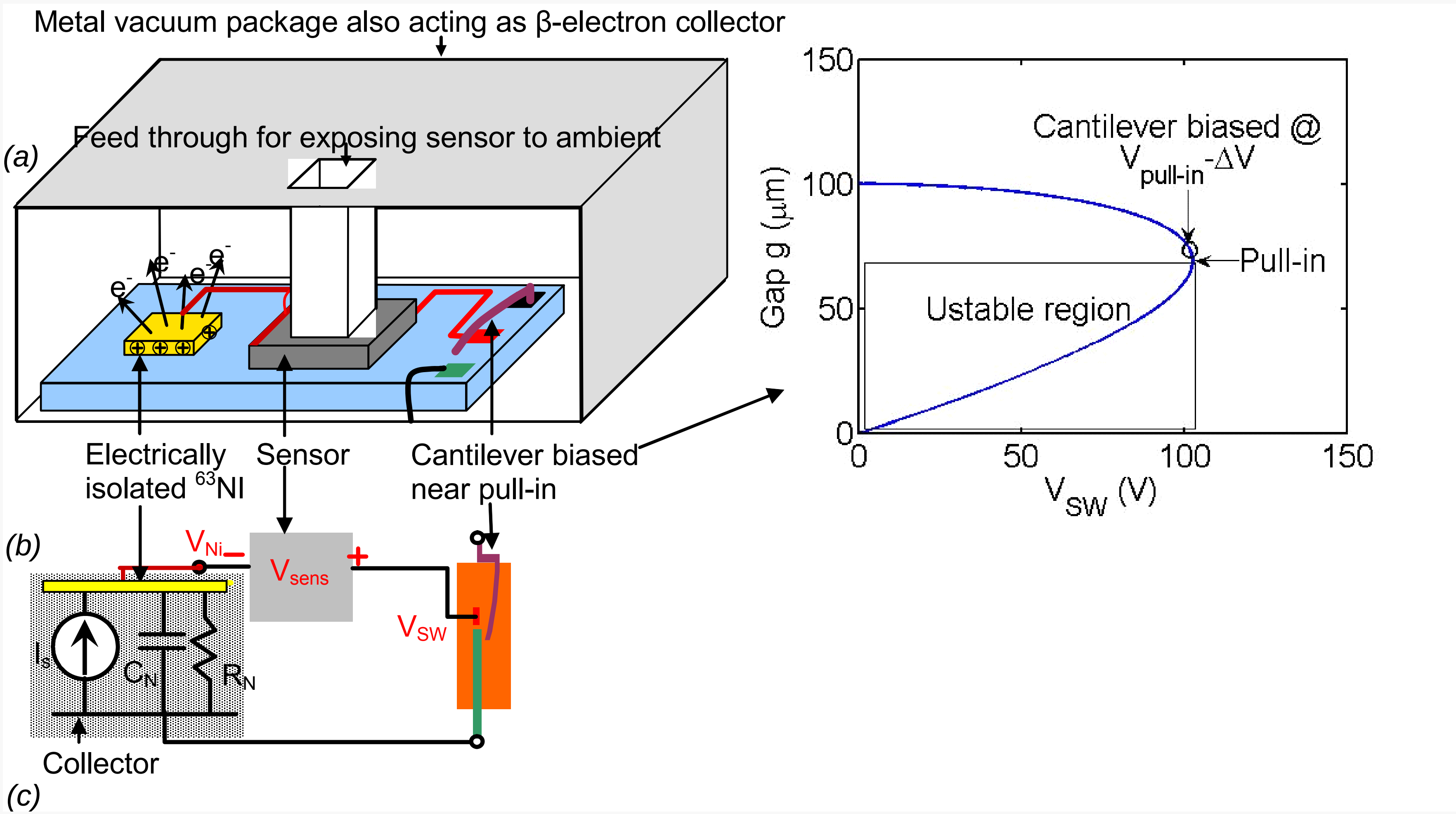


- 10 pF capacitor in parallel, 2 milliCi ^{63}Ni source

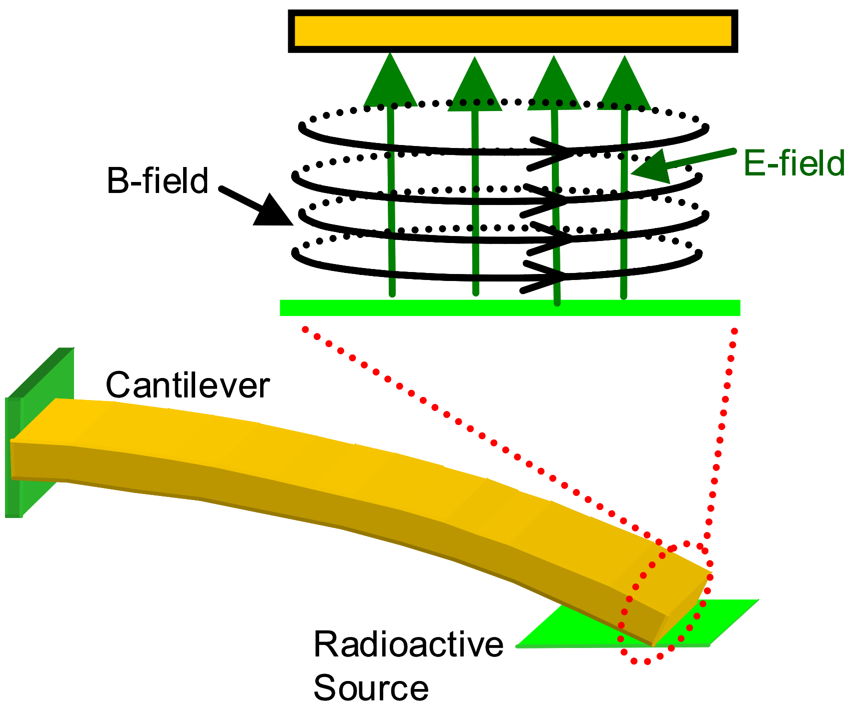
Self-powered Humidity Sensor: Concept

