An introduction to micro-power management for energy harvesting applications

Aldo ROMANI

Department of Electrical, Electronic, and Information Engineering “Guglielmo Marconi”

Advanced Research Center on Electronic Systems “E. De Castro”

Campus of Cesena, University of Bologna

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA
CAMPUS DI CESENA

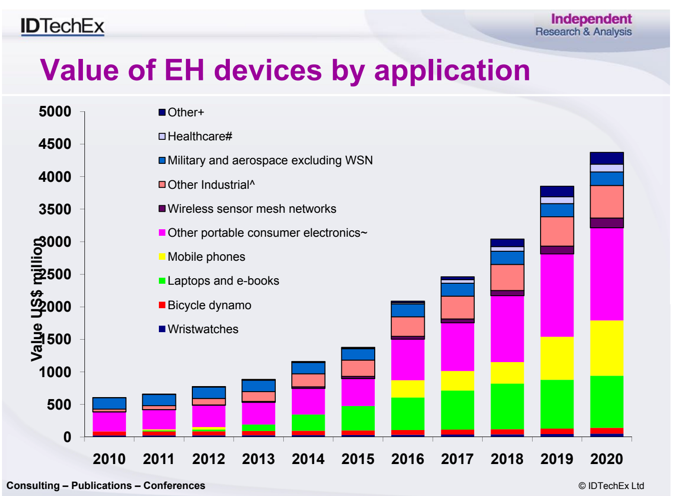
Outline

- Introduction to energy harvesting
- Types of energy transducers
- Techniques and design trade-offs in power management circuits
  - Maximizing harvested power: DC sources, Piezo sources, Multi-source configurations, Ultra-low Voltage Sources
  - Reducing the intrinsic Power
- Evolution and trends in power management circuits

Introduction to energy harvesting

Market Trends

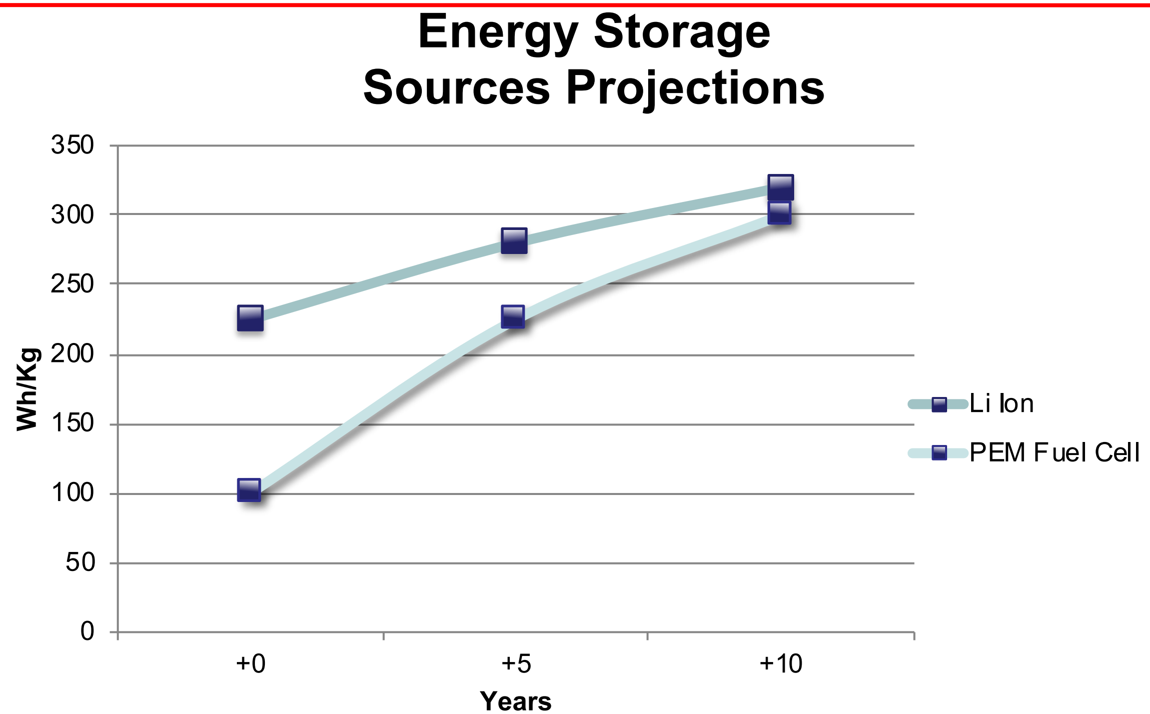
- The energy harvesting market is **growing slower than predicted**
  - Power from miniature source is actually very low, in the order of μW
  - Batteries are still cheaper than energy transducers
  - Applications and circuits (sensors, RF transceivers, power converters, etc.) are conceived for operating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



IDTechEx, Energy Harvesting Europe 2010

EETimes, 2016

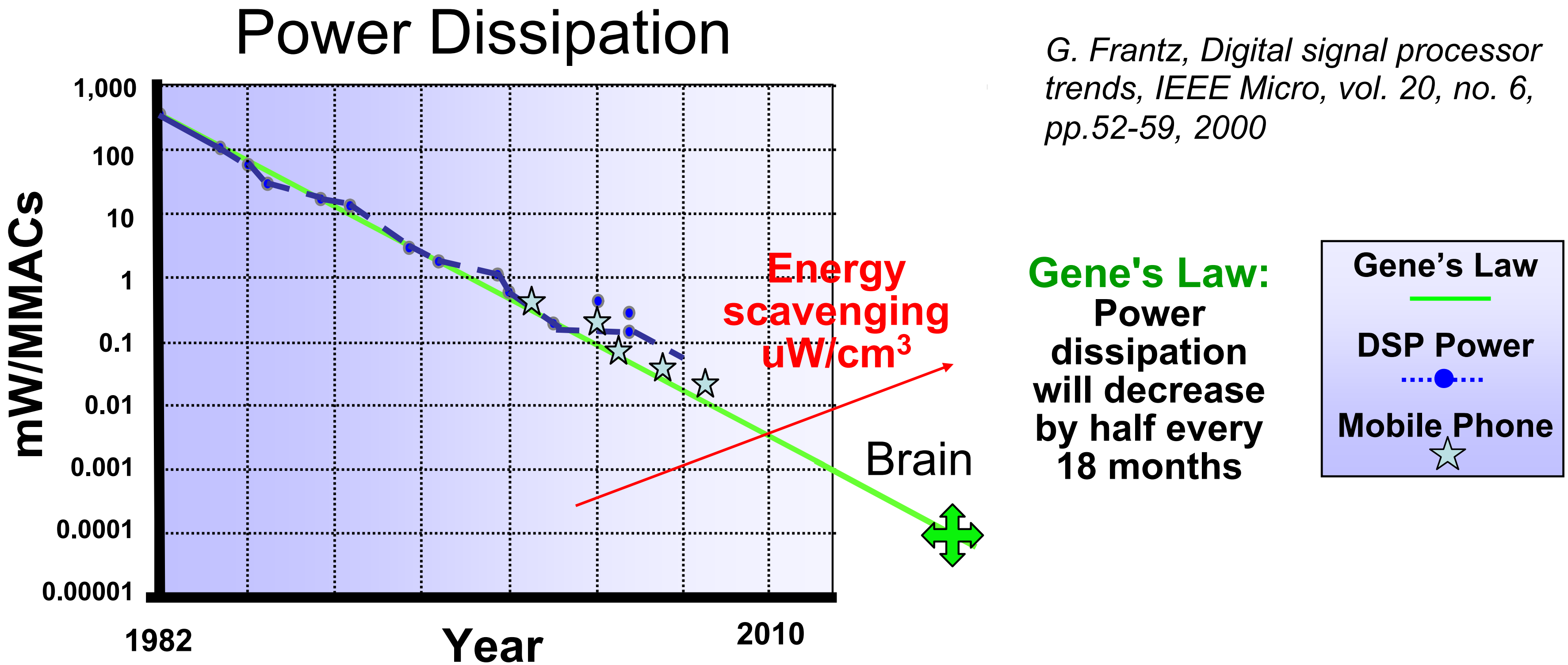
The Bad



- 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)

