Energy Management

Trends in micro-power conversion and management for energy harvesting applications

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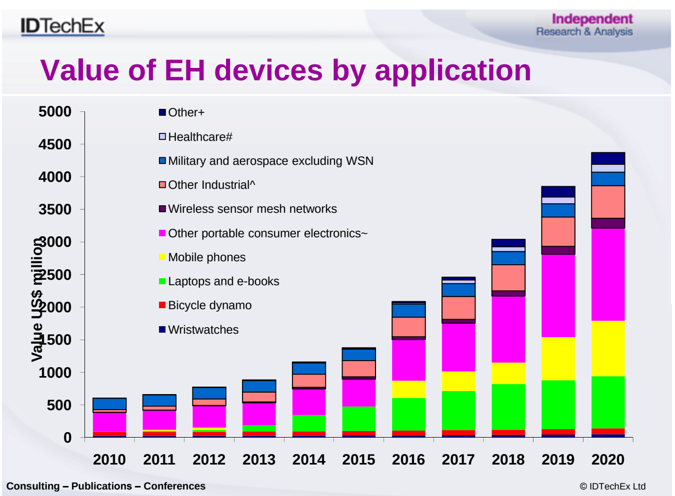
Outline

- Introduction to power management for energy harvesting and environmental energy sources
- Techniques and design trade-offs in power management circuits
- Evolution and trends in power management circuits

Introduction to energy harvesting

Market Trends

- The energy harvesting market is **growing slower than predicted**
  - Power from miniature source is actually very low, in the order of µW
  - Larger batteries are still cheaper than energy transducers
  - Applications and circuits (sensors, RF transceivers, power converters, etc.) are thought for operating with batteries and not in extreme power- and voltage- constrained scenarios



IDTechEx, Energy Harvesting Europe 2010

EE Times Connecting the Global Electronics Community

designlines MCU

News & Analysis

Chips for Energy Harvesting: The Next Billion-Dollar Market

Peter Clarke
4/29/2016 02:00 PM EDT
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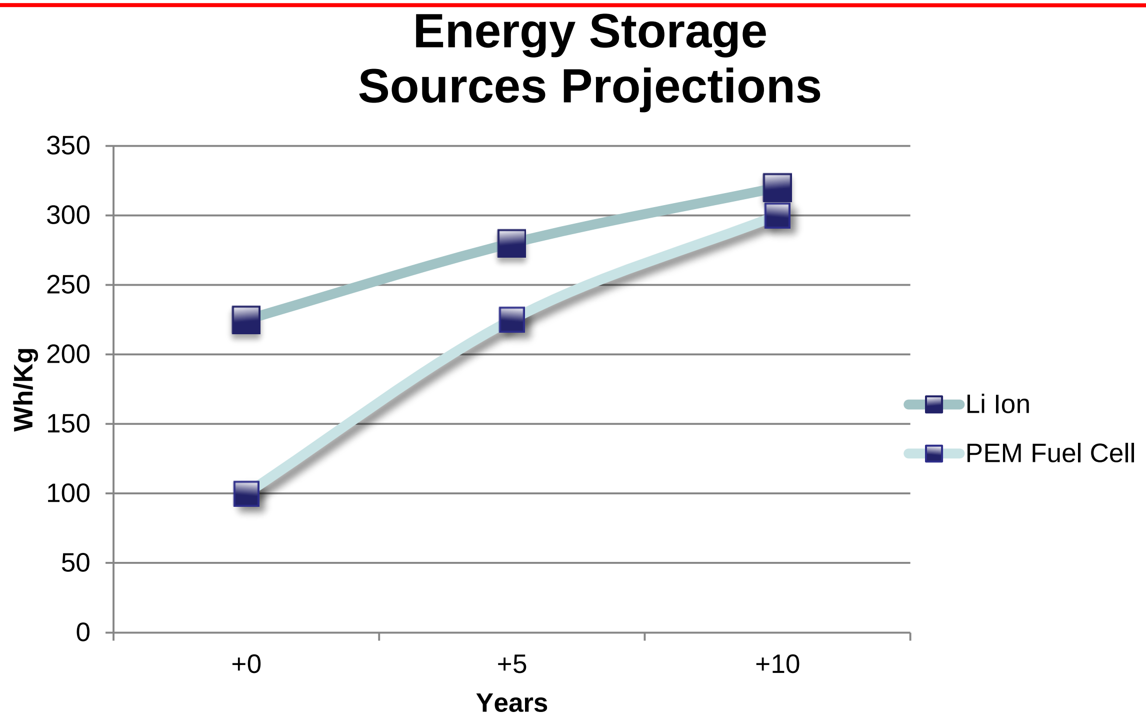
LONDON—Although energy harvesting has failed to take off to date – usually because it is has been uneconomic compared with installed battery power – it will drive semiconductor sales worth $3 billion in 2020, according to Semico Research (Phoenix, Ariz.).

This drive will be from values of about $200 million and 40 million units shipped in 2015.

EETimes, 2016

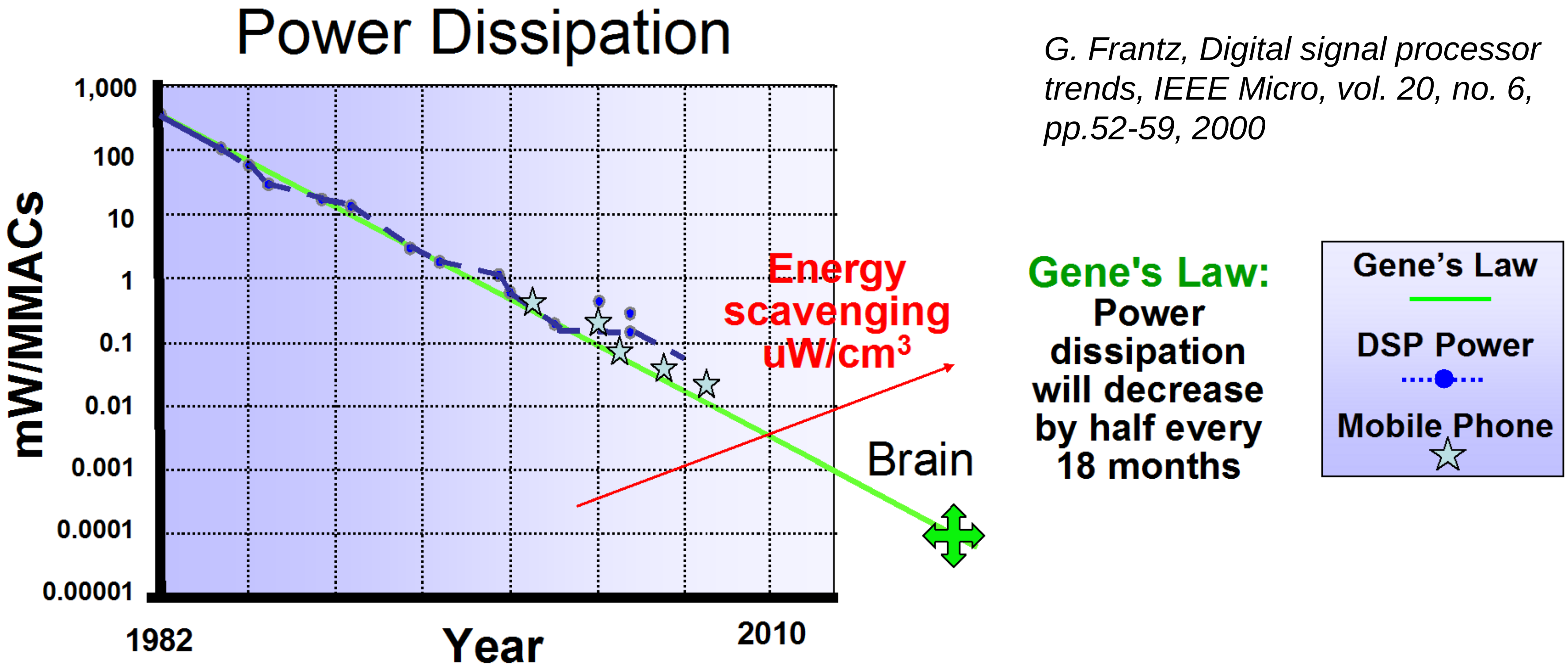
The Bad



- Gene’s law does not apply to analog sensing and transmission (slower decrease)
- Energy storage density increases only ~1.5x/decade (**~1.04x/year**)

Energy autonomous systems: future trends in devices, technology, systems, CATRENE Working Group on Energy Autonomous Systems, 2009

The Good



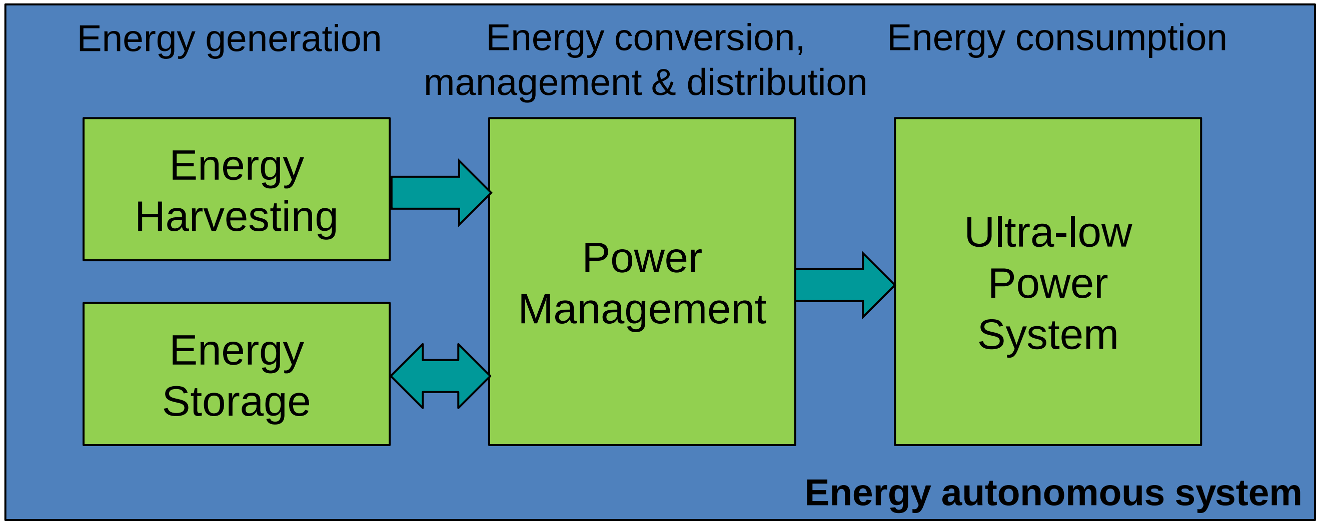
G. Frantz, Digital signal processor trends, IEEE Micro, vol. 20, no. 6, pp.52-59, 2000

(G. Frantz, SoC in the new Paradigm of IC technology, IEEE Consumer Electronics Society – Dallas Chapter, Aug 2008)

The energy per bit per computation decreases according to the technology trend

(Gene's law: energy/bit ~1.6x/year)

Components of an Energy Autonomous System



- **Energy generation**:
  - Energy Harvesting: “transducers” making energy available from correlated or uncorrelated sources of energy
  - Energy Storage: Any kind of energy storage element that could be used to accumulate energy in excess from the harvester (e.g. batteries, (super)capacitors, etc.)
- **Energy conversion, management and distribution**.
  - any energy conversion system that trades and optimizes the energy flow from the Energy Generation block, to the user load, from/to the energy storage
- **Energy Consumption**
  - Data acquisition, elaboration, storage and transmission.

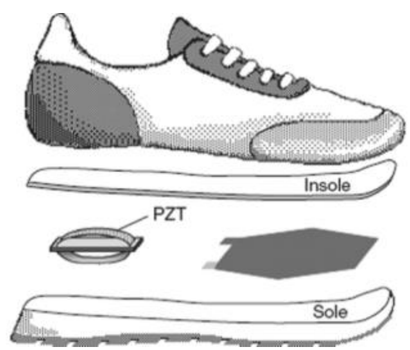
Energy harvesting: what applications?

Smart clothing:
A small wearable antenna collects energy from electromagnetic waves

M.Dini et al., A fully autonomous integrated RF energy harvesting system for wearable applications, EuMW 2013

Body-powered devices:
Battery can be replaced with PV cells, thermoelectric generators that harvests energy from light and human body heat.