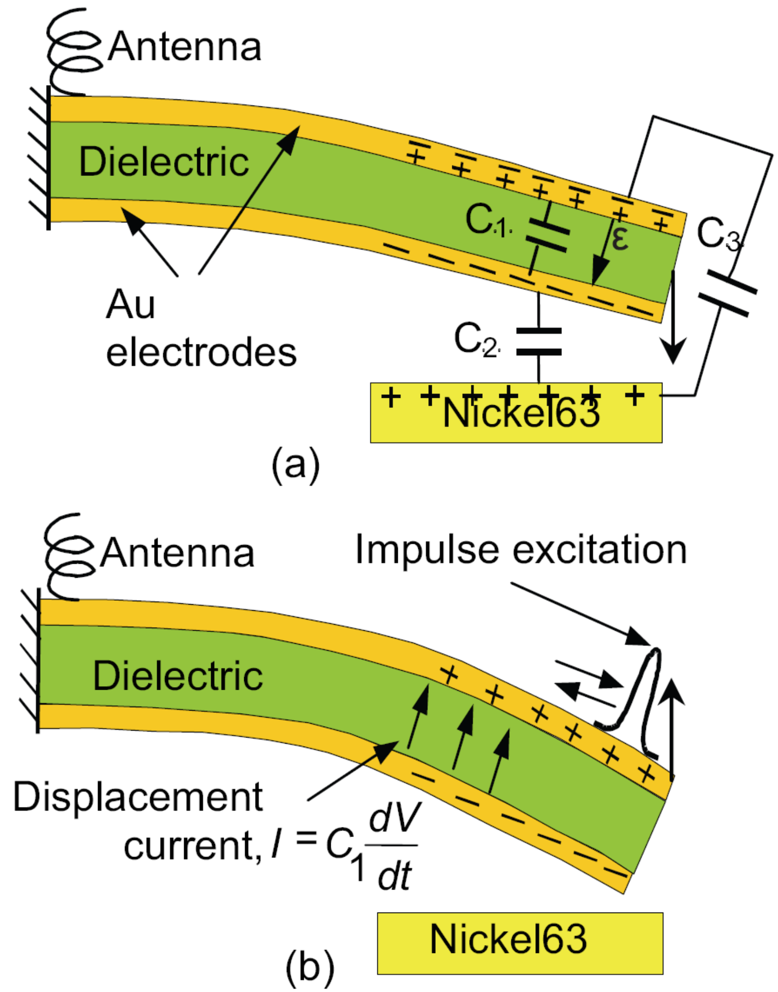


Self-powered Sensor Vision

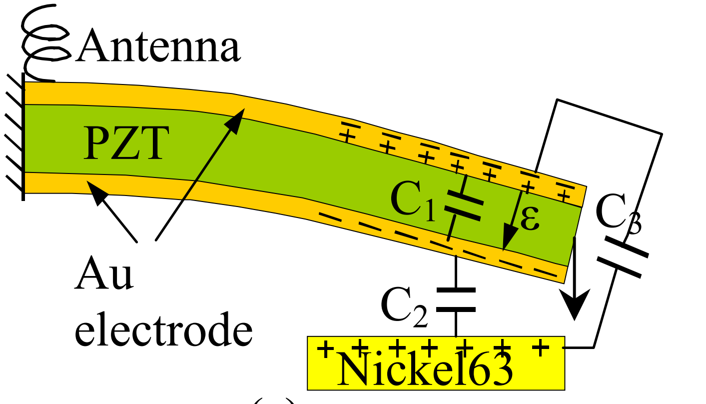


Are we Utilizing All Energy in IRPG?