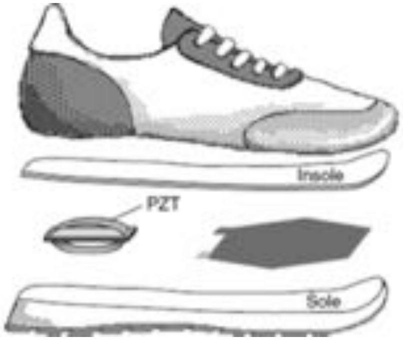
Energy harvesting: what applications?

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’

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

Energy harvesting: what applications?

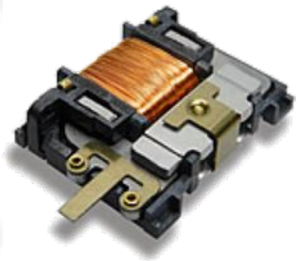
- Industrial machinery
- ‘Smart’ rotating parts
  - Reliability / monitoring
  - Improved control
- Inaccessible sensor nodes

Review of main energy transducer types

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

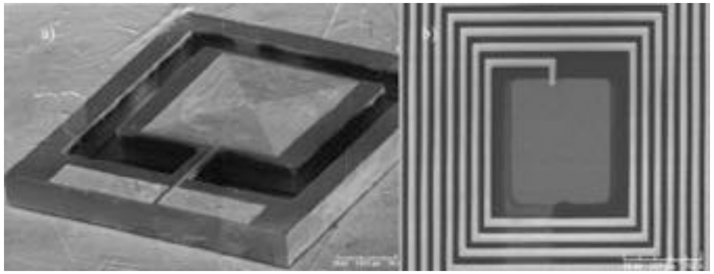


[1] Perpetuum Ltd., http://www.perpetuum.com

[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



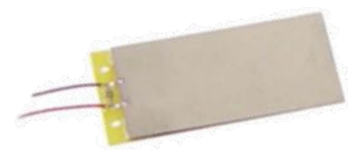
Piezoelectric transducers

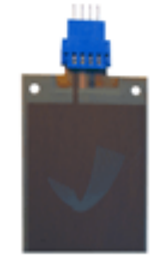
- Common materials:
  - **PZT** (Lead Zirconate Titanate) is a ceramic material with a high coupling coefficient *k*. The material is rigid, fragile, and contains lead.
  - **PVDF** (Polyvinylidene fluorid) is a polymeric material with a lower k. It's non-toxic, bendable and can resist high shocks or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





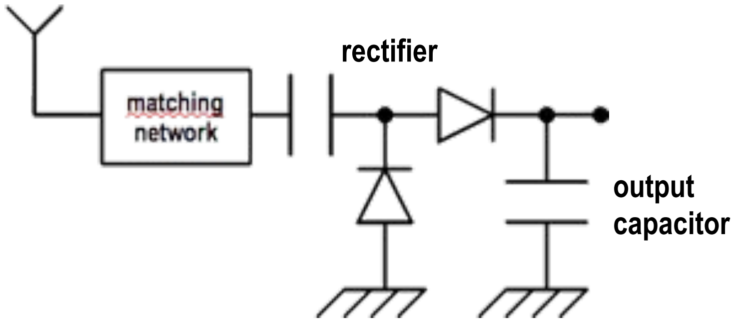
MIDE

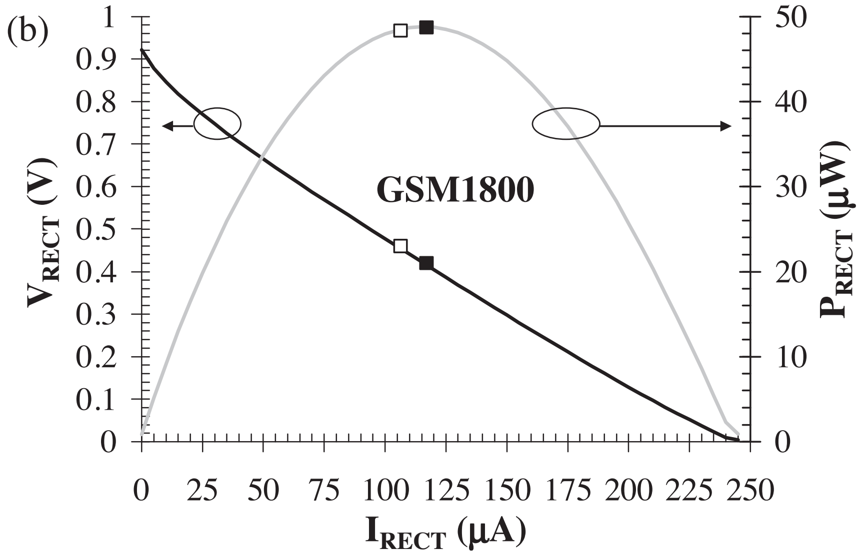
MEAS-SPEC

MEAS-SPEC (PVDF)

RF Energy Harvesting

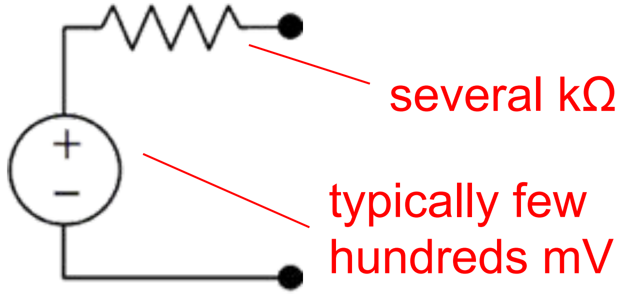
- RF carriers can be rectified in order to store locally energy
  – **Rectenna** = rectifying antenna
  – Matching network must be designed according to the expected input power





V-I and P-I transfer characteristics

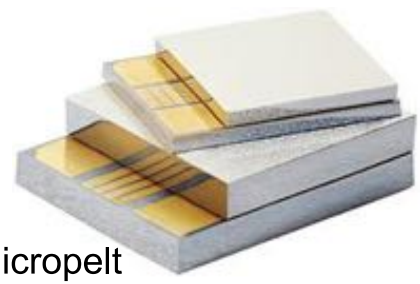
- Simplified representation:



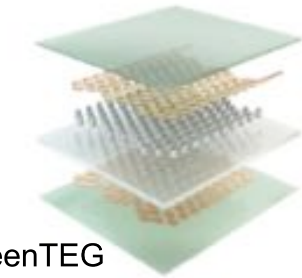
Micro-Thermoelectric Generators

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

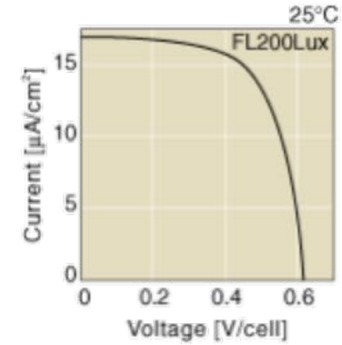
Nextreme

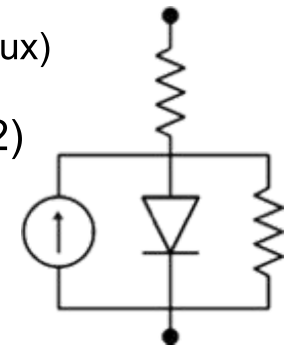
Manufacturer - Product	Size [mm]	V_{OUT} [V] (matched load)	P_{MAX} [W] (matched load)	Power density [W/cm³/K]	Process
Eu. Thermodynamics - GM200-449-10-12	WxL=54x57 H=3.8	11.4 @ ΔT=170K	14.6 @ ΔT=170K	7.34e-3	Standard
Eu. Thermodynamics - GM200-127-10-15	WxL=30x30 H=3.7	4.14 @ ΔT=170K	2.72 @ ΔT=170K	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

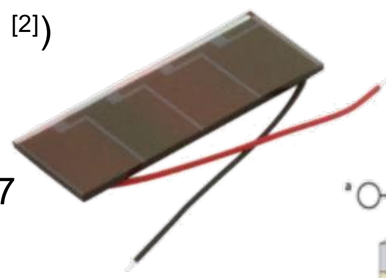
Miniature commercial devices and emerging technologies

- 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])

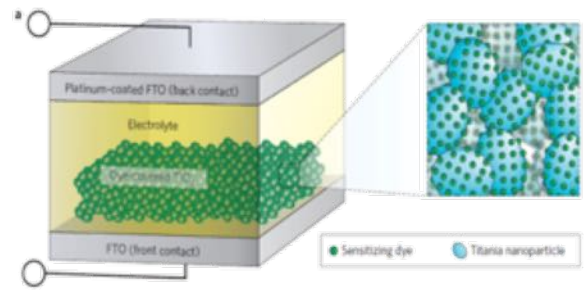


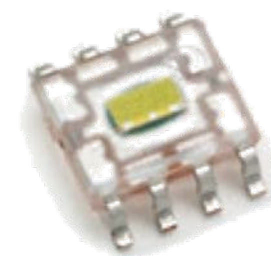


equivalent circuit



Sanyo AM1407





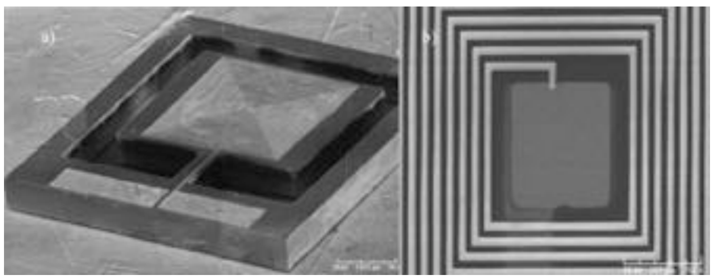
CPC1822

[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
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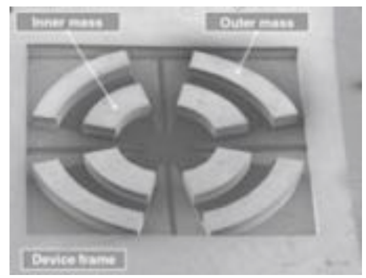
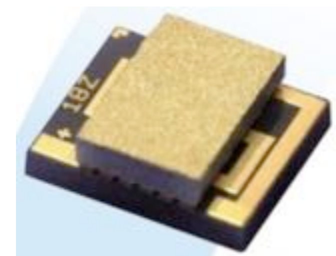
electrodeposited copper coil
S. Kulkarni et al., Sensors and Actuators A, vol. 145, 2008
(Tyndall Institute, Univ. Southampton)

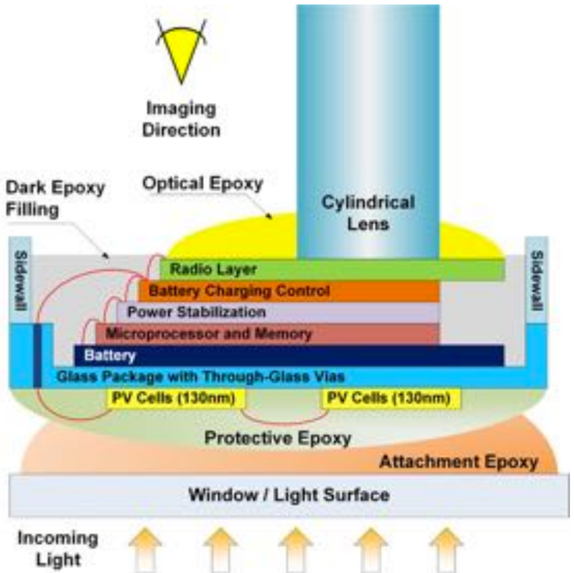


Piezoelectric
200 nW @0.5g @400 Hz
16 mm^2, deposited AlN
J. Iannacci et al., Microsystem Technologies, vol. 20, 2014
(FBK, Delft Univ. Tech, Munich Univ. Tech.)

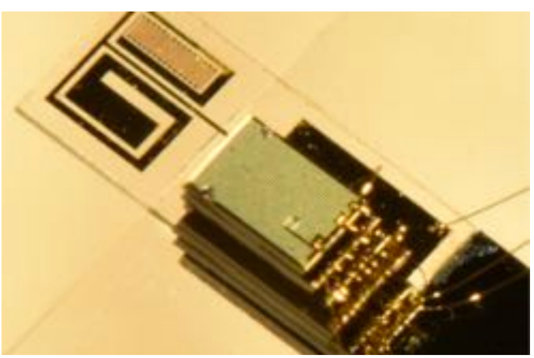


Thermoelectric
6-20 mV/K, 2-10 Ω
3-9 mm^2, 8-16 uW @1K
thin film semiconductor, thermally conductive AlN ceramics
Laird Technologies eTEG

Nano-Power Micro-Motes

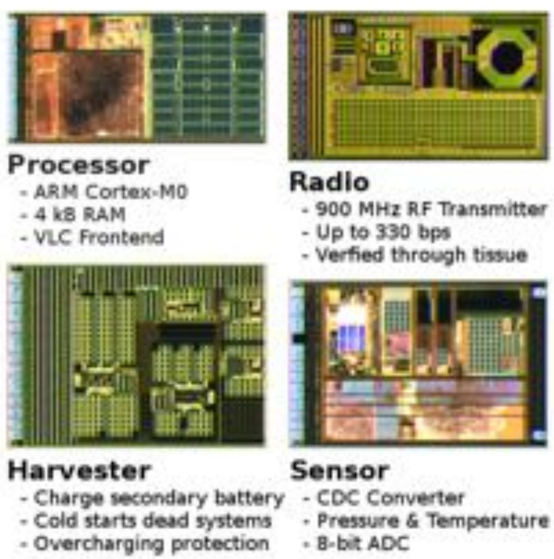


University of Michigan
Micro-Motes M^3



CubeWorks micro-sensing nodes

Imaging Cube | Temperature Cube | Pressure Cube



Redefining Ultra-Low Power. Enabling perpetual computing.