V. Leonov, C. Van Hoof, R. Vllers, Thermoelectric and hybrid generators in wearable devices and clothes, BSN 2009, 6th Workshop on Body Sensor Networks,

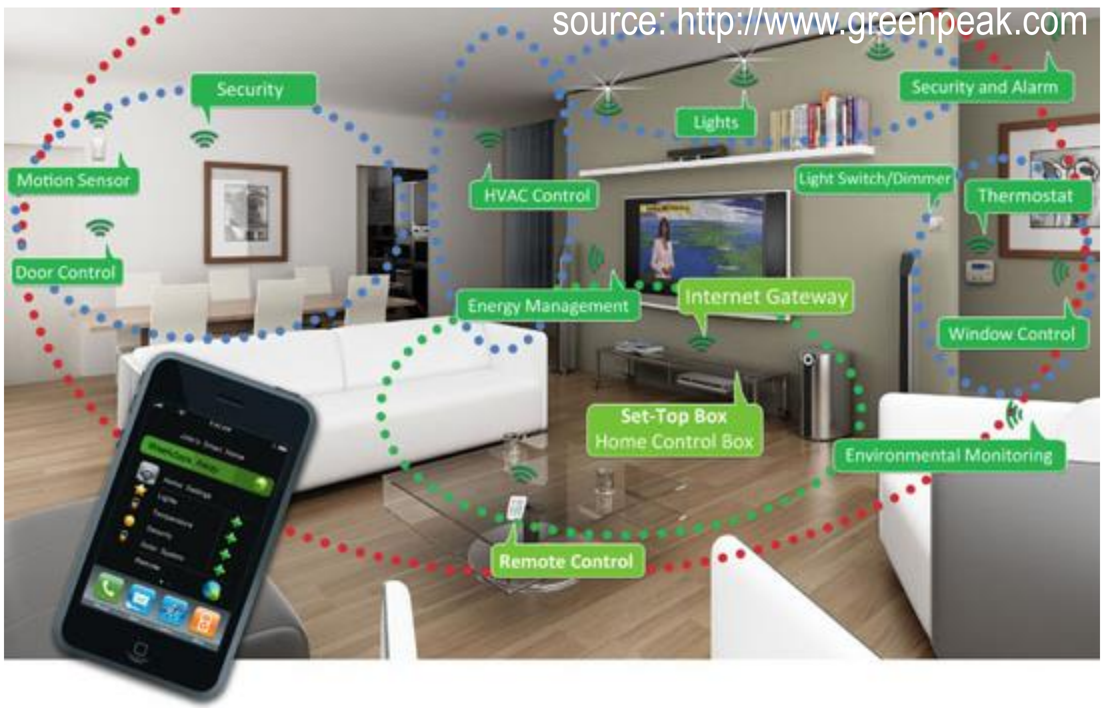


Smart shoes:
Vibrations can be used for powering small systems such as wireless pedometer.

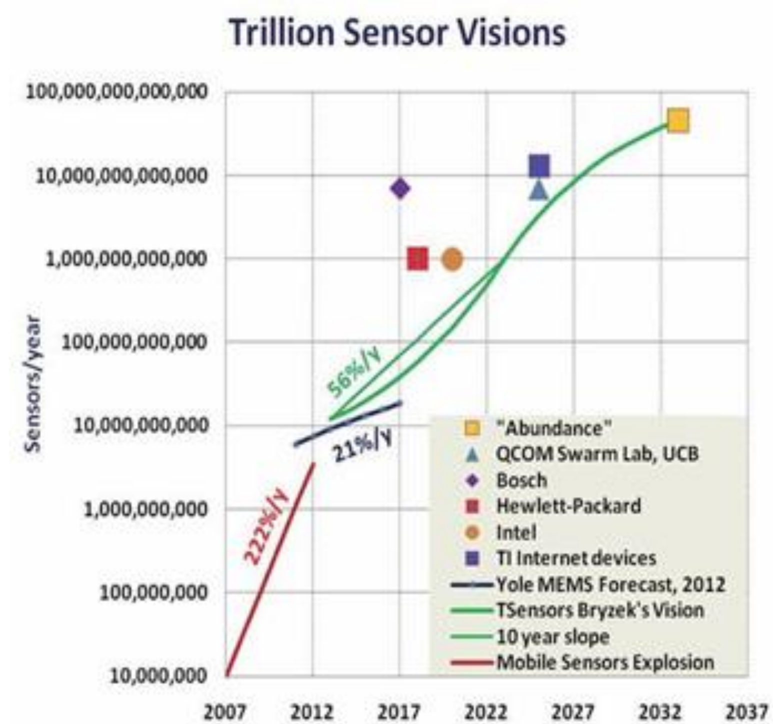
N. Schenk, J. Paradiso, Energy scavenging with shoe-mounted piezoelectrics, Micro, IEEE , vol.21, no.3, 2001

Energy harvesting: what applications?

- Smart home/cities/objects
- ‘True’ Internet-of-Things
- Roadmap towards trillion (connected) sensors → The ‘Abundance’



source: http://www.greenpeak.com

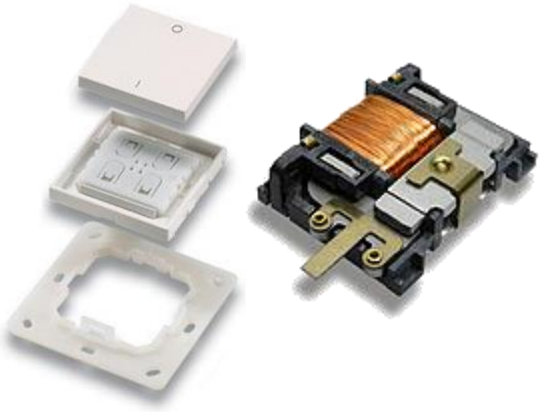


J. Bryzek, Emergence of Trillion Sensors Movement, IEEE MEMS, 2014

Electromagnetic energy harvesters

- **Perpetuum[1] energy harvester**
  - Frequency tuned on mains frequency 50/60 Hz BW<1Hz
  - Output power up to 20 mW
  - Diameter: 68 mm, height: 63.3 mm

- **Enocean motion energy harvester[2]**
  - Used for wireless light switches
  - Dimensions: 29 x 19 x 7 mm^3
  - Energy output: 200 µJ @2V

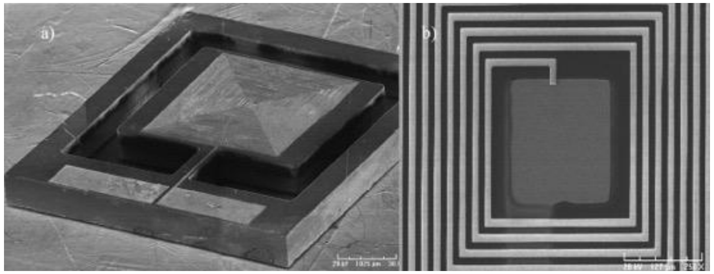


[1] Perpetuum Ltd., http://www.perpetuum.com

[2] Enocean, PTM200 Datasheet, http://www.enocean.com

[3] S. Kulkarni et al., Design, fabrication and test of integrated micro-scale vibration-based electromagnetic generator, Sensors and Actuators A, vol. 145, 2008 (Tyndall Institute, Univ. Southampton)

- **MEMS realizations[3]**
  - 0.1 cm^3 volume
  - 23 nW output power @1g @9.83 kHz
  - electrodeposited copper coil



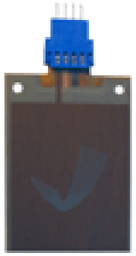
Piezoelectric transducers

- Common materials:
  - **PZT** (Lead Zirconate Titanate) is a ceramic material with a high coupling coefficient *k*. The material is rigid, fragile, and contains lead.
  - **PVDF** (Polyvinylidene fluorid) is a polymeric material with a lower k. It's non-toxic, bendable and can resist high shocks or impacts.
- Typical frequencies: from few to hundreds Hz

Commercial piezoelectric transducers

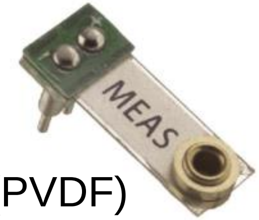
Transducer	Material	Capacitance per area [F/cm²]
PIEZO SYSTEMS Q220-A4-503YB	PSI-5A4E Ceramic material	12.2 nF/cm²
MIDE VOLTURE V25W	Ceramic material	8.56 nF/cm²
MEAS - SPEC. DT SERIES PIEZO (DT1-028K)	Meas-spec piezo film	380 pF/cm²
MEAS - SPEC. MiniSense 100	PVDF	254 pF/cm²

PIEZO SYSTEMS



MIDE

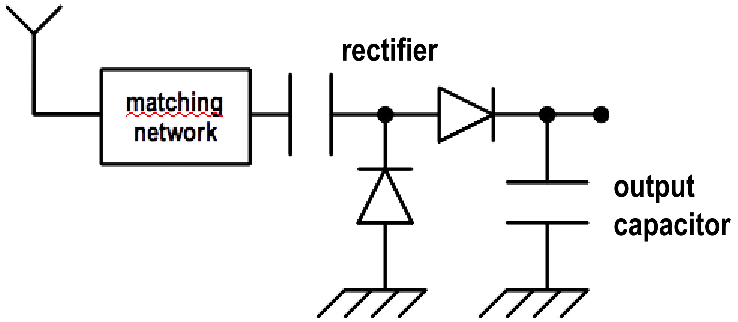
MEAS-SPEC

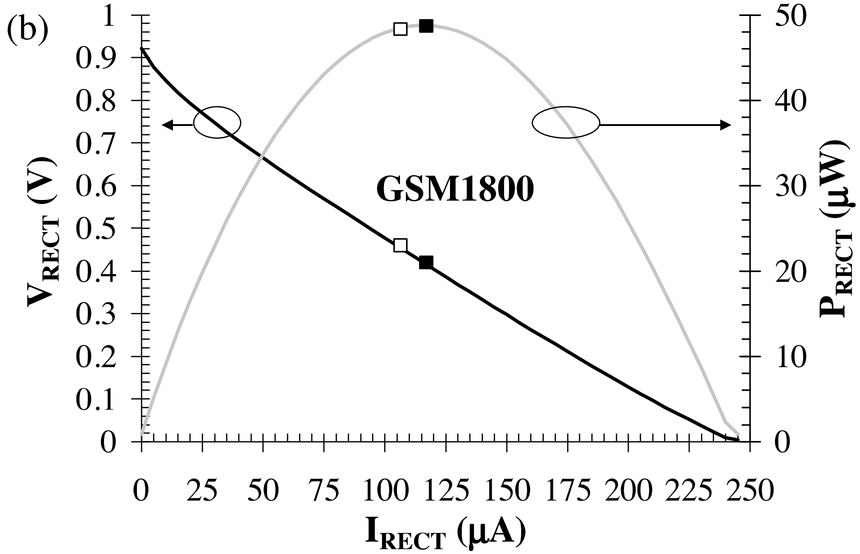


MEAS-SPEC (PVDF)

RF Energy Harvesting

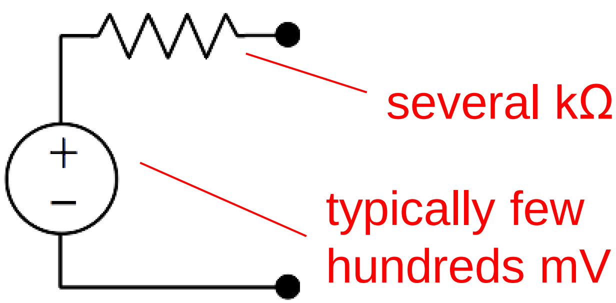
- RF carriers can be rectified in order to store locally energy
  - **Rectenna** = rectifying antenna
  - Matching network must be designed according to the expected input power





V-I and P-I transfer characteristics

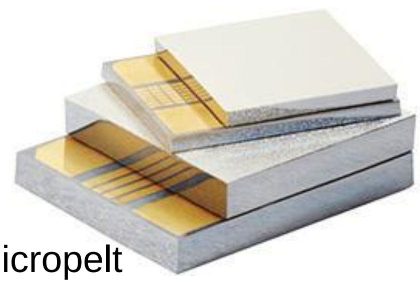
- Simplified representation:



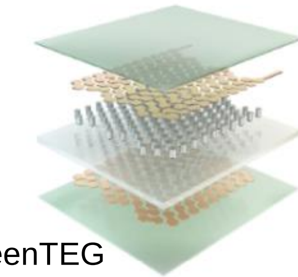
Micro-Thermoelectric Generators

ΔT is the temperature difference between hot side (T_H) and cold side (T_C).

* Temperature difference between hot side and ambient temperature.