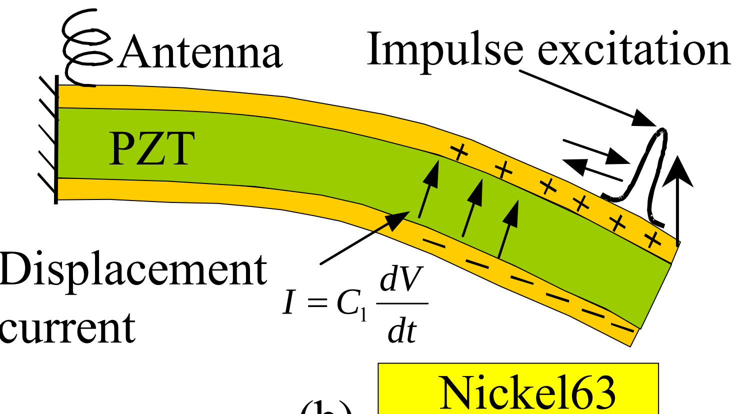




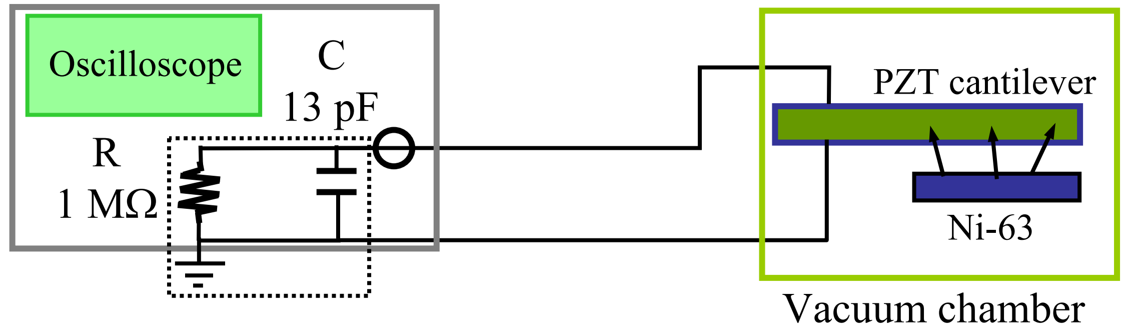
Self-powered RF pulse generation