CubeWorks' sensing systems average a record-setting **8 nW** power draw in standby mode. Under indoor ambient light, our patented energy harvester generates 10 nW from 1 mm^2 solar cell, facilitating perpetual lifetime of sensor operation.

http://cubeworks.us/

https://www.eecs.umich.edu/eecs/about/articles/2015/Worlds-Smallest-Computer-Michigan-Micro-Mote.html

Current and Future Power Sources

1W
100 mW
10 mW
1 mW
100 µW
10 µW
1 µW
100 nW
10 nW
1 nW

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

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

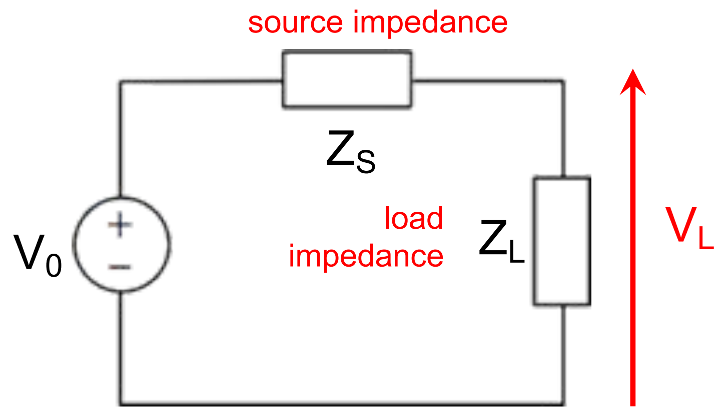
MEMS devices, CMOS on-chip photodiodes, microfabricated thermoelectrics (mm-sized devices) (near future)

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

Techniques and design trade-offs for power management circuits

Maximizing the harvested power

Maximum Power Transfer

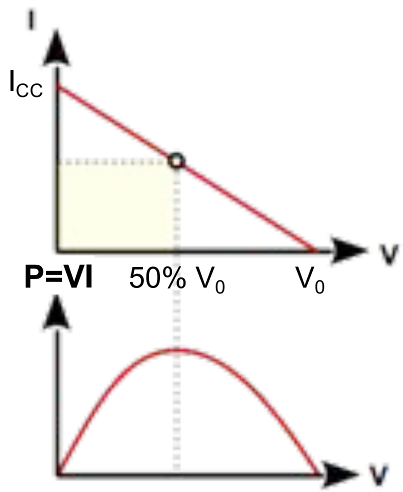


- The theorem of maximum power transfer states that the power transferred to a load is maximized when $Z_L = Z_S^*$
  - where $Z_S = R_S + jX_S$ is the source impedance and $Z_L = R_L + jX_L$ is the load impedance
- For a linear source:
  - $V_L = V_0 / 2$
  - $P_L = V_L^2 / R_L = V_0^2 / 4R_L$

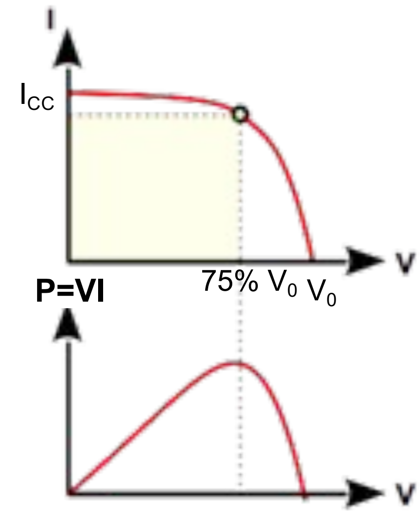
Power Transfer Characteristics

- **The static 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, $V=R_L I$
  - NOTE: reactive components are not accounted for, these are DC transfer characteristics
- 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

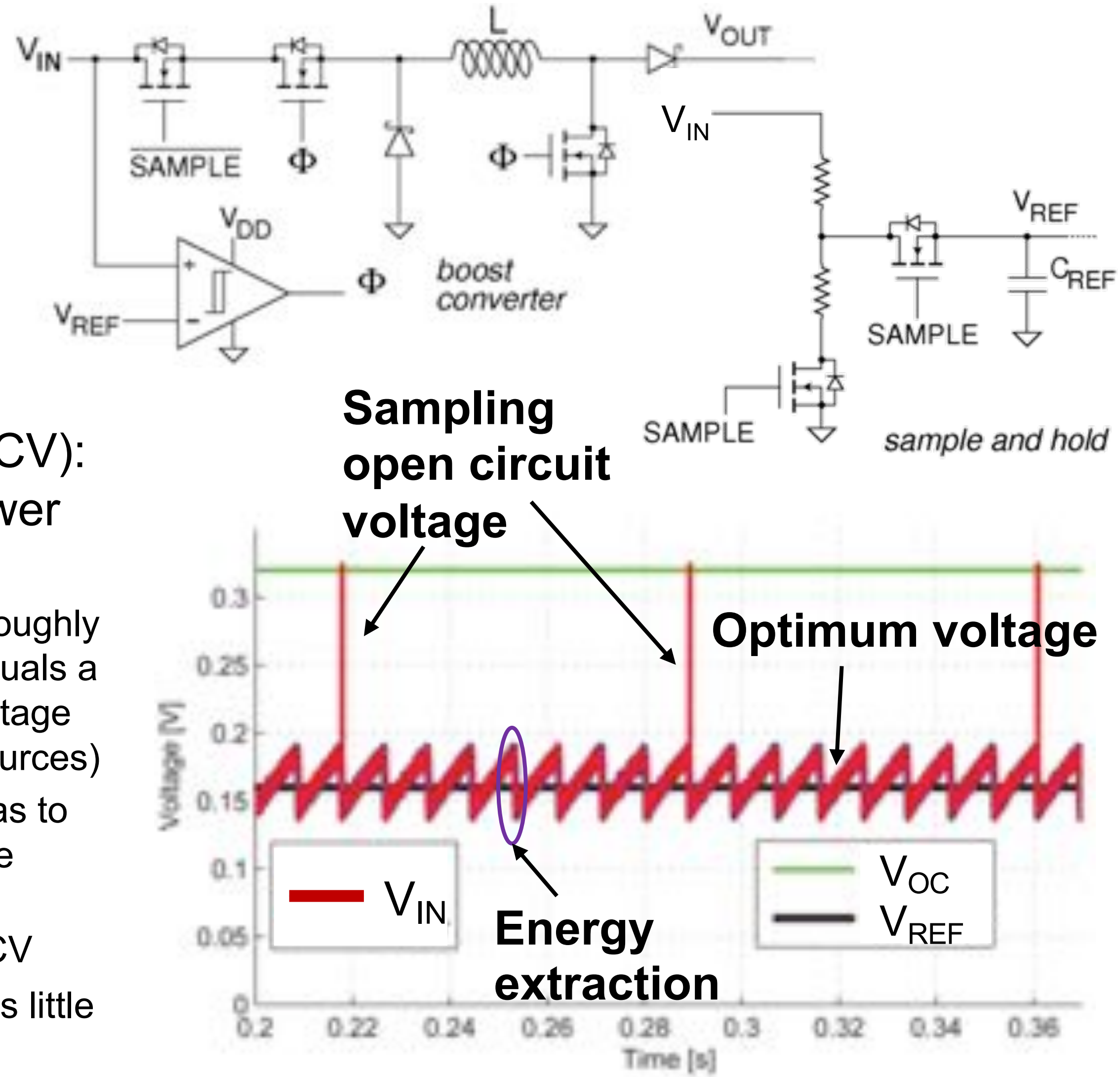


- In order to extract all the available power, a power converter should draw from the source a current that keeps its output voltage in proximity of the MPP
- I-V curves are also useful to estimate other features of the source (e.g. rise time, etc.)