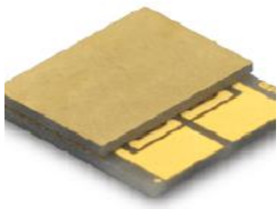


Micropelt



GreenTEG

Nextreme

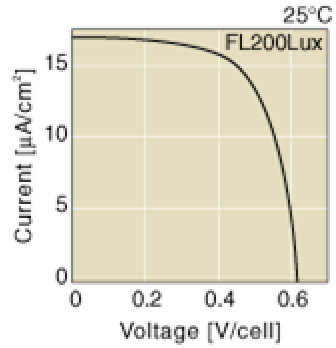


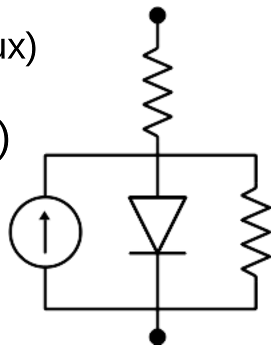
Manufacturer - Product	Size [mm]	V_{OUT} [V] (matched load)	P_{MAX} [W] (matched load)	Power density [W/cm³/K]	Process
Eu. Thermodynamics - GM200-449-10-12	WxL=54x57 H=3.8	11.4 @ ΔT=170K	14.6 @ ΔT=170K	7.34e-3	Standard
Eu. Thermodynamics - GM200-127-10-15	WxL=30x30 H=3.7	4.14 @ ΔT=170K	2.72 @ ΔT=170K	4.80e-3	Standard
Nextreme - PG8005/6	WxL=11.2x10.2 H=1.1	0.85 @ ΔT=50K	0.13 @ ΔT=50K	2.07e-2	Thin film
Micropelt - MPG-D751	WxL=4.2x3.35 H=1.09	2.33 @ ΔT=30K	13.6e-3 @ ΔT=30K	2.96e-2	Thin film
GreenTEG – gTEG B*	WxL=7.1x7.1 H=0.63	0.388 @ ΔT=37K	178e-6 @ ΔT=37K	1.51e-4	Thin film

Photovoltaic Energy Harvesting

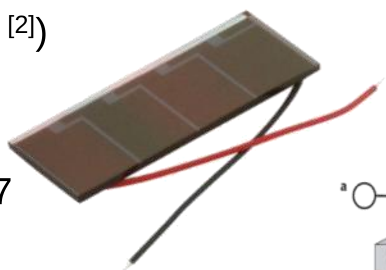
Miniature commercial devices and emerging technologies

- Sanyo amorphous silicon PV cells (e.g. AM1407)
  - Optimized for indoor fluorescent light (40-1000 Lux)
  - Output power (AM-1407) ≈ 100 μW (indoor FL light, 240 Lux)
- Ixys© PV module in tiny SMD packages (e.g. CPC1822)
  - Output power ≈ 100 μW at direct sunlight (6000 Lux)
- DSSC - Dye synthesized solar cell [1]
  - Photoelectrochemical system (no silicon)
  - Can be flexible and transparent
  - Growing efficiency (up to 15% [2])

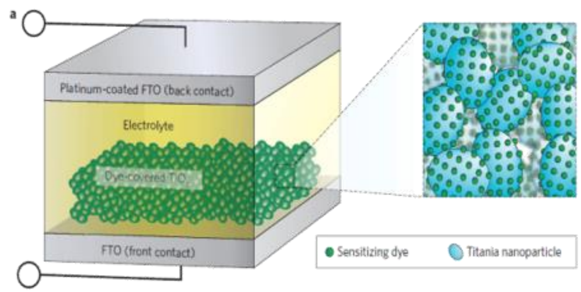


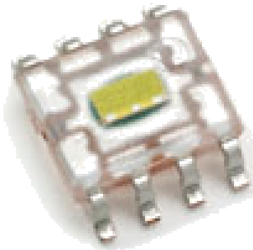


equivalent circuit



Sanyo AM1407



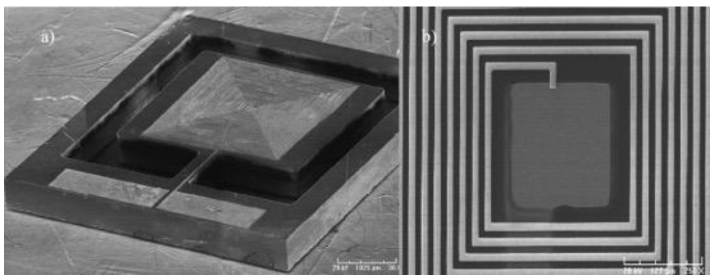


CPC1822

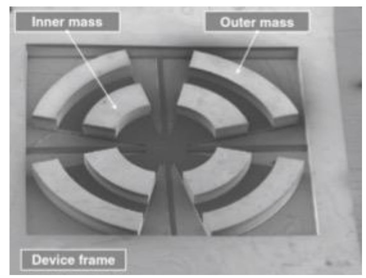
[1] Hardin, Brian E., Henry J. Snaith, and Michael D. McGehee. "The renaissance of dye-sensitized solar cells." Nature Photonics 6.3 (2012): 162-169.
[2] Burschka, Julian, et al. "Sequential deposition as a route to high-performance perovskite-sensitized solar cells." Nature (2013).

Towards MEMS Energy Harvesters

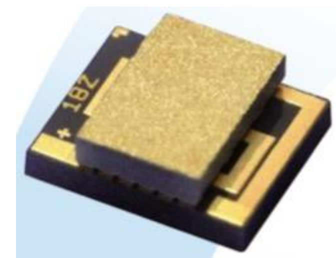
- The current trend is to **further shrink down** energy transducers thanks to MEMS technologies or wafer-level processing (output power also scales!)



Electromagnetic
0.1 cm^3, 23 nW @1g @9.83 kHz
electrodeposited copper coil
S. Kulkarni et al., Sensors and Actuators A, vol. 145, 2008 (Tyndall Institute, Univ. Southampton)



Piezoelectric
200 nW @0.5g @400 Hz
16 mm^2, deposited AlN
J. Iannacci et al., Microsystem Technologies, vol. 20, 2014 (FBK, Delft Univ. Tech, Munich Univ. Tech.)



Thermoelectric
6-20 mV/K, 2-10 Ω
3-9 mm^2, 8-16 uW @1K
thin film semiconductor, thermally conductive AlN ceramics
Laird Technologies eTEG

Current and Future Power Sources

solar panels, micro wind turbines, miniature mechanical generators (consolidated)

cm-sized energy harvesting transducers: piezoelectric, electromagnetic, thermoelectric, RF, small-sized PV (present)

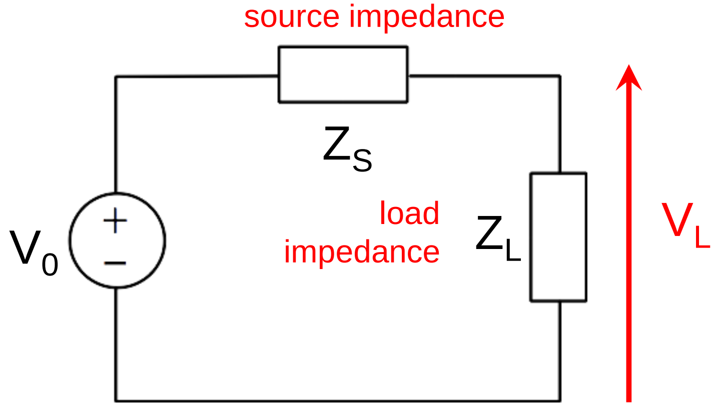
MEMS devices, CMOS on-chip photodiodes, microfabricated thermoelectrics (mm-sized devices) (near future)

bio-potentials, heart beat, nanowires (piezo, PV, thermal) (future?)

Techniques and design trade-offs for power management circuits

Maximizing the extracted power

Maximum Power Transfer

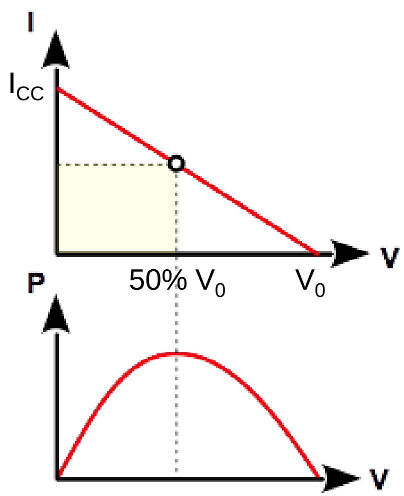


- The theorem of maximum power transfer states that the power transferred to a load is maximized when $Z_L = Z_S^*$
  - where $Z_S = R_S + jX_S$ is the source impedance and $Z_L = R_L + jX_L$ is the load impedance
- For a linear source:
  - $V_L = V_0 / 2$
  - $P_L = V_L^2 / R_L = V_0^2 / 4R_L$

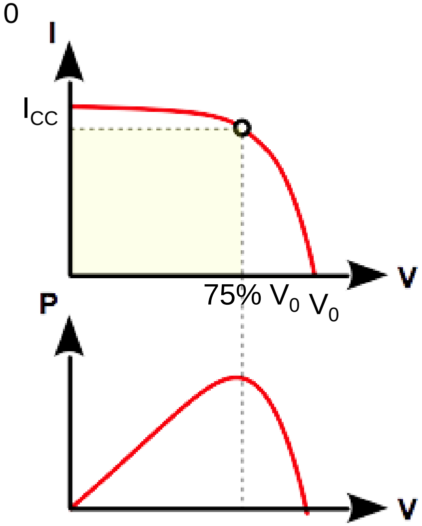
Power Transfer Characteristics

- The I-V curves are a convenient way to describe the properties of a source in view of the design of the power converter
  - All curves combining two parameters among (P, V, I, R_L) are equivalent: P=VI, V=R_LI
- For a linear load, the MPP is located at 50% of V_0
- For a PV cell, the MPP is located around 70-80% of V_0

I-V and P-V curves for linear sources



I-V and P-V curves for a PV source

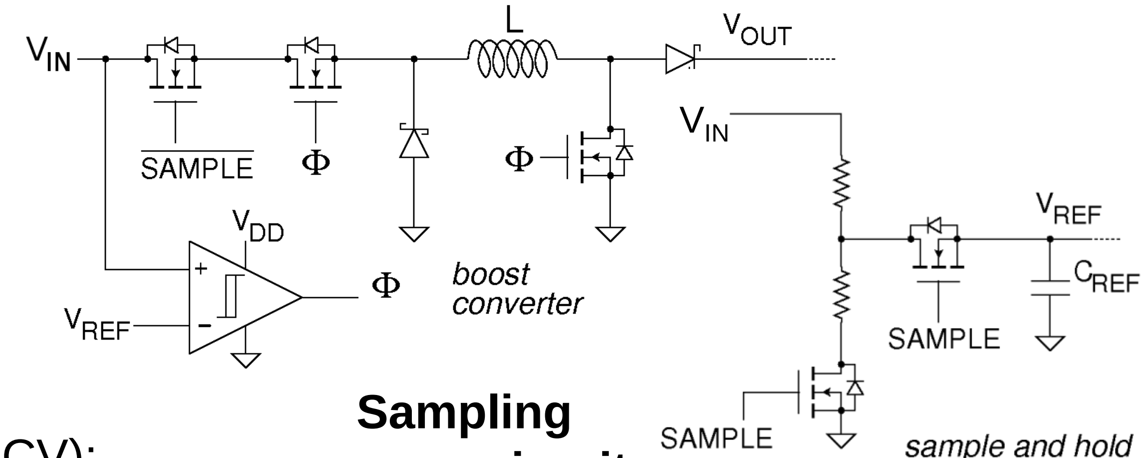


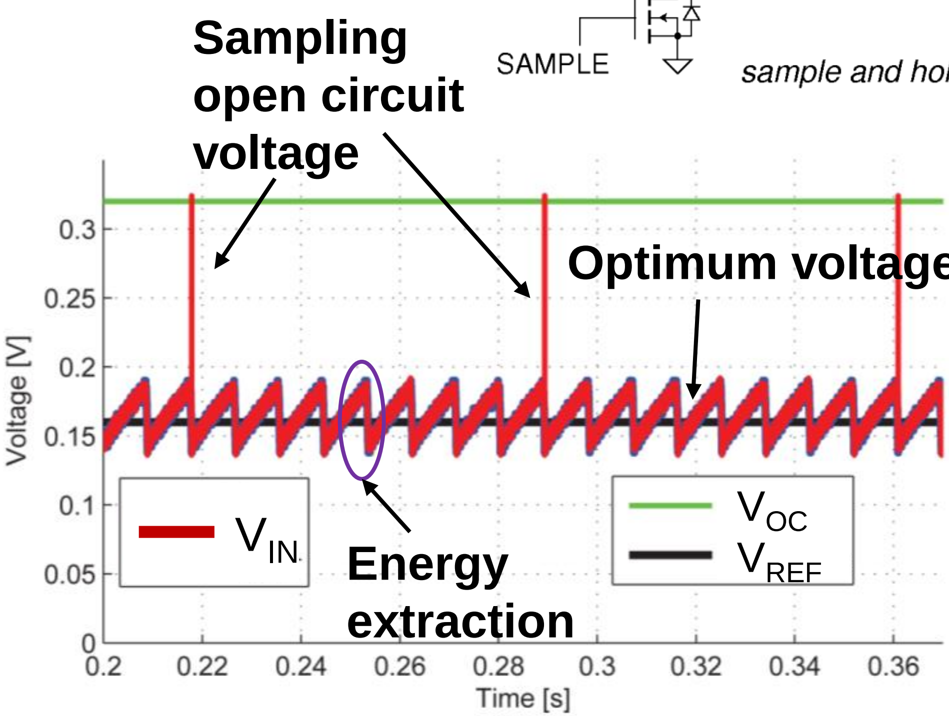
- In order to extract all the available power, a power converter should draw from the source a current that keeps the actual voltage in proximity of the MPP
- I-V curves are also useful to estimate other features of the source (e.g. rise time, etc.)

MPPT for DC sources

- P_{OUT} depends on both the source condition and on the output current, and…
- …yes, there is a maximum! (MPP).