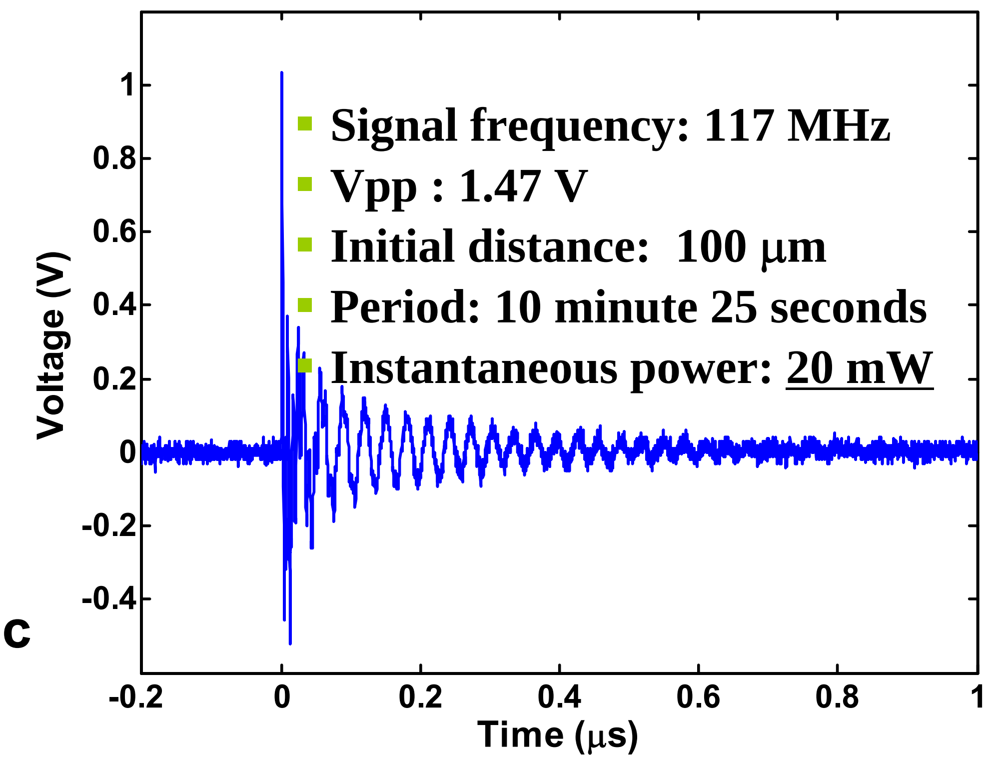


(a)



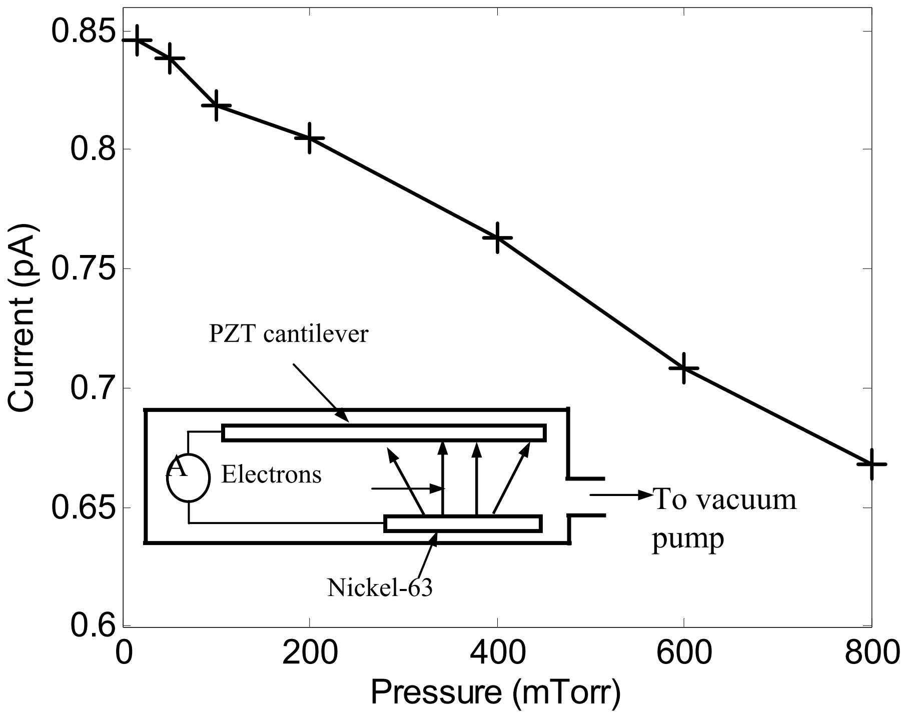
(b)