FOCV MPPT for DC sources

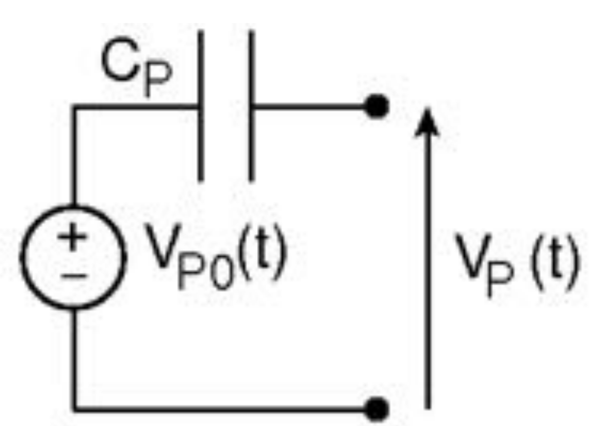
- P_{OUT} depends on both the source condition and on the output current, and…
- …yes, there is a maximum! (MPP).

- **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

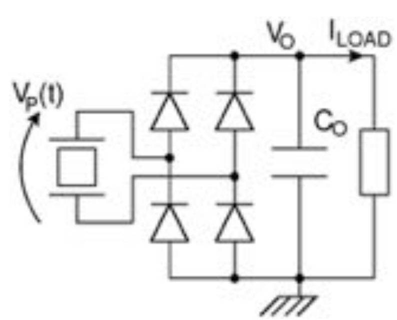


Piezoelectric Sources

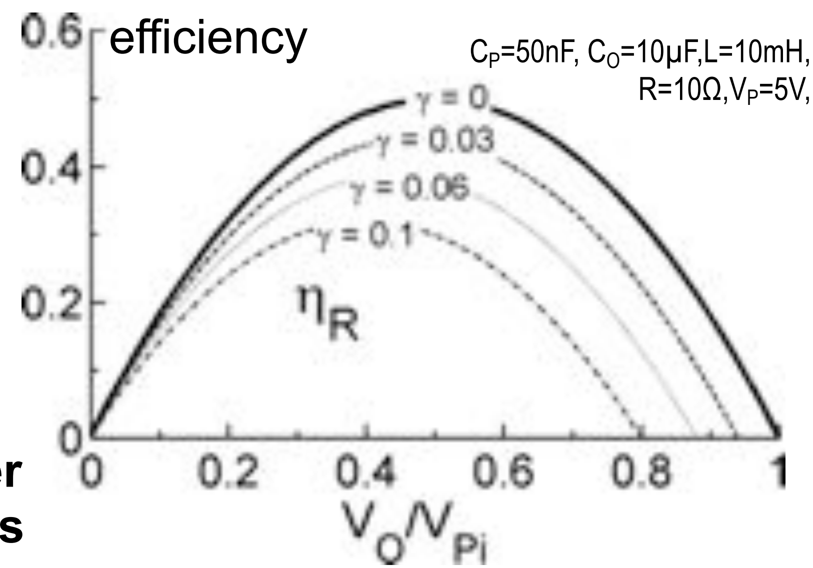
- Let us now consider the simplified equivalent circuit of a piezoelectric transducer
- If we apply the matched load (i.e., an unrealistically big L), power would seem to become infinite (ideal voltage source)!
  - **NOTE**: some parameters were neglected (series resistance, electromechanical parameters, etc.). However, much higher power might still be available than with a purely resistive load.
- A rectifier is the simplest circuit for extracting power, but
  - has limited and variable efficiency that depends on the state of the output and of input vibration
  - Does not perform any cancellation of the capacitive reactance of the source