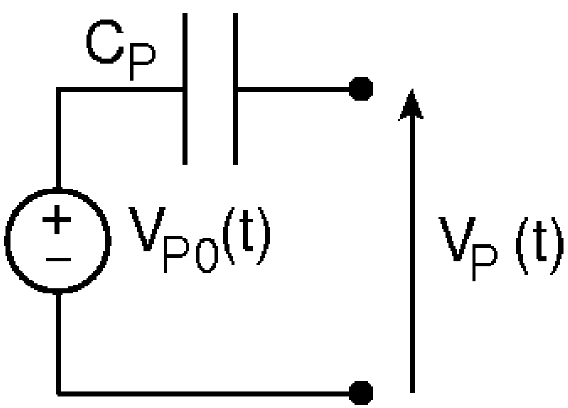
- **Fractional open-circuit voltage MPPT technique** (FOCV): good compromise between power spent and extracted
  - For each type of source the MPP roughly occurs when the source voltage equals a fixed fraction of the open-circuit voltage (e.g. 75% for PV, 50% for linear sources)
  - A DC/DC converter can switch so as to keep the source around this voltage
  - The reference voltage should be periodically refreshed based on OCV
  - …yes, it's suboptimal but consumes little energy



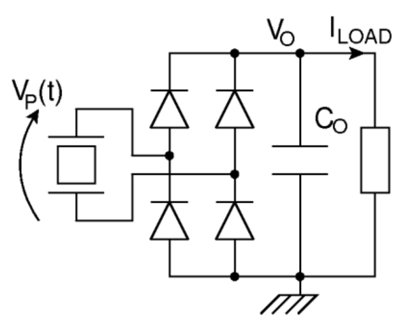


Piezoelectric Sources

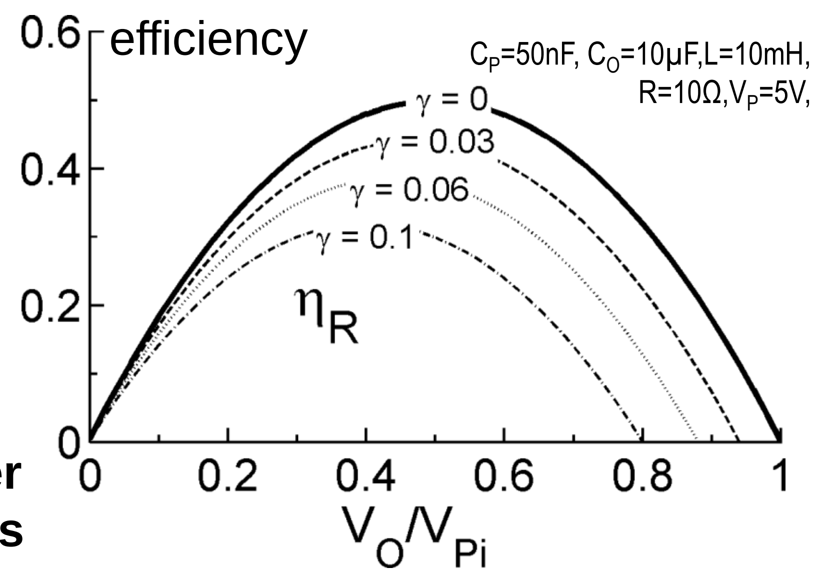
- Let us now consider the simplified equivalent circuit of a piezoelectric transducer
- A rectifier is the simplest circuit for extracting power, but has limited and variable efficiency
- If we apply the matched load (i.e., an unrealistically big L), power would seem to be infinite (ideal voltage source)!
  - **NOTE**: some parameters were neglected (series resistance, electromechanical parameters, etc.). However, much higher power might still be available



simplified equivalent circuit

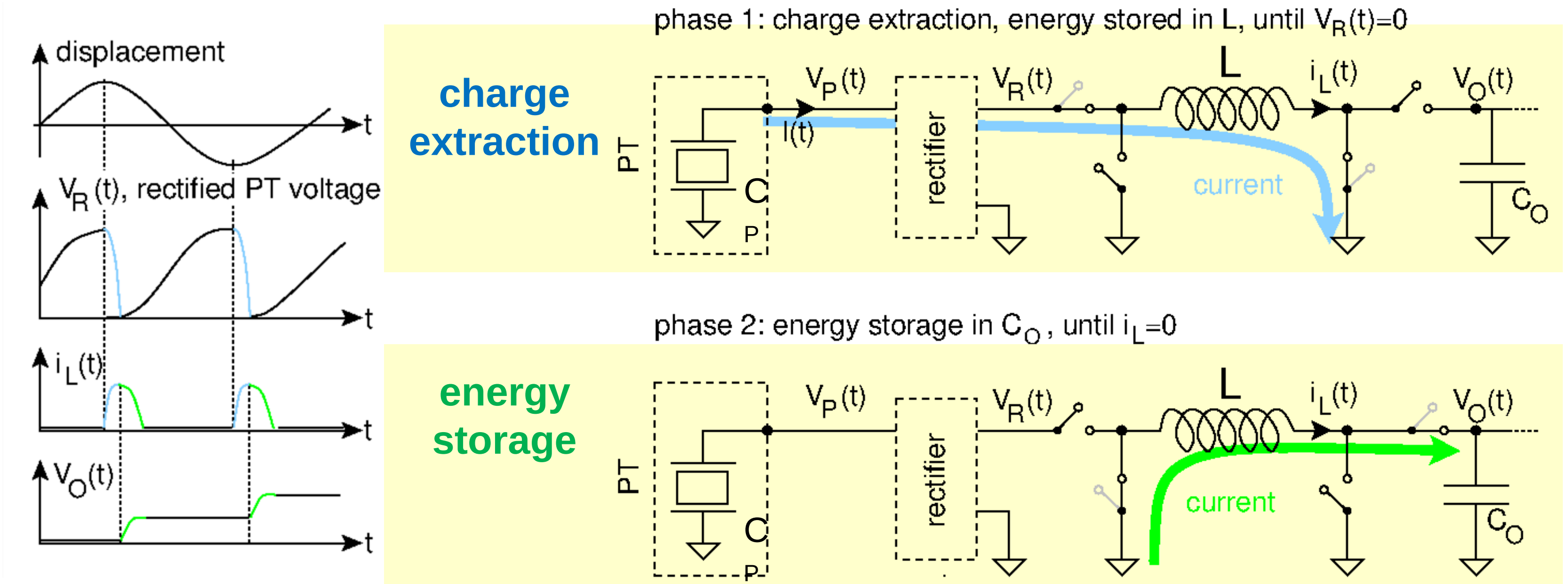


power transfer characteristics



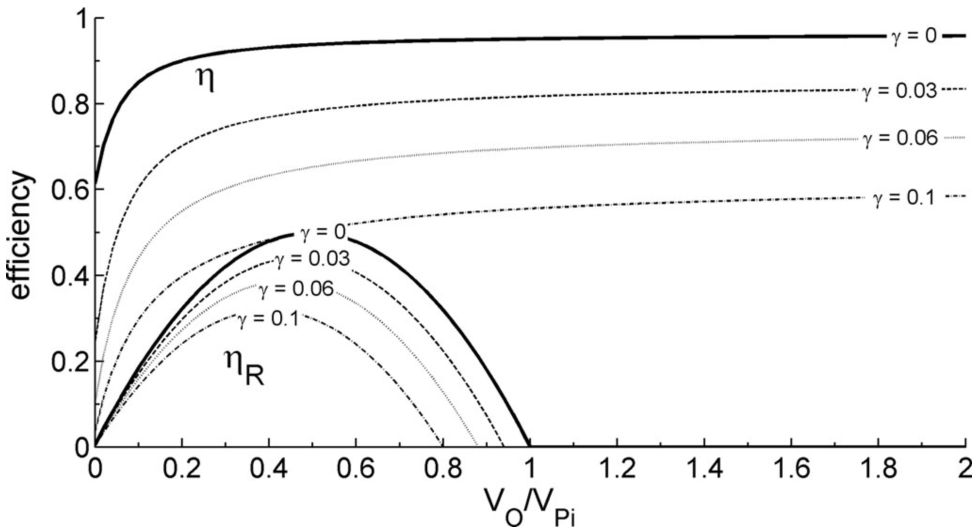
Synchronous Electric Charge Extraction for AC Piezoelectric Sources

- Piezo transducers are (low-frequency) AC sources with **maximum energy** achieved **only twice per period**
- **Synchronous Electric Charge Extraction (SECE) technique:** Two resonant circuits can be used used to remove charge from the transducer: L-C_P and L-C_O
- Electrical charge is extracted in correspondence of maximum and minimum voltages → **very low duty cycle** (< 1%) → very low consumed energy



Efficiency of SECE

- SECE uncouples the source from the load → efficiency almost constant
- It converts energy only when available (tracks maxima) → suitable for irregular vibrations
- The peak-to-peak voltage on the transducer gets doubled → Energy per cycle increases
- Phase 1 has constant duration and then constant efficiency
- Phase 2 has variable duration → variable efficiency

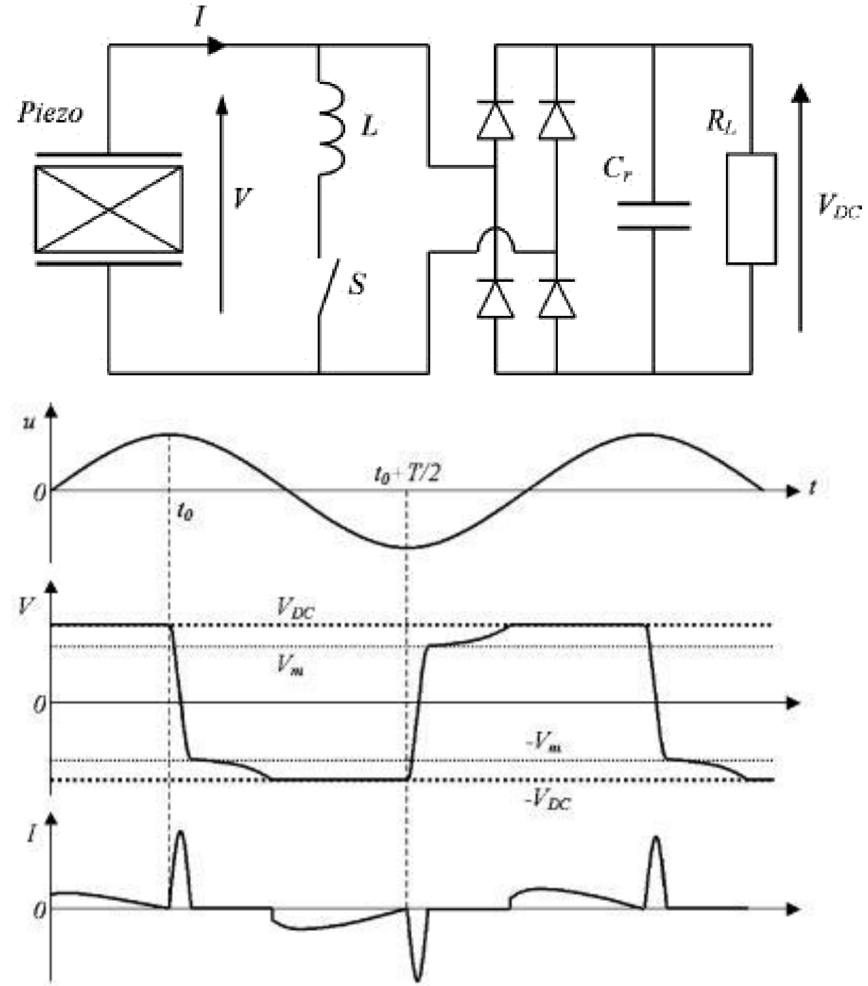


The rectifier interface is outperformed by SECE

A. Romani et al., Micropower design of a fully autonomous energy harvesting circuit for arrays of piezoelectric transducers, IEEE Trans. Power Electron., 2014

Synchronized Switch Interfaces

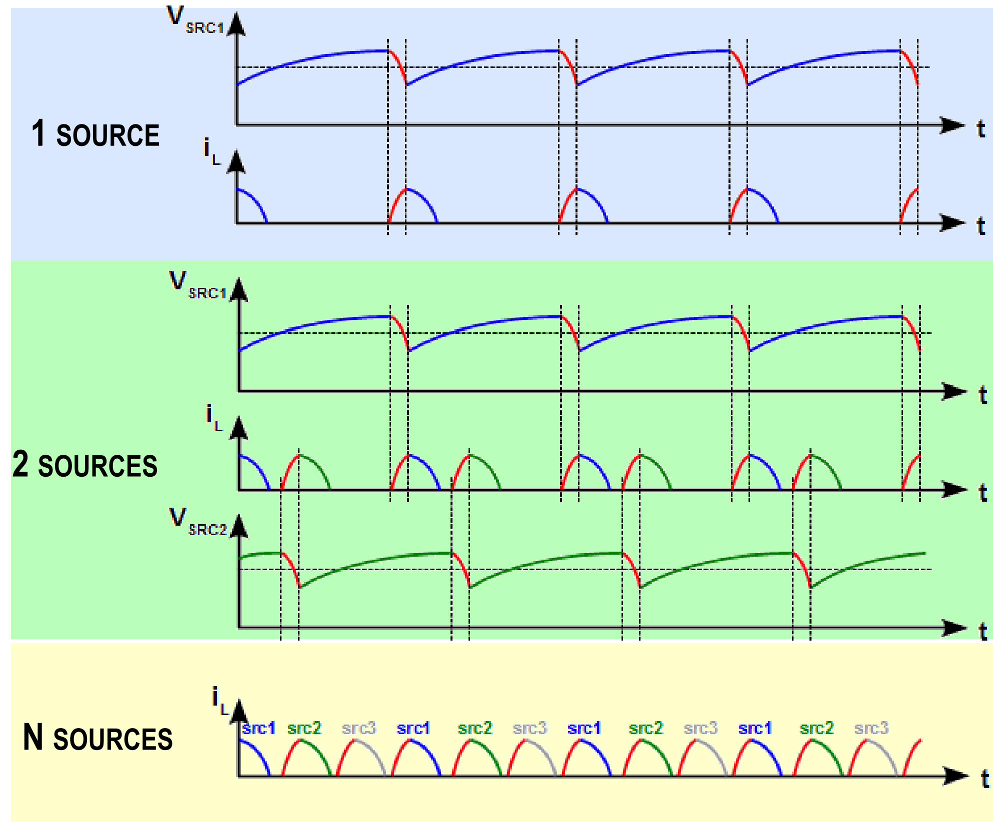
- **Synchronized-Switch Harvesting on Inductor** (SSHI) consists in:
  - an inductor L in series with an electronic switch connected in parallel with the piezoelectric element
  - The electronic switch is briefly turned on when the mechanical displacement reaches a maximum or a minimum.
  - The switch is turned off after a half electrical period, resulting in a quasi-instantaneous inversion of V.
- **Many variations have been presented in literature**