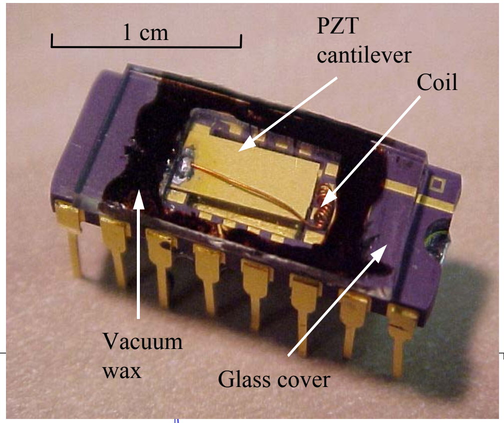


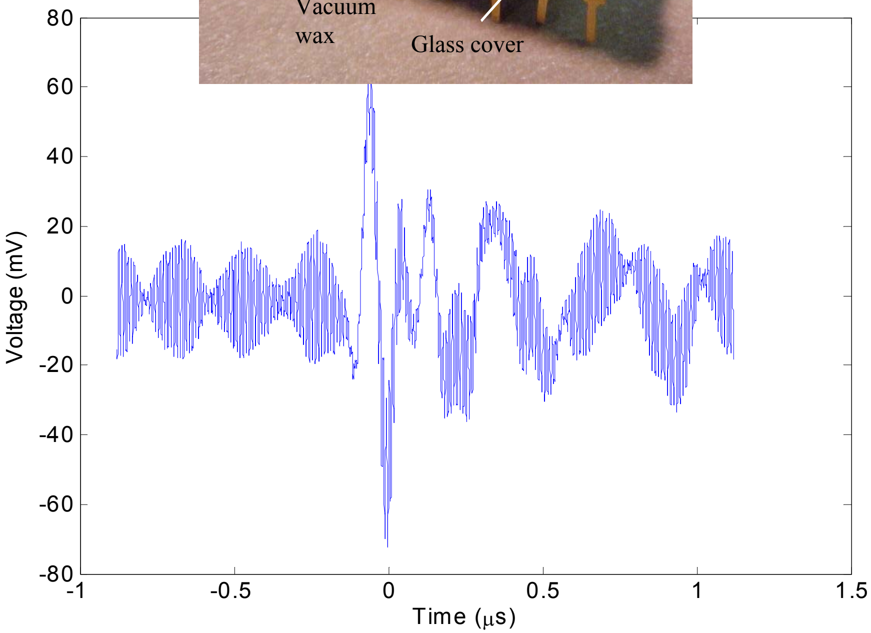


- **Parasitic energy in dielectric**
- **Impulse response of dielectric is excited**

Self-powered Pressure Sensor





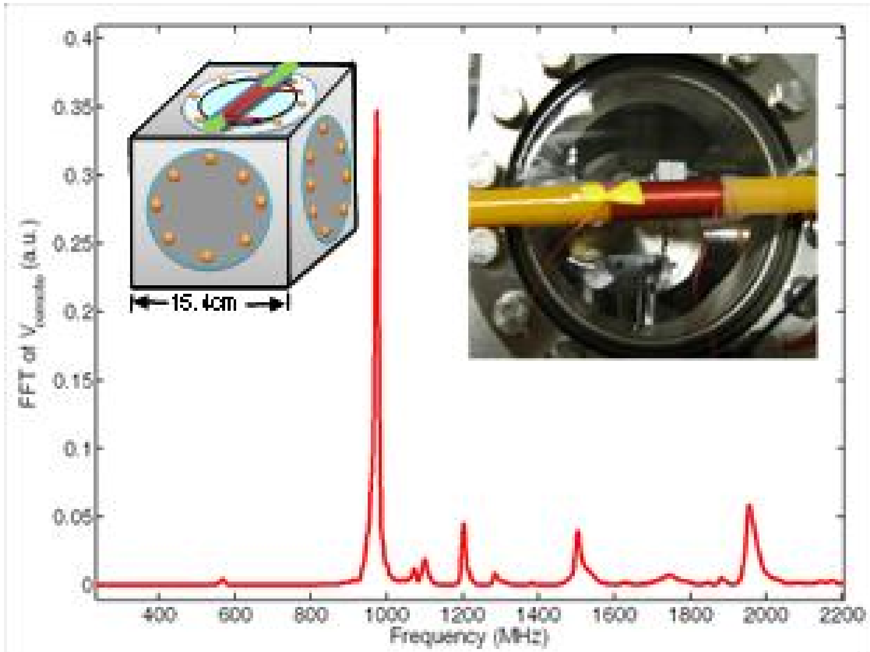


- **The current provided by the ^{63}Ni source varies with the pressure**
- **This changes the reciprocation time of cantilever and RF-pulse**