simplified equivalent circuit

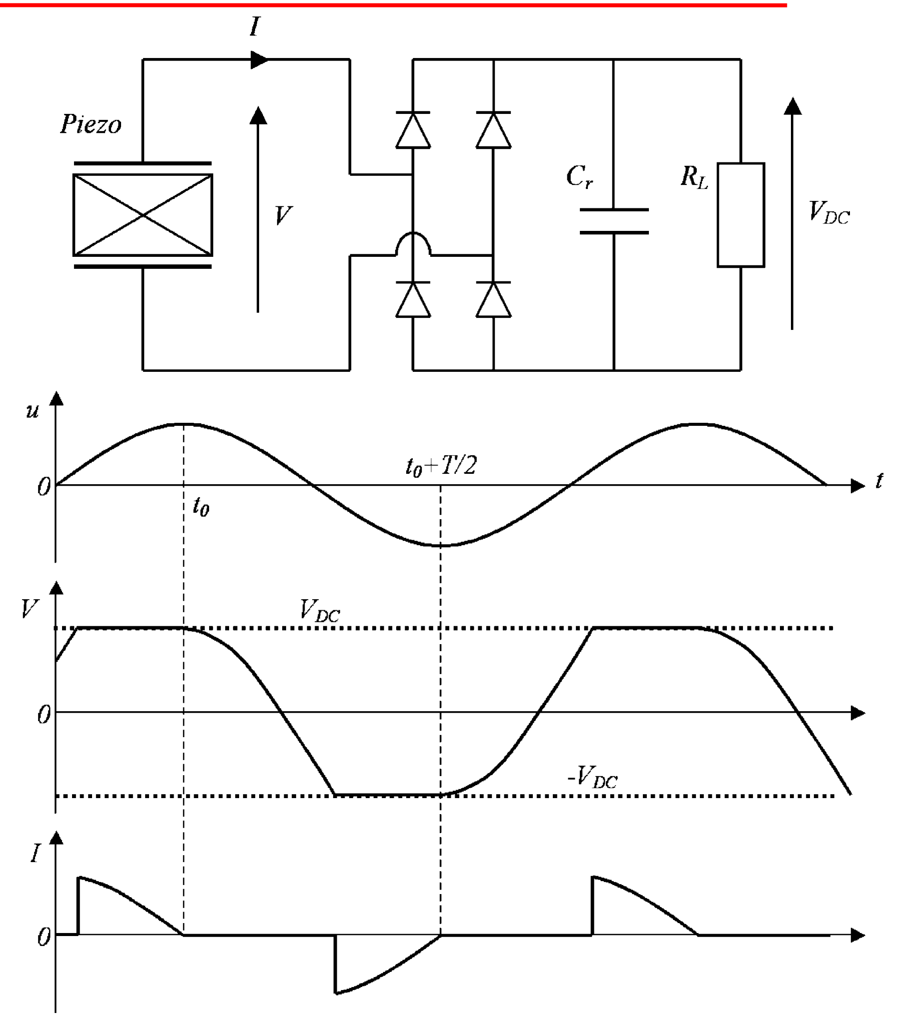


power transfer characteristics



Rectifiers

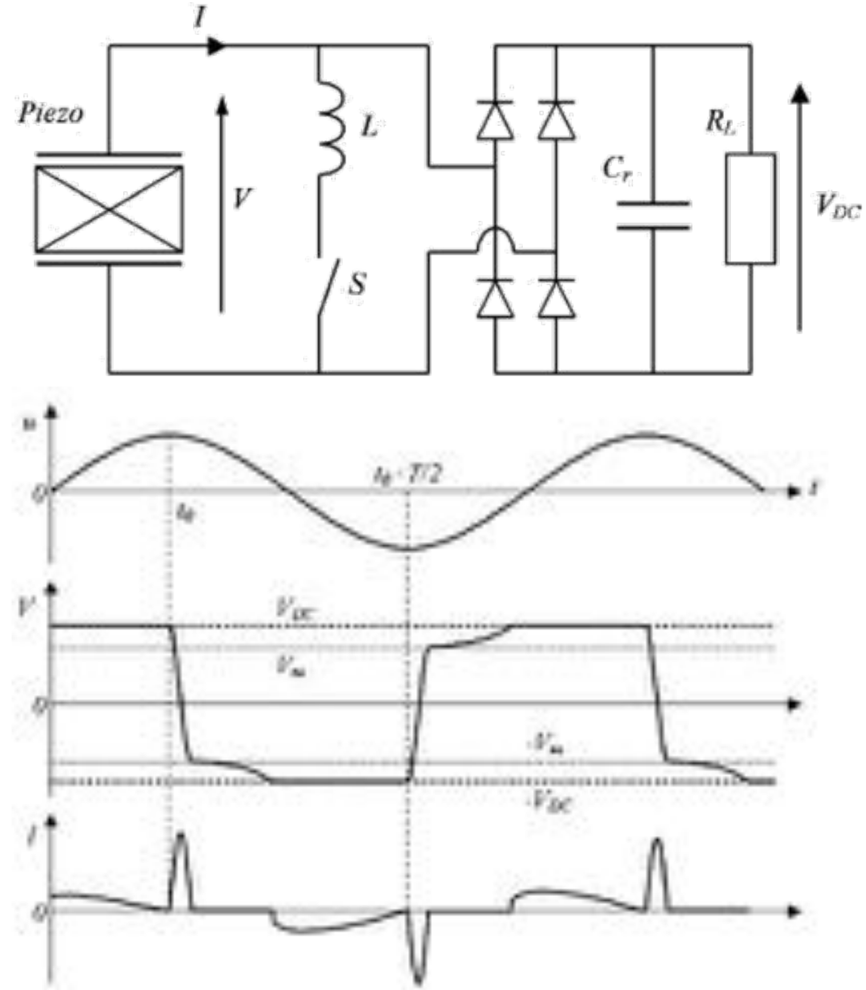
- With a **rectifier** the input voltage amplitude V(t) in every period gets clamped to the current value V_{DC} of the output node ($C_r >> C_P$)
- The rectifier stops conducting in correspondence of elongation peaks (i.e. when the piezoelectric current changes its sign)
- As V_{DC} gets progressively charged, the conduction angle decreases → less power is harvested per cycle
- Usually, the voltage drop through the rectifier is relevant



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

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 (i.e. when the rectifier stops conducting)
  - The switch is turned off after a half electrical period, resulting in a quasi-instantaneous inversion of V.
- The rectifier is conducting most of the time!
- **Many variations have been presented in literature**



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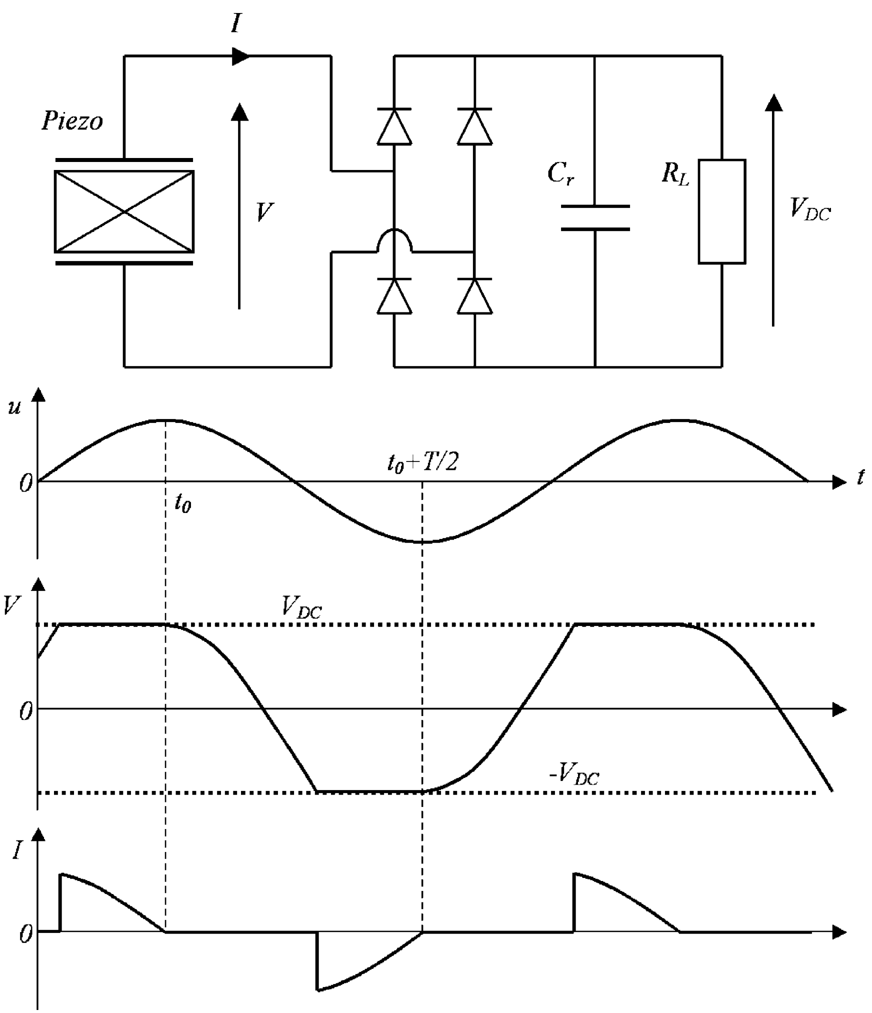
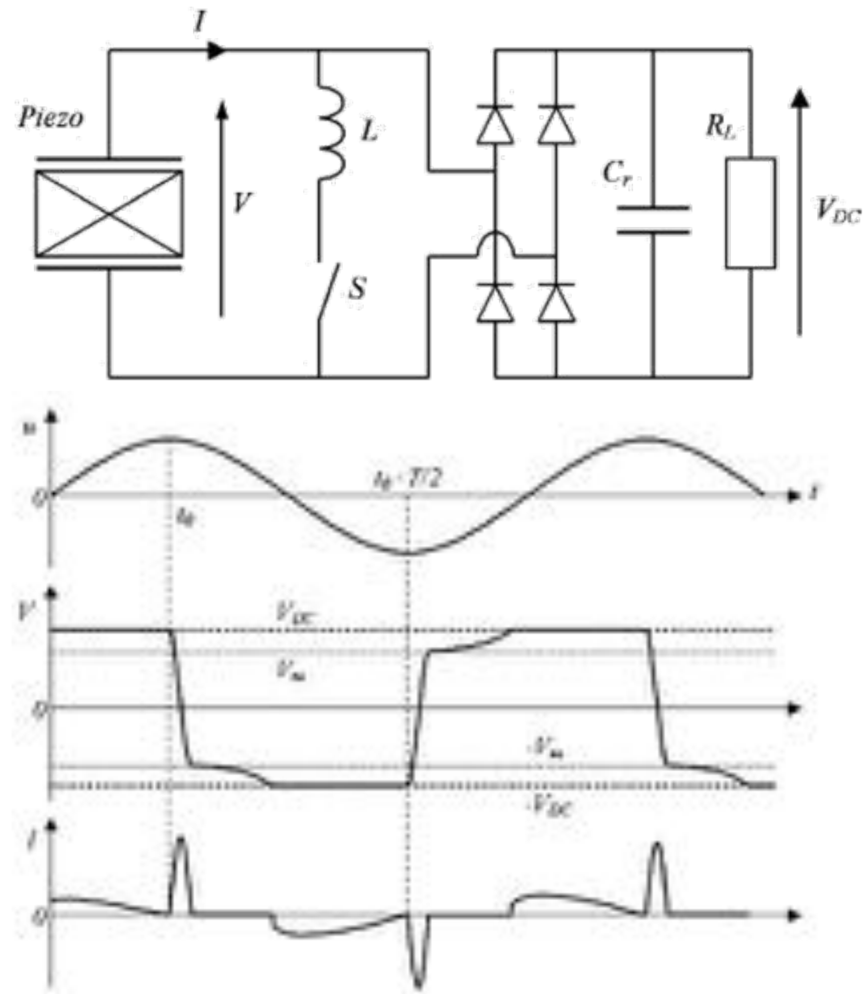
Synchronized Switch Interfaces