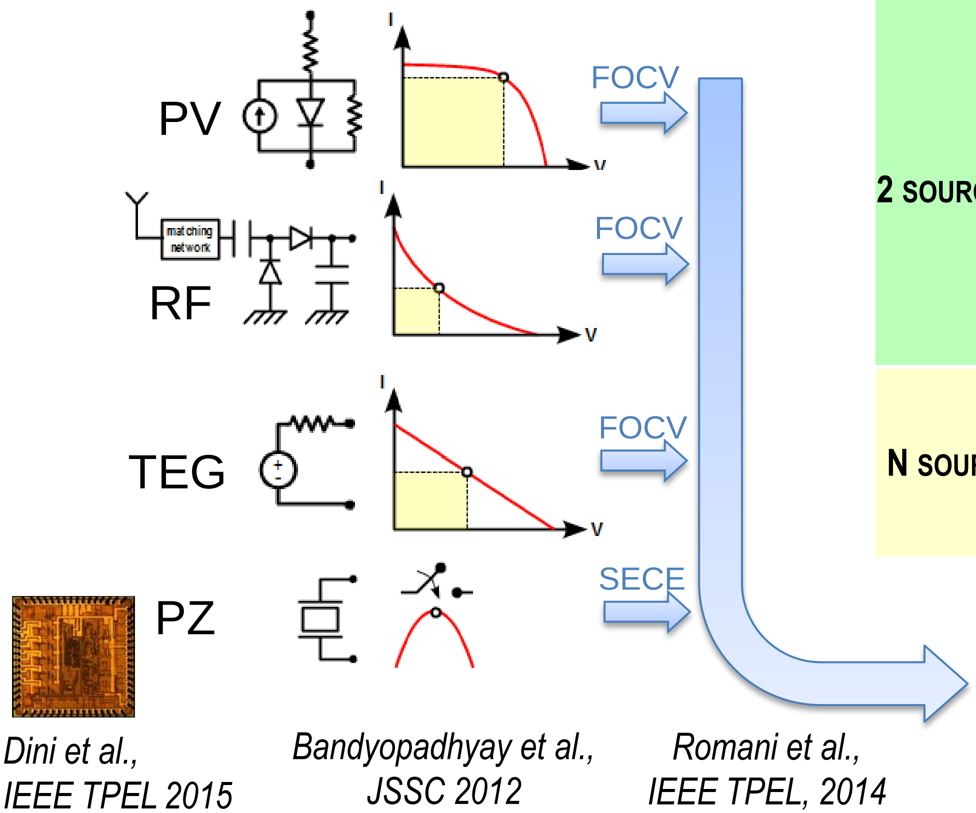


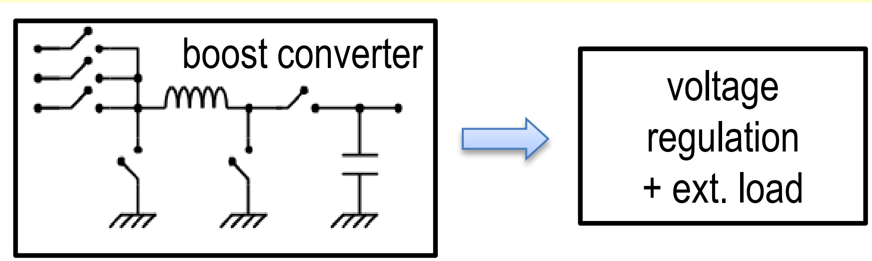
E. Lefeuvre, et al., "A comparison between several vibration-powered piezoelectric generators for standalone systems," Sensors Actuators A, 2006.

Multi-Source Harvesting Idea

- Micro-power conversion likely to occur in discontinuous conduction
- A single time-shared inductor & multi-input boost converter



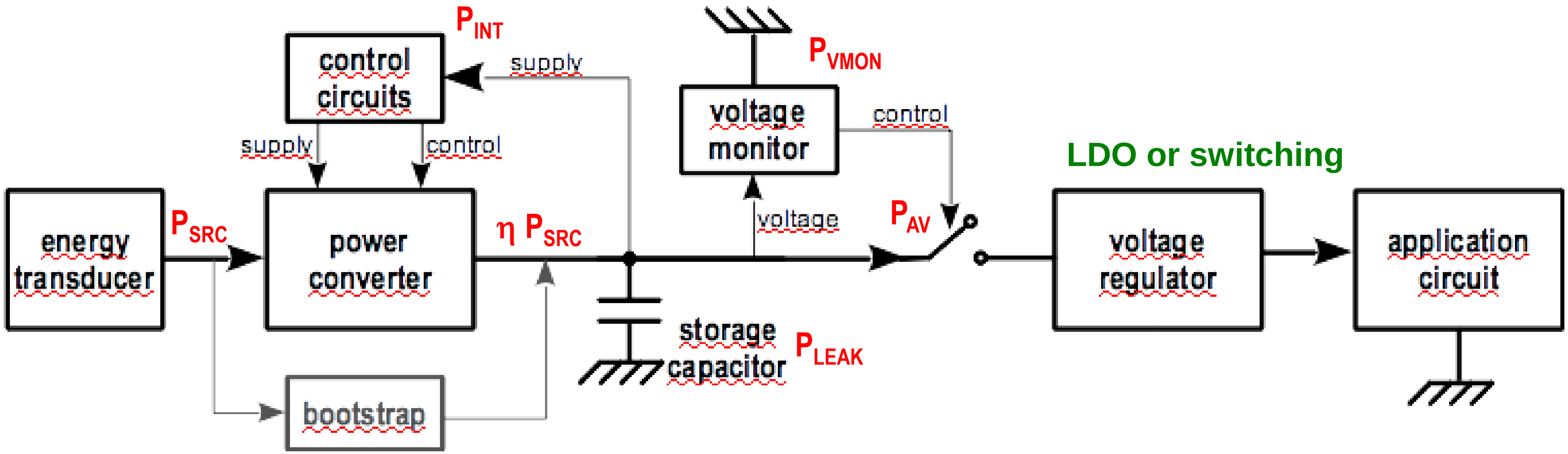




Techniques and design trade-offs for power management circuits

The importance of reducing intrinsic power

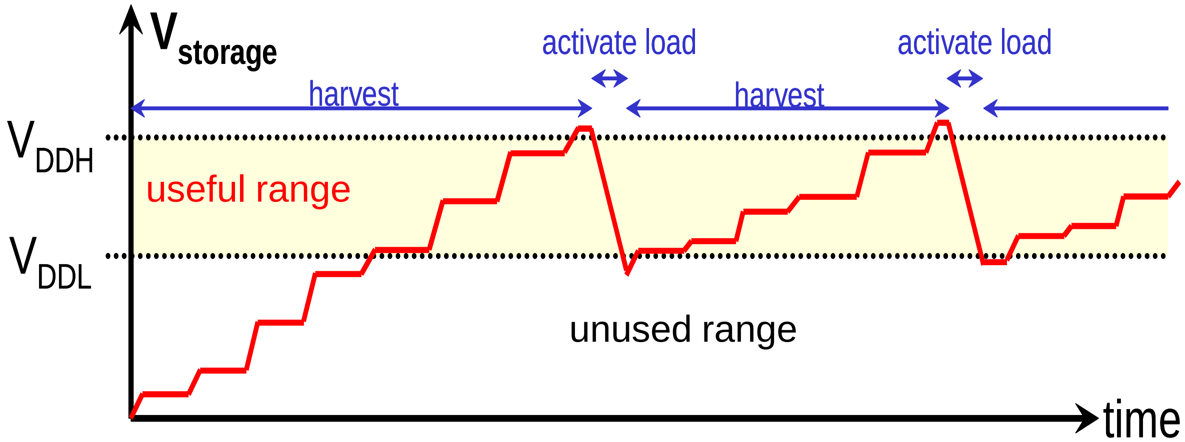
Battery-less Reference Architecture



- The power converter has efficiency η and draws $\mathbf{P_{SRC}}$ from the source
- The control circuits of the power converter steal an intrinsic power $\mathbf{P_{INT}}$ (static + dynamic)
- The storage capacitor has a leakage current: $\mathbf{P_{LEAK}}$
- The voltage monitor draws a power $\mathbf{P_{VMON}}$
- The power available for the load is: $\mathbf{P_{AV} = \eta\ P_{SRC} - P_{INT} - P_{LEAK} - P_{VMON}}$

P_{INT}, P_{SRC} and η are correlated → trade-off based on the maximum source power

Duty-cycled Operation



energy available for the load

$$\Delta E = \frac{1}{2} C_{STORE} (V_{DDH}^2 - V_{DDL}^2)$$

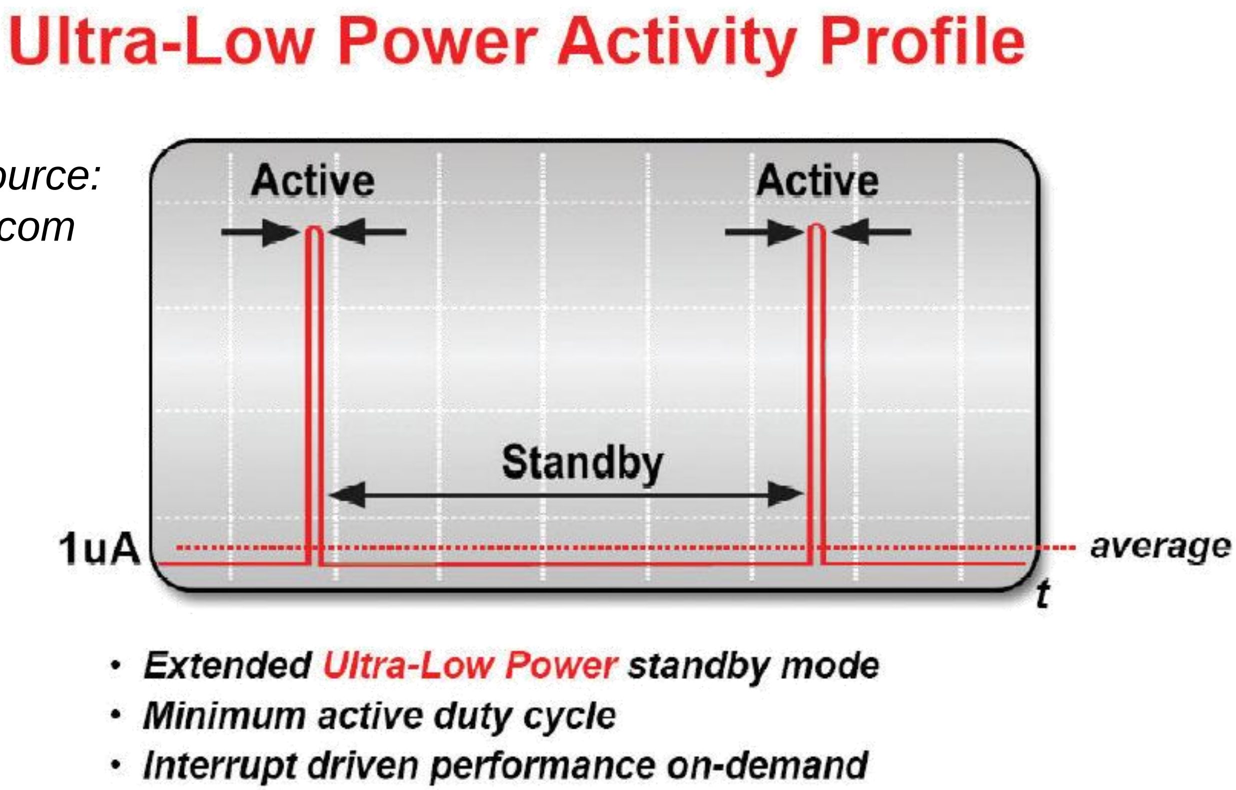
baseline energy

$$E_{BASE} = \frac{1}{2} C_{STORE} V_{DDL}^2$$

- When $P_{LOAD} > P_{AV}$ duty-cycled operation is necessary
- The linear or switching regulator that supplies the load requires a minimum voltage V_{DDL} for operating
- Given the energy ΔE required by the load per activation, the maximum voltage V_{DDH} depends on C_{STORE}
- Large C_{STORE} → large E_{BASE} → long wake-up time
- Small C_{STORE} → higher V_{DDH} → higher P_{LEAK} and P_{INT}, less efficient regulation
- **Trade-offs are generally required!**

Managing The Harvested Power

- **Typical energy harvesting applications:** when the power consumed by the application is higher than the harvested power, the duty-cycle of activation must be reduced



source: ti.com

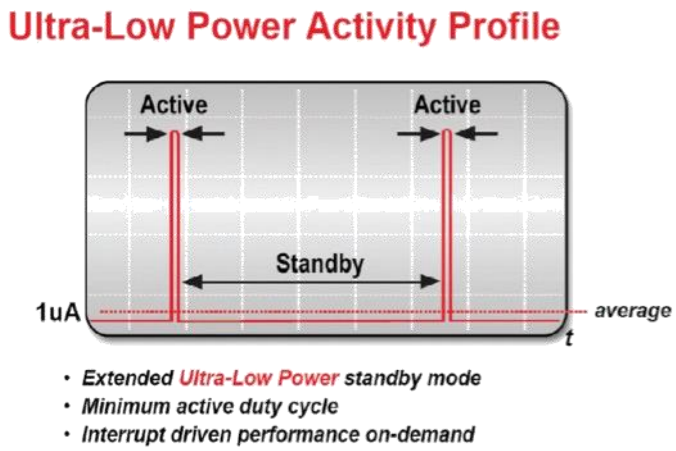
The average consumed power decreases with the duty-cycle…

…at least, until we reach the baseline consumption asymptotically!