A typical pulse detected by the coil placed 0.1 m away from the DIP package, centered at 100 MHz

IREMPG RF Transmitter

Self-powered ARC Radios



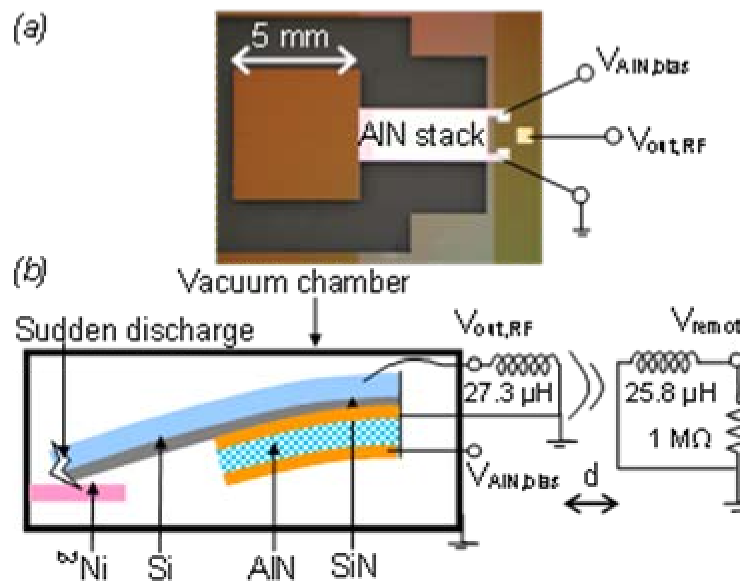
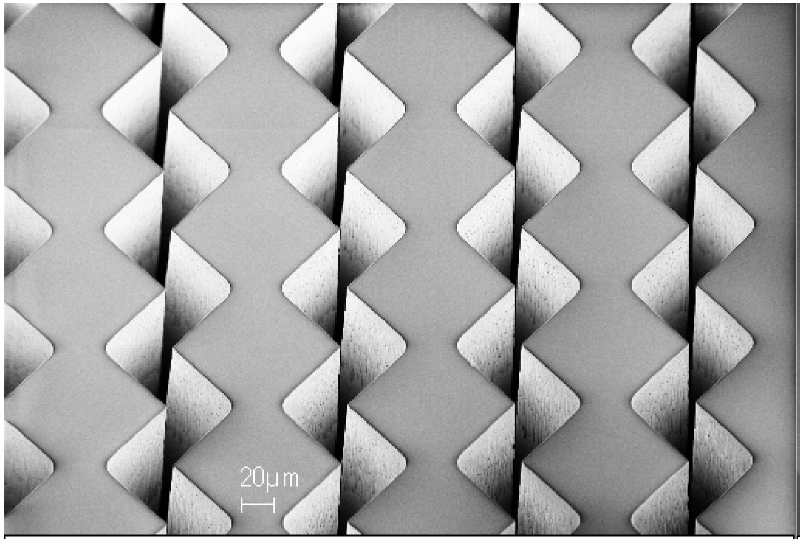


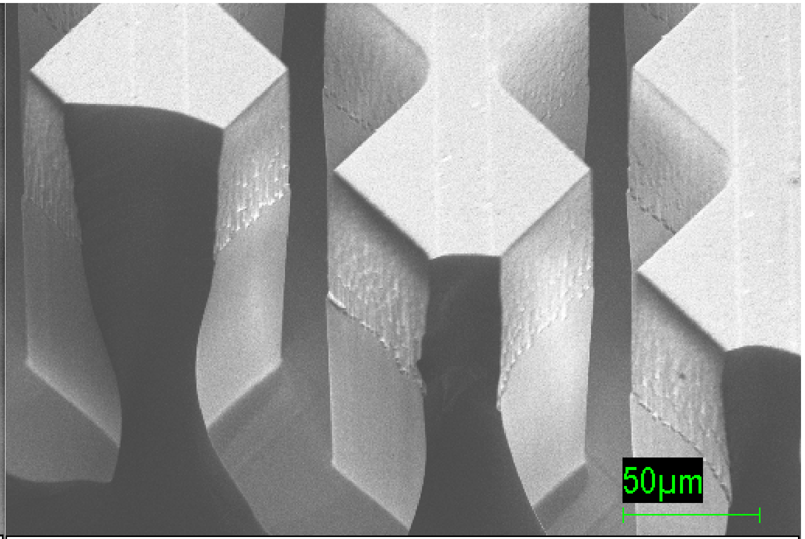
Figure 6. (a)Top-view photograph of the micro AlN-Si cantilever, and (b) schematic of wireless RF signal characterization set-up.