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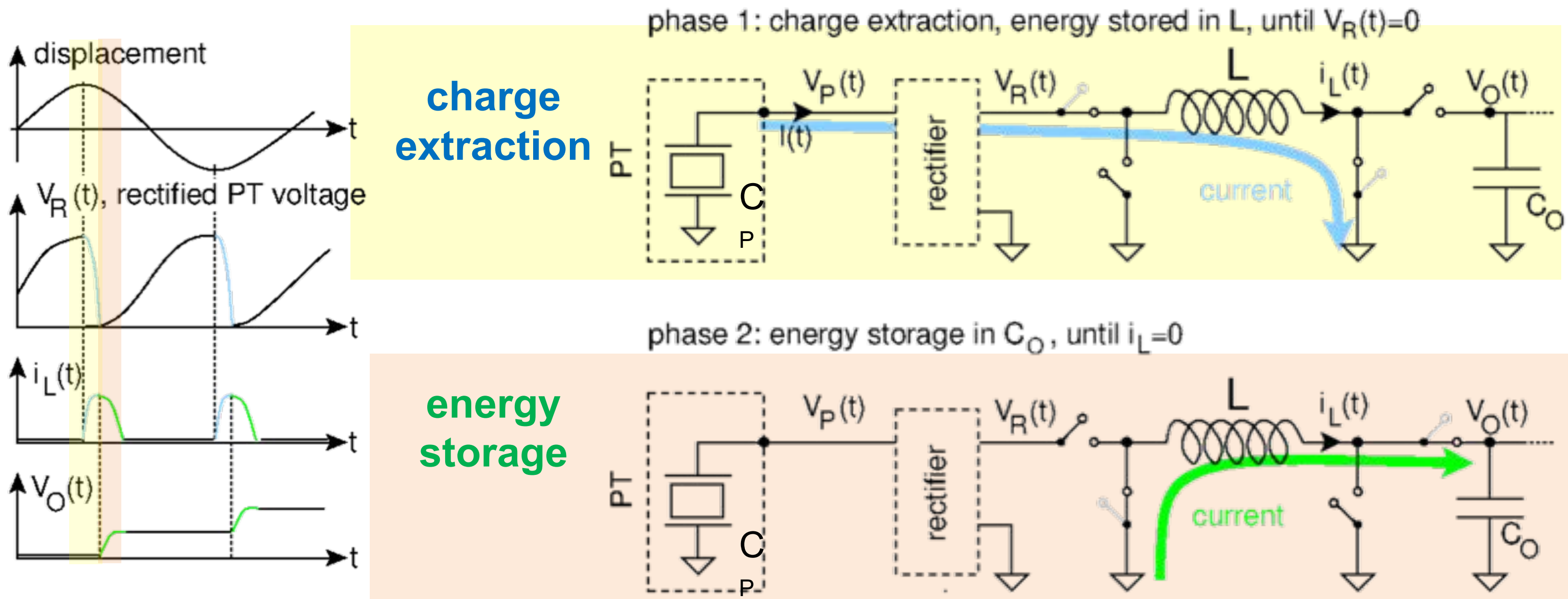
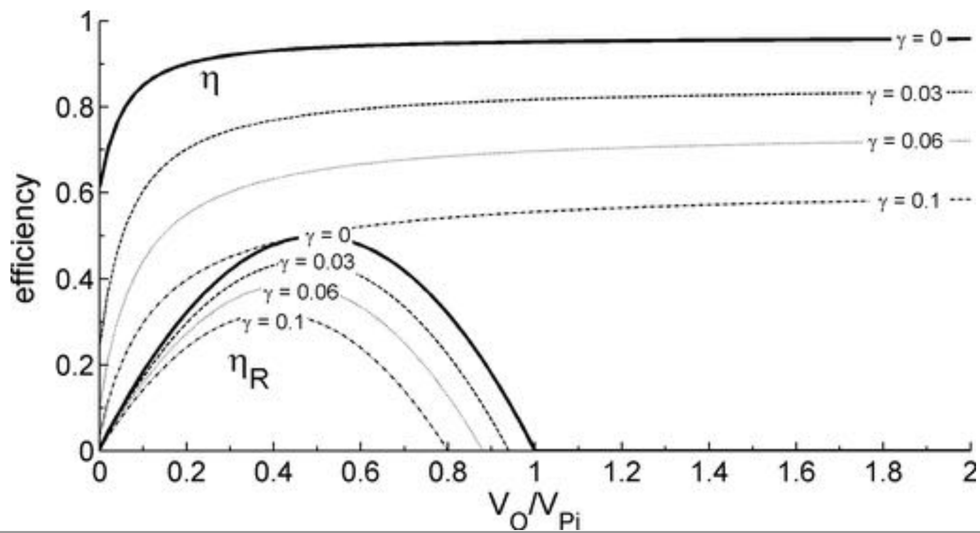
Synchronous Electric Charge Extraction for AC Piezoelectric Sources

- 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**
- Source and load are uncoupled → **suitable for irregular vibrations**



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

(when electromechanical coupling is low)

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

Synchronous Electric Charge Extraction for AC Piezoelectric Sources – Drawbacks

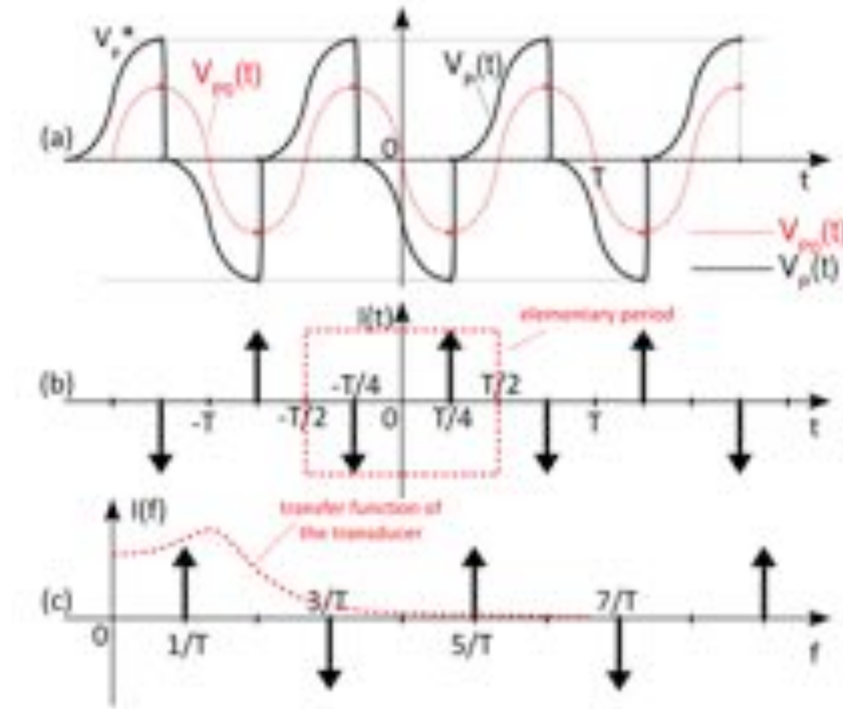
- In AC, SECE applies a periodic series of current pulses to the transducer
- The first harmonic of current drawn from the transducer depends on frequency, on capacitance of transducer and on the actual voltage amplitude

$$I(t) = C_P V_P^* \cdot \sum_{j=-\infty}^{+\infty} \left[\delta\left(t - \frac{T}{4} - jT \right) - \delta\left(t + \frac{T}{4} - jT \right) \right],$$

$$I(t) = \sum_{n=0}^{+\infty} (-1)^n \left(\frac{4 C_P V_P^*}{T} \right) \sin\left(2\pi (2n+1) \frac{t}{T} \right).$$

$$I_1(t) = 4f \cdot C_P V_P^* \cdot \sin(2\pi f t),$$

- **Damping may arise in transducers unless electromechanical coupling is negligible** (piezo transducers also behave like actuators)



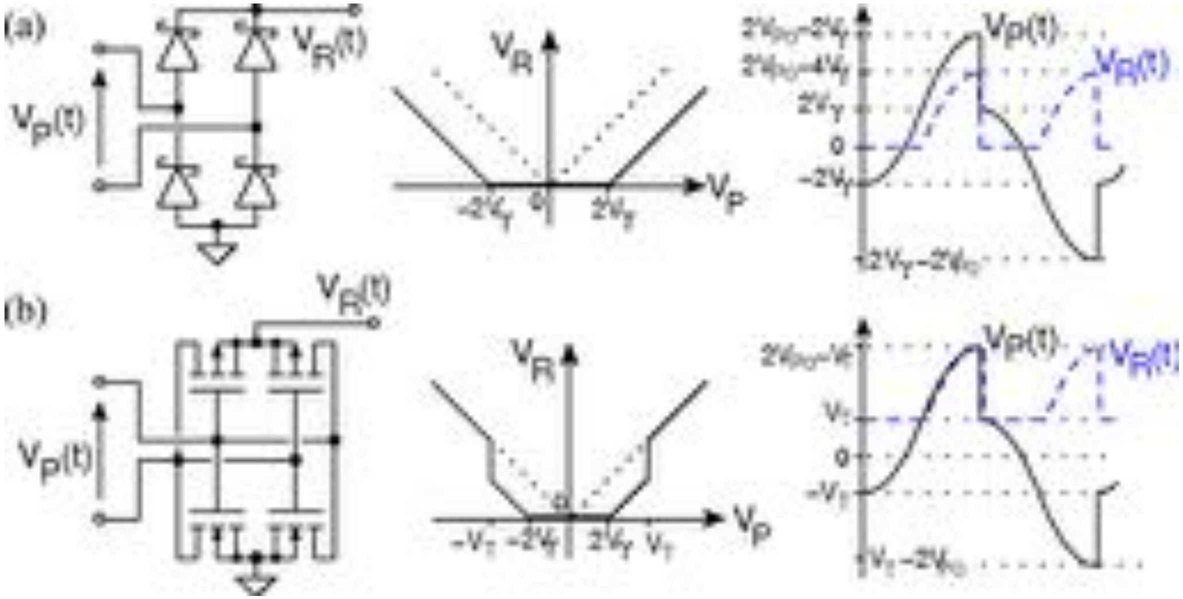
A. Romani et al., IEEE Sensors J., 2013

SECE with Residual Charge Inversion

- Rectifiers used for SECE have a threshold voltage → voltage drops or residual charge left on the transducer at the end of every energy transfer cause lower amplitudes of piezoelectric voltage

- SECE may be combined with the advantages offered by voltage flipping

full bridge rectifier

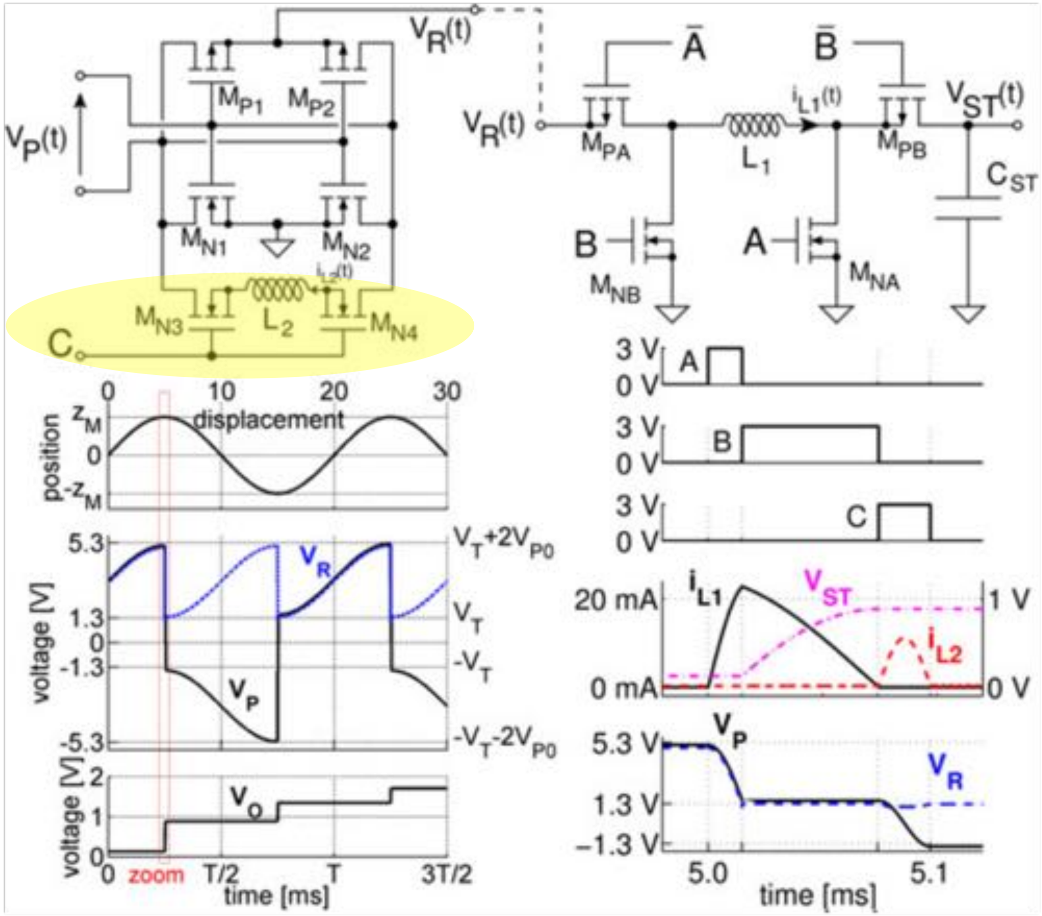


negative voltage converter

M. Dini, A. Romani, M. Filippi, and M. Tartagni, "A Nanopower Synchronous Charge Extractor IC for Low-