Input power can be lower than this!

Baseline Consumptions

- As duty cycle → 0, the consumed power approaches the **'baseline' consumption,** i.e.:
  1. The stand-by/sleep power of the application circuits (e.g. CPU, radio, etc)
  2. If the load supply is cut off, the static current of the supervisor circuit (voltage monitor)
  3. In last instance, the intrinsic power of the power converter



- The **hard limit for any energy harvesting application is the intrinsic consumption of the power converter**.
  – the maximum source power must be necessarily higher in order to achieve a positive power budget (i.e. to progressively store energy)

NOTE: keep in mind that if you want high η and also P_{SRC} close to the MPP you'll generally have to spend higher P_{INT}, but in power-constrained scenarios the quantity to maximize is: $\mathbf{P_{AV} = \eta\, P_{SRC} - P_{INT}}$

Evolution & Trends in Power Management Circuits for Energy Harvesting Applications

Advantages of ICs

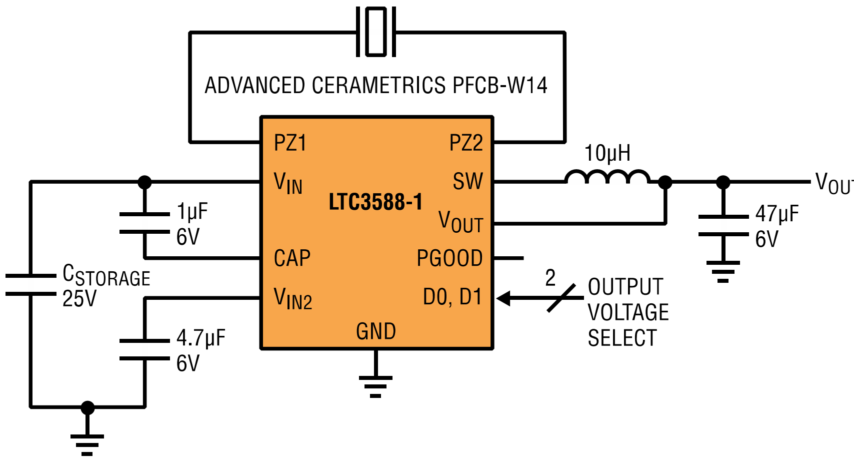
- **Why ASICs for energy harvesting?**
  - Very low parasitics and leakage currents → extremely low intrinsic power (at least 10x with respect to discrete components)
  - Possibility of fine tuning of all design parameters
  - Size is also reduced, but usually is not an issue (transducers, inductors and storage are usually larger)
- **What technology?**
  - No need for extreme integration: analog and power conversion circuits do not benefit significantly from high miniaturization
  - Older processes tend to handle higher voltages and have lower leakage currents

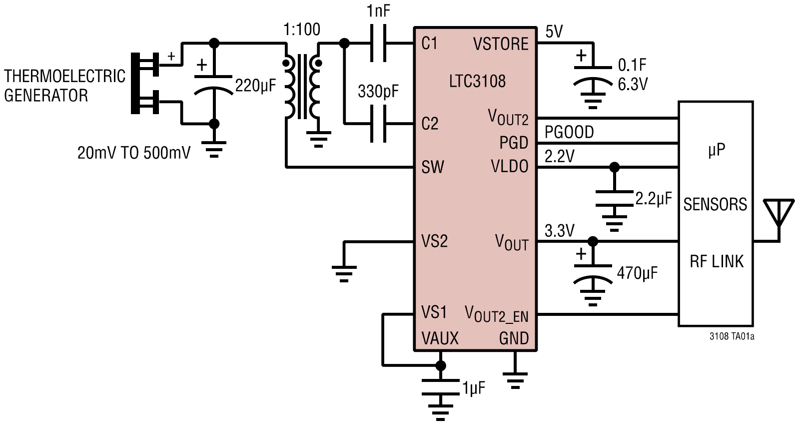
Commercial devices

- The “Energy harvesting” words have been often appearing in many datasheets in the last decade
- The first devices had still (relatively) high intrinsic consumption limiting the efficiency
- Most of them were basically implementing a DC/DC converter with an input rectifier for vibrational sources
- The next generation of devices implemented more specific MPPT techniques for squeezing more power out of the power source
- The latest generation target ultra-low intrinsic consumption and look forward towards 1 µW operations

Linear Technologies

- Among the first semiconductor companies with a dedicated class of products
- **LTC3588** (2010). Basically an hysteretic switching regulator from a 'large' input capacitor charged autonomously by the source.
  - Relatively high voltage thresholds
  - 2.7V min input voltage, ~85% efficiency, quiescent current up to 2.5 µA
  - No evident MPPT technique
- **LTC3108** (2009). An Armstrong-Meissner oscillator based on a transformer and a depletion-mode FET + an output rectifier + LDO
  - Min input voltage down to 20 mV with a 1:100 transformer
  - No MPPT
  - Relatively low efficiency
- …and many more!





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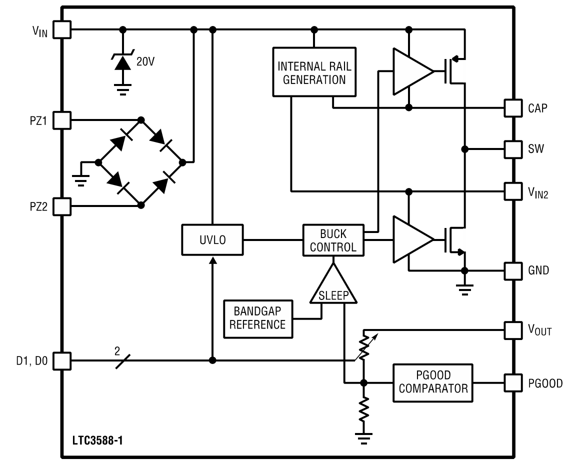
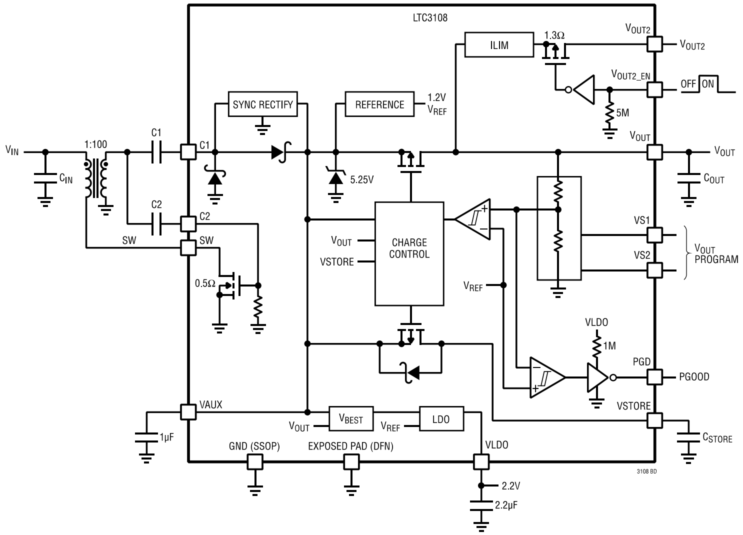


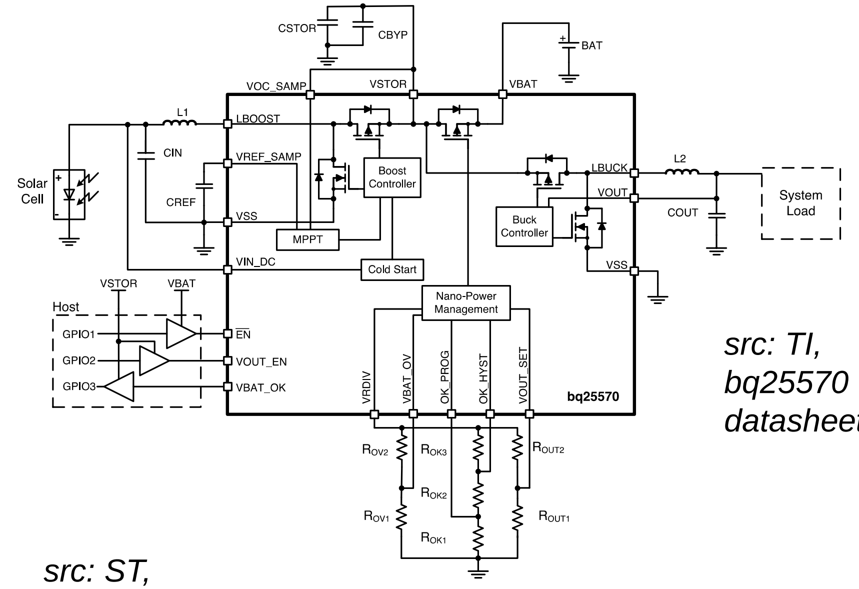


TI and STM

- The TI bq255xx and the ST SPV1050 implement a buck-boost topology with **FOCV MPPT** (16s refresh period)
  - Best trade-off for minimizing intrinsic consumption and for ULP sources
  - Low voltage ‘cold’ start-up is performed with internal charge pumps
  - The ICs are supplied from the storage device

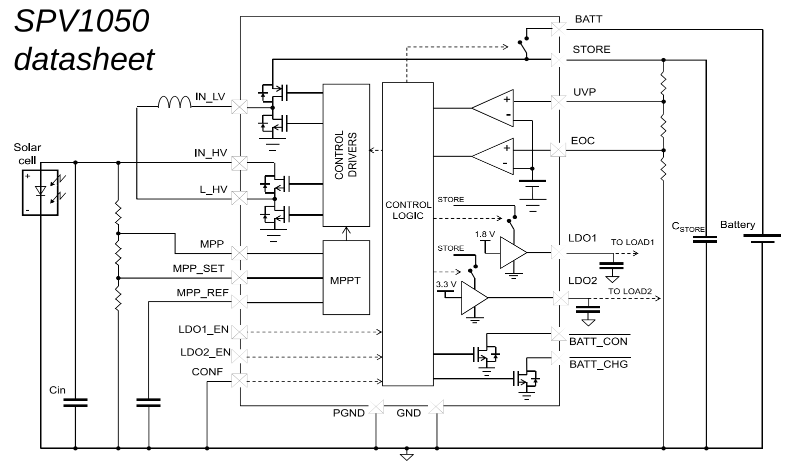
- **TI bq255xx**
  - cold start-up from 330mV and 15 µW
  - sustained from 100 mV and 5 µW
  - efficiency ~75%
  - OCV sampling: 400 ms every 16 s

- **ST SPV1050**
  - cold start-up from 550 mV
  - sustained from 75 mV and 2.5 µW
  - efficiency ~80%
  - OCV sampling: 256 ms every 16 s