High Energy Density Betavoltaics

SEMs of Microfabricated 3D Betavoltaic



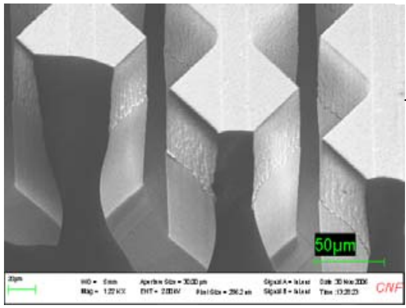
Top surface



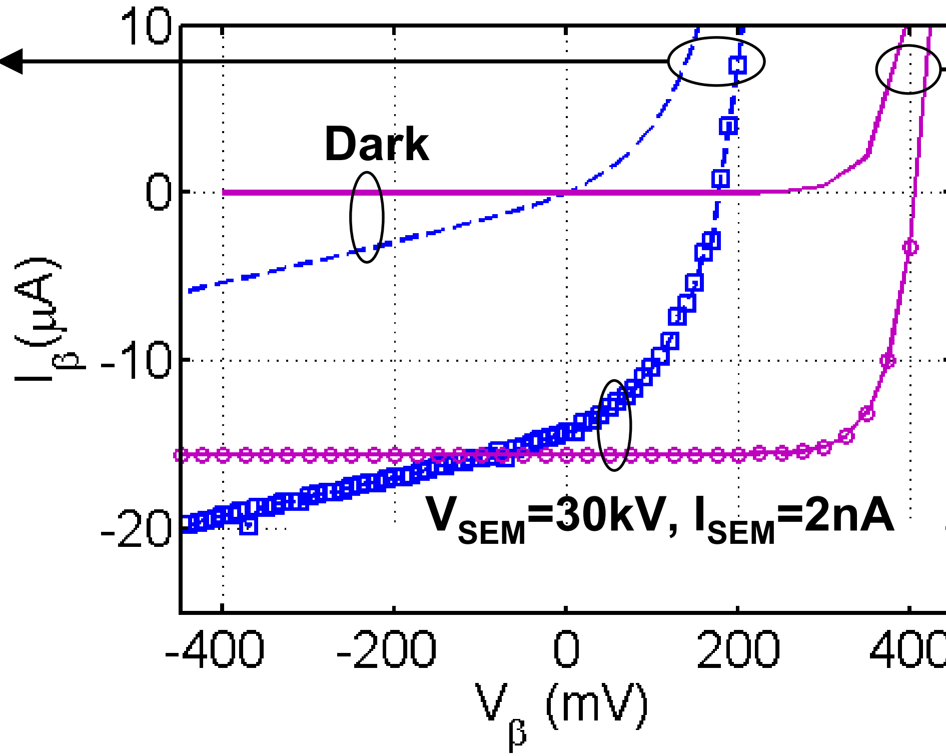
Cleaved cross-section

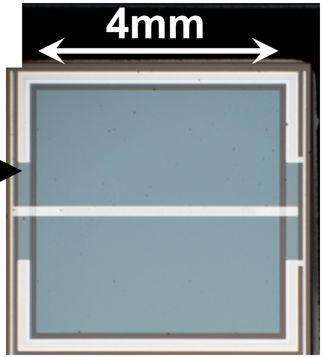
3D Betavoltaics vs. Planar Betavoltaics for Same Substrate and Process Flow

1 mm² SEM electron beam irradiation



0.64 cm² 3D betavoltaic chip





0.16 cm² planar betavoltaic chip

High I_0

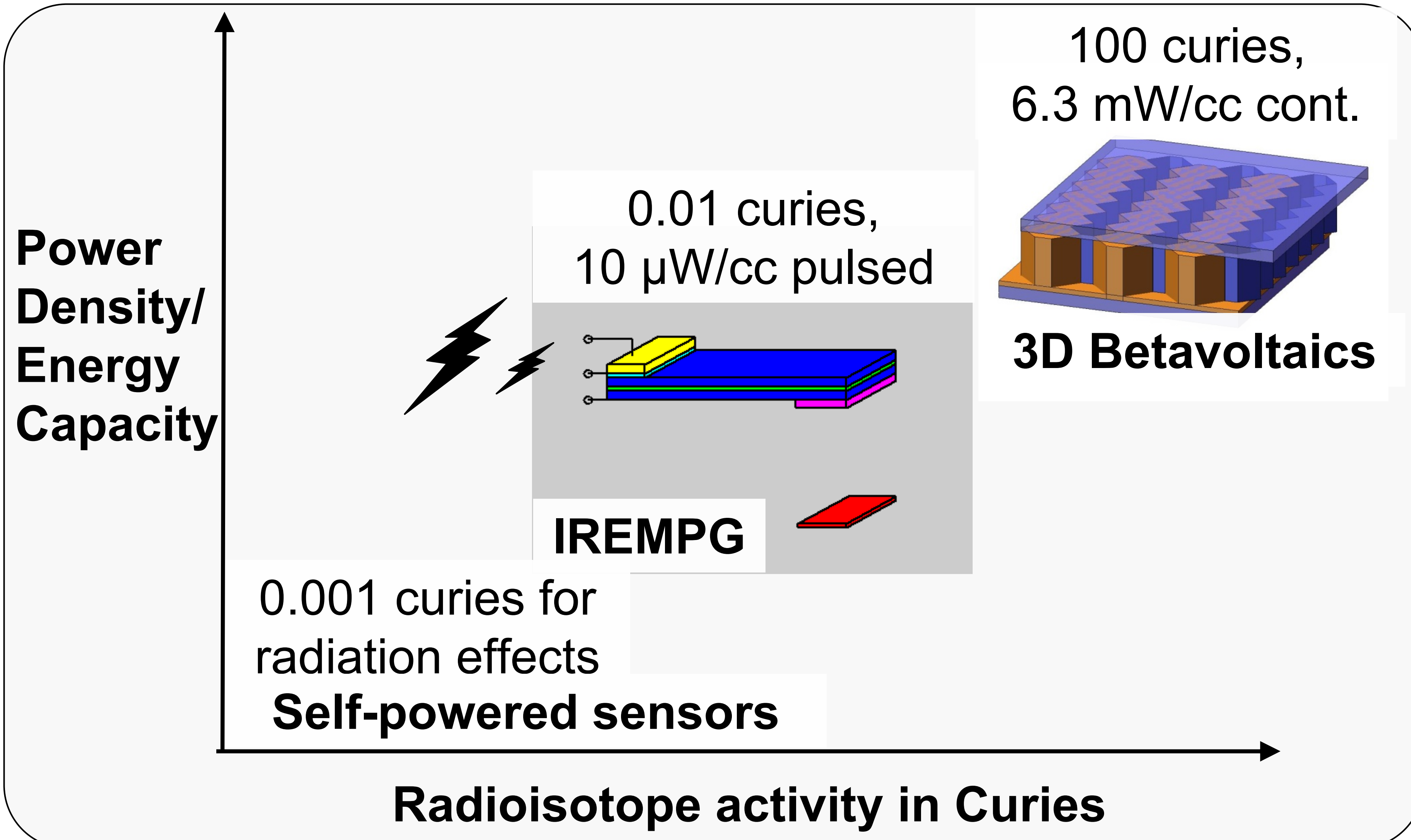
V_{oc} = 180 mV
FF = 43 %
η_β=1.61%

Low I_0

V_{oc} = 410 mV
FF = 74 %
η_β=4.6%

High Leakage leading to low efficiency

Radioisotopes in Microsystems



Conclusions/Future

- **Radioisotopes (in particular pure beta emitters) can provide nano-thin film sources energy**
- **High energy particles require impedance matches – MEMS provides this in multiple ways: Pulsed RF, Pulsed Mechanical, DC**
- **Self-powered Light Sources, Vacuum Pumps, Cyclotrons, Counting clocks, random number generators – nuclear physics on a chip!**
- **NEXT: Packaged Self-Powered Sensor Node – operate at high and low temp, 100 year lifetime**