src: TI, bq25570 datasheet

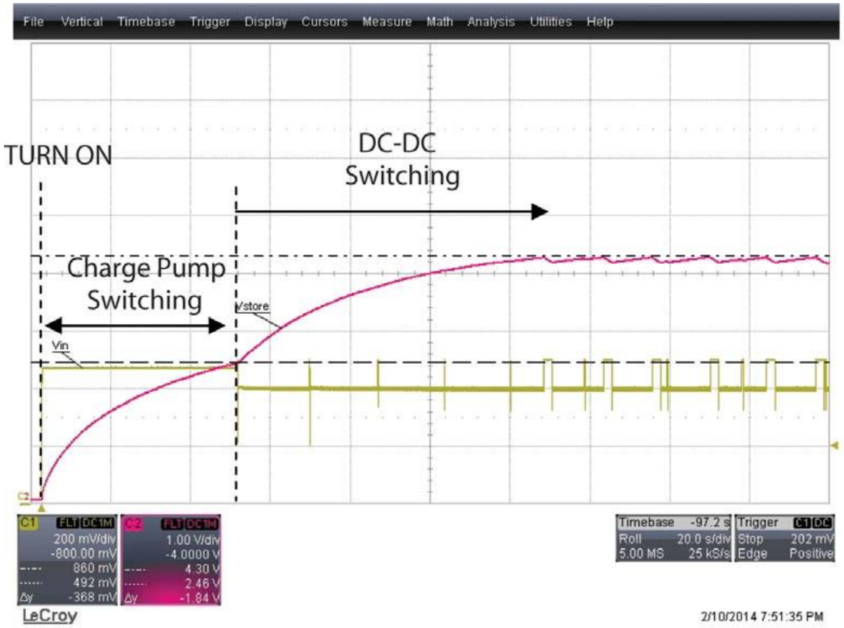
src: ST, SPV1050 datasheet



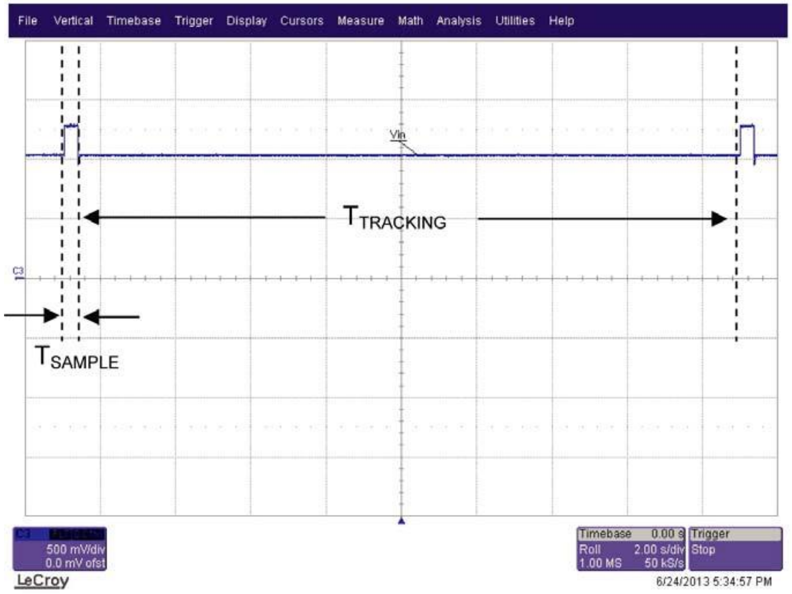
ST SPV1050

- Typical operation

source: SPV1050 datasheet



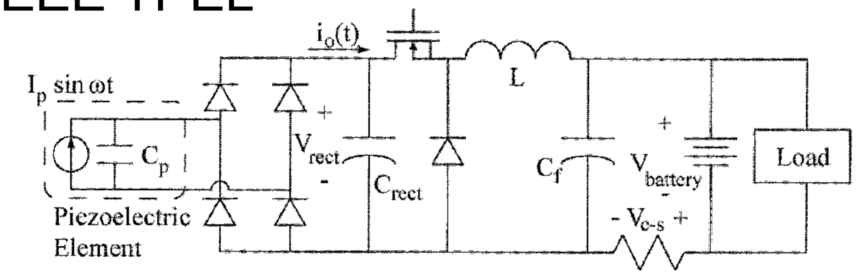
cold start-up

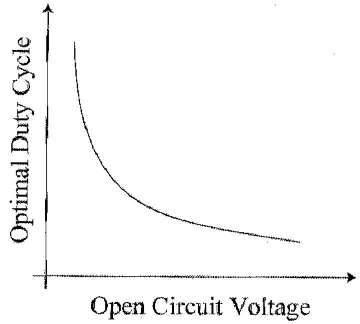


FOCV sampling

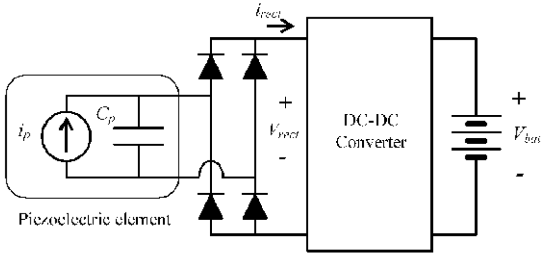
Meanwhile in scientific literature…

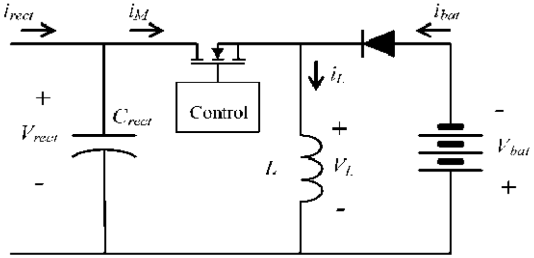
- **2003**.G. Ottman et al., Optimized Piezoelectric energy harvesting circuit using step-down converter in discontinuous conduction mode, IEEE TPEL





- **2007**. E. Lefeuvre et al., Buck-boost converter for sensorless power optimization of piezoelectric energy harvester, IEEE TPEL
  - 85% efficiency with P_{IN} 200 µW – 1.5 mW

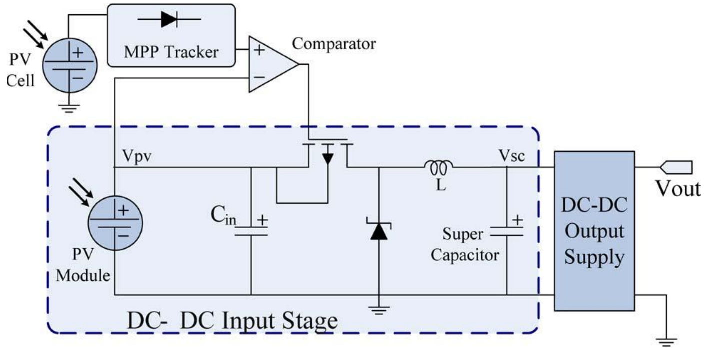




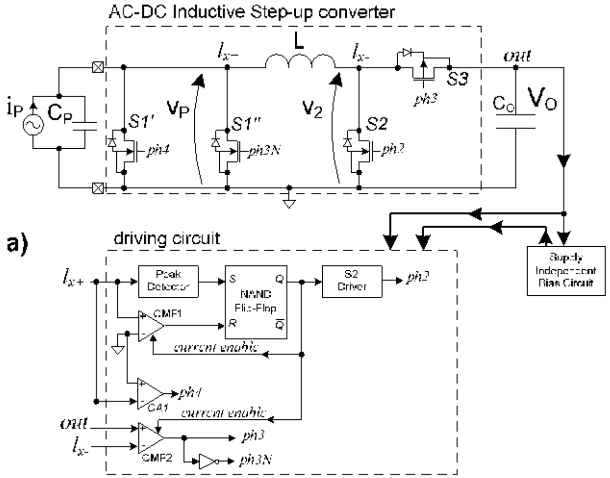
- Similar approach as first product (rectifier + DC/DC)

Meanwhile in scientific literature…

- **2008**. D. Dondi et al., Modeling and optimization of a solar energy harvester system for self-powered wireless sensor networks, IEEE TIE
  - Use of the FOCV MPPT technique
  - Based on a 'pilot' power source

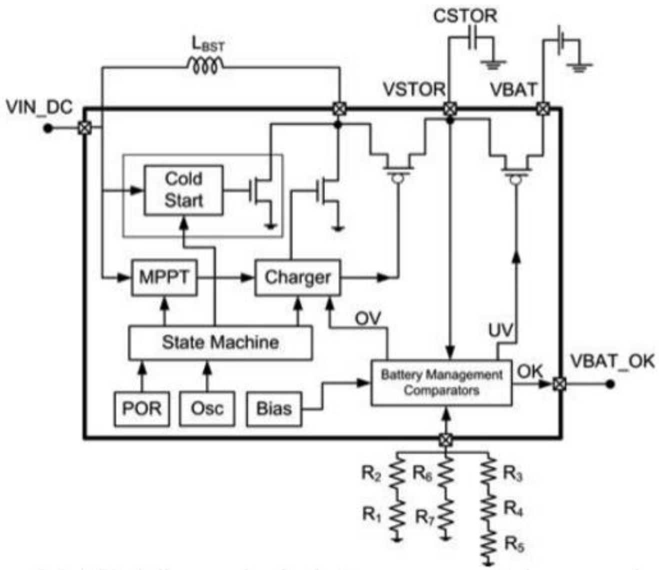


- **2009**. E. Dallago et al., Electronic interface for piezoelectric energy scavenging system
  - CMOS implementation of SECE
  - 700 nA quiescent current
  - 5V maximum voltage

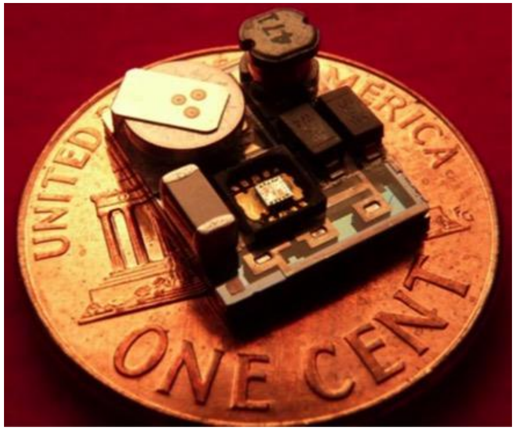


Meanwhile in scientific literature…

- **2012**. K. Kadirvel et al., *A 330 nA energy-harvesting charger with battery management for solar and thermoelectric energy harvesting*, IEEE ISSCC
  - Nanopower implementation of FOCV MPPT
  - 150 nA quiescent current
  - Minimum V_{IN}=330 mV and P_{IN}=5 µW.
  - efficiency >80% for V_{IN}=500 mV

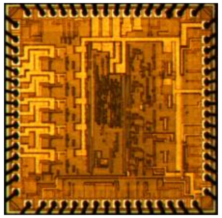


- **2014.** E. Aktakka, K. Najafi, *A micro inertial energy harvesting platform with self-supplied power management circuit for autonomous wireless sensor nodes*, IEEE JSSC
  - All components in a single package
  - SSHI on a miniature piezo source
  - 0.5 µW consumption in active mode, 10 pW in sleep-mode

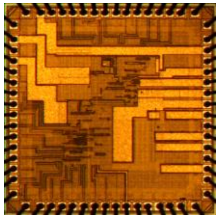


Meanwhile in scientific literature…

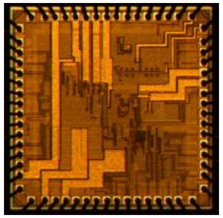
- **2013-2015.** M. Dini et al. (UNIBO), Developed a series of nanopower ASICs for DC, piezoelectric, and heterogeneous energy harvesting sources, IEEE TPEL, ESSCIRC, PRIME



0.32 µm STM technology
Multi-source (9 piezo&DC) with independent MPPT and shared L
I_{DDq} ≅ 360 nA (40 nA/source)
Efficiency up to 85%



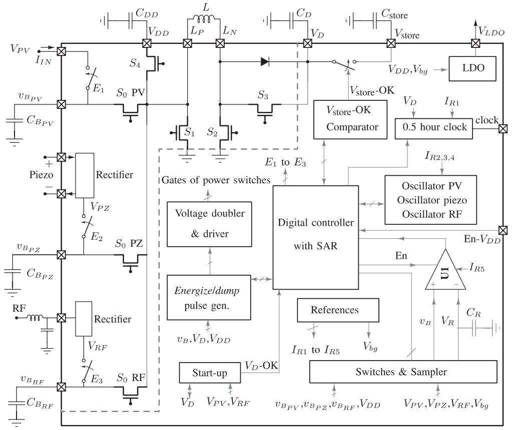
0.32 µm STM technology
Implements SECE-RCI
Separate IC/load supplies
P_{MIN} = 296 nW (@7 Hz, 0.5V_{PK})



0.32 µm STM technology
FOCV MPPT for DC srcs
Cold start-up @0.2V
Separate IC/load supplies
P_{MIN} ≅ 1 µW, I_{DDq} ≅ 300 nA

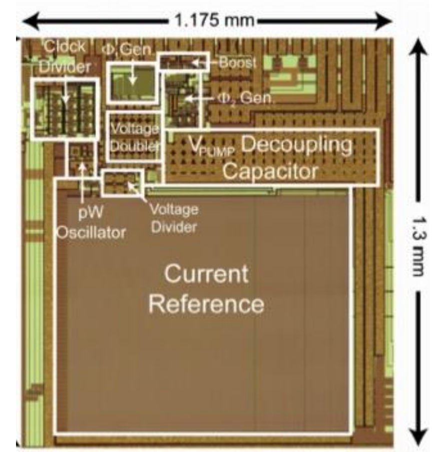
- **2015-2016**. A. Camarda et al. (UNIBO), developed an integrated ultra-low voltage bootstrap circuit (15 mV) based on a piezoelectric transformer

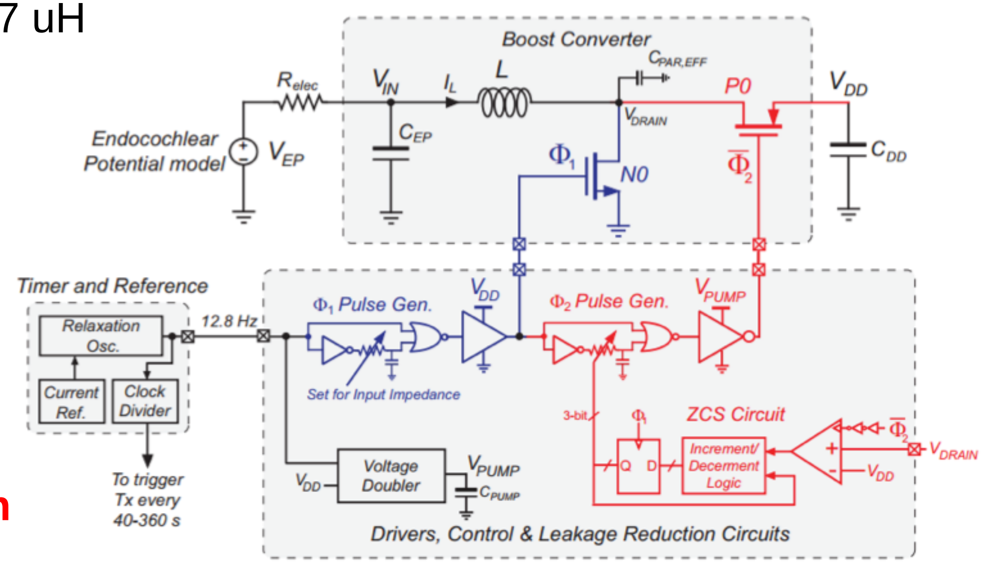
- **2016**. G. Chowdary et al., *An 18 nA, 87% efficient solar, vibration and RF energy-harvesting power management system with a single shared inductor,* IEEE JSSC
  - Multi-source IC with single shared inductor
  - P_{MIN} = 25 nW, I_{DDq} = 18 nA, 87% efficiency



State of the art of nano-power PMICs

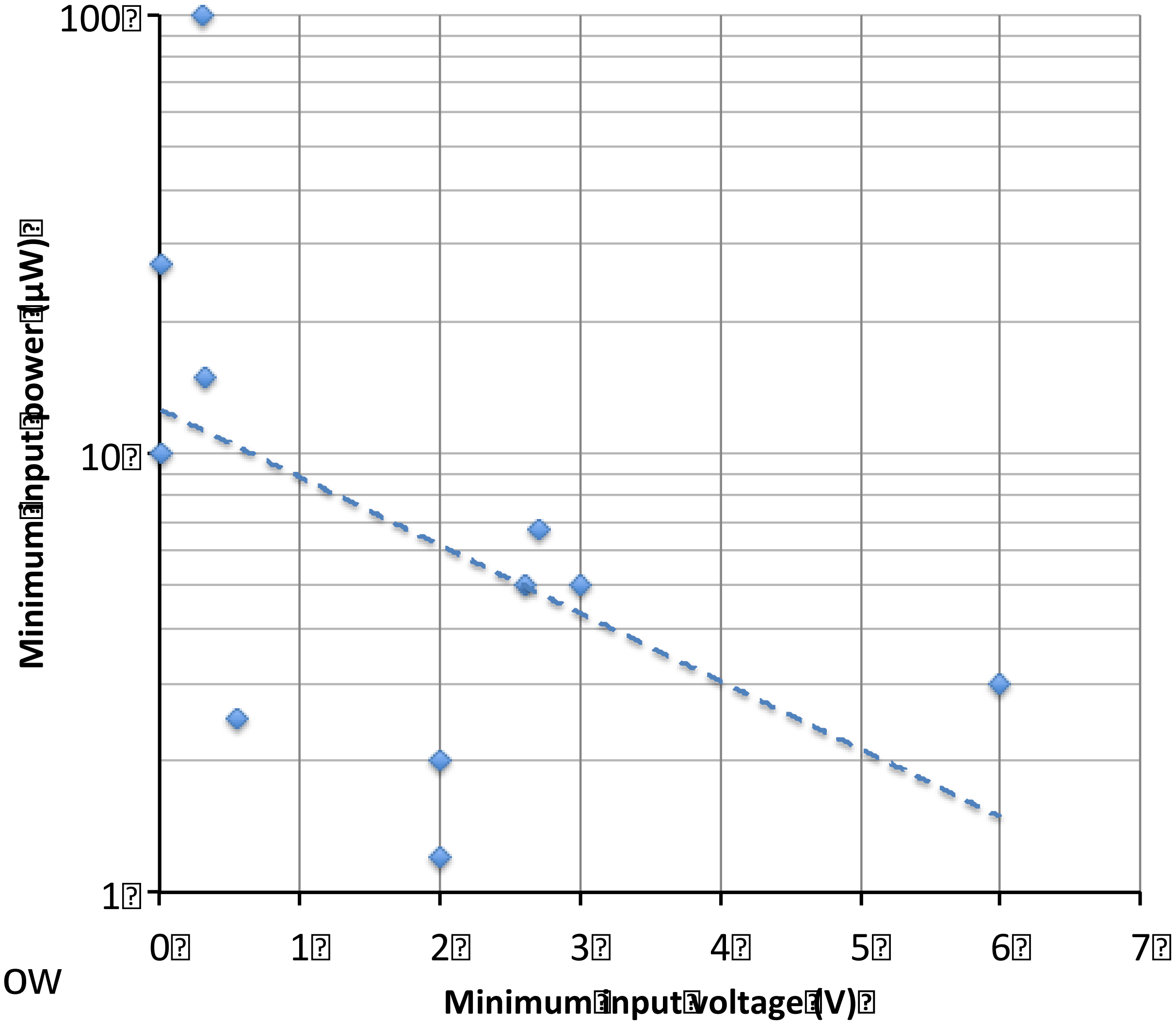
- S. Bandyopadhyay et al., *A 1.1 nW energy harvesting system with 544pW quiescent power for next-generation implants*, IEEE JSSC 2014
- **Features**
  - 70-100 mV input from endo-cochlear bio-potential inside ear
  - Efficiency > 53% @ V_{DD}=0.9V, L=47 uH
  - Boost converter topology with 12 Hz switching frequency
  - Trade-off between switching frequency, FET sizes and power losses carefully investigated
  - 0.18 µm CMOS
  - Cannot self-start
  - **The lowest intrinsic consumption reported up to now**





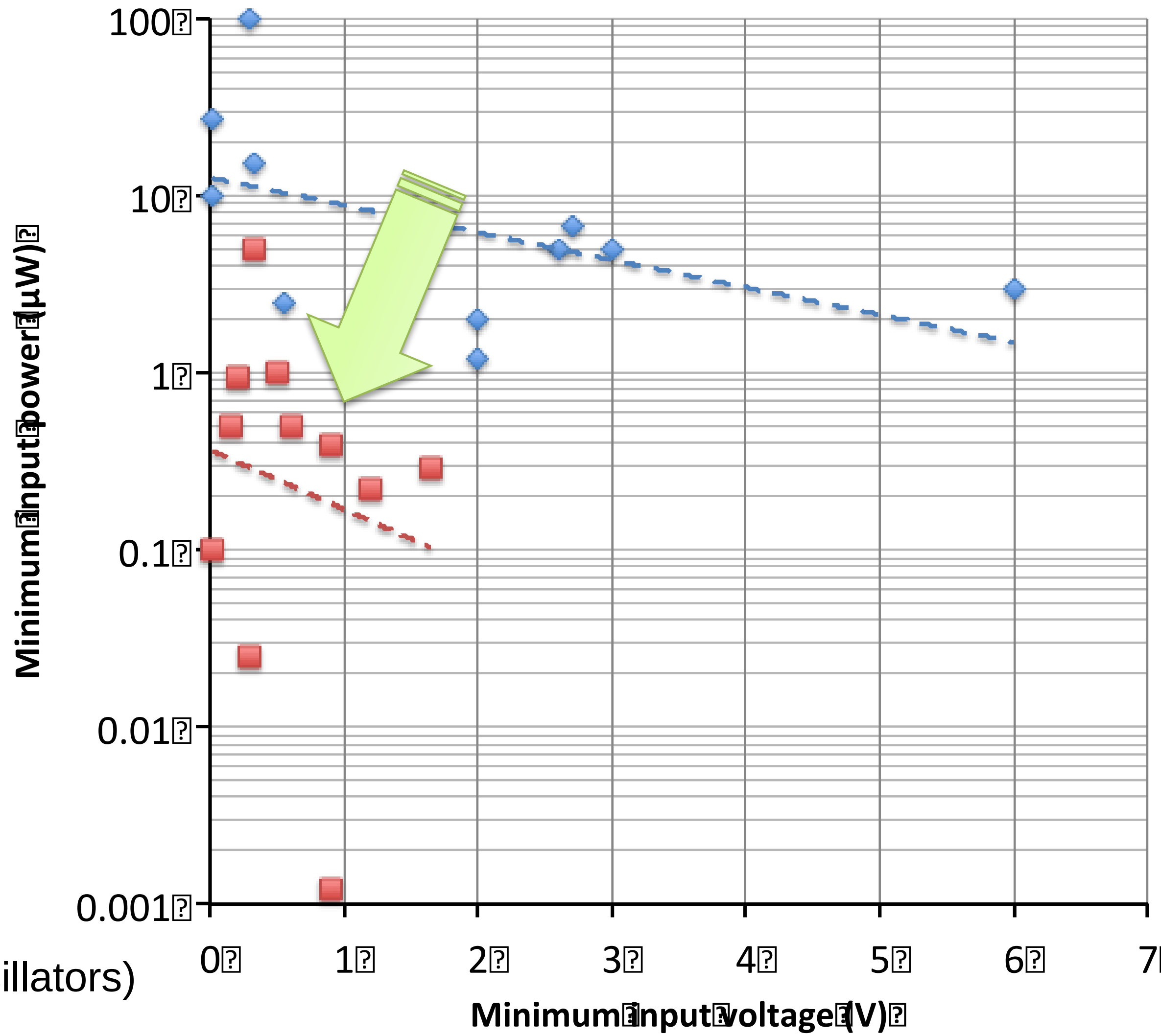
Trends: Commercial PMICs

- Two parameters analyzed: minimum start-up voltage and minimum input power
- Most effective products target today few µW and few hundreds mV power sources
- However, many enviromental sources often provide less than that in their worst case
- No synchronized switch harvesters for piezo sources available up to now



Trends: Industry and Research

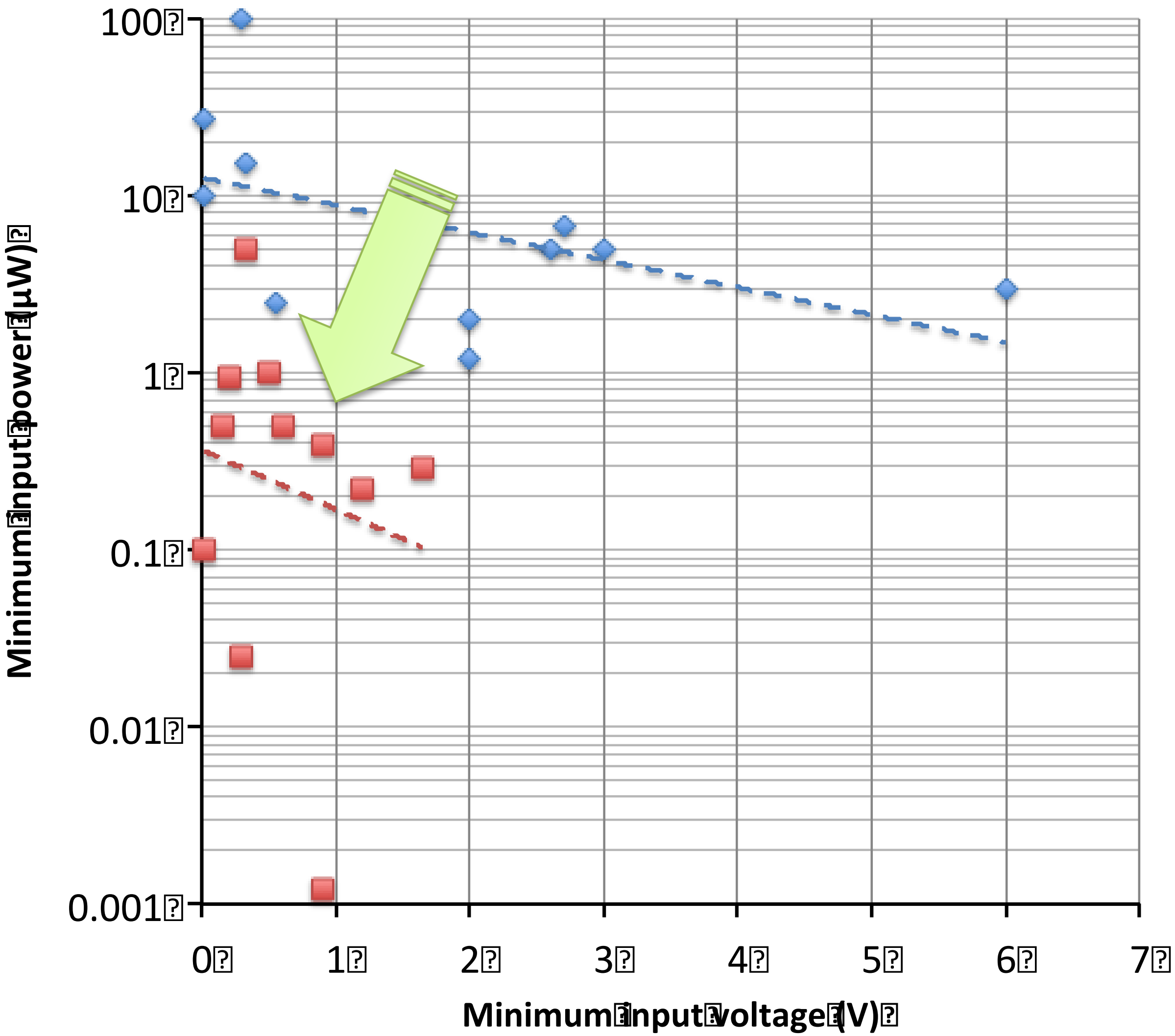
- Commercial PMICs stay on the 'safe' side
  - reliability
  - higher output current required by external circuits
- Research is keeping on pushing the limits towards lower power and voltages
  - Very good trade-offs on power can be found
  - Voltage is practically limited by $V_{GS,TH}$ (sub-100mV typically achieved by step-up oscillators)



Trends: Industry and Research

- **Sub-μW operation** is likely to be achieved in commercial PMICs in the near future as market demands more power efficient components (MCUs, radios, analog front-end for sensors, etc.)

- **Ultra-low voltage circuits** are expected to stay in a niche (lower efficiency and higher min. power), with a envisaged use for battery-less circuit start-up from fully discharged states



Conclusions

Conclusions

- **Energy harvesting** is an exciting research field experiencing continuous advancements
- The **micropower barrier was broken** in research. Many commercial power management ICs are becoming available. Careful designs can yield to very interesting results
- **Energy-aware and design techniques** for operation in **power-constrained scenarios** are progressively being applied to CPUs, sensors, radios, etc. This is necessary to go further.

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- Cypress, MB39C811 datahseet
- Maxim, MAX17710 datashet

Thanks for your attention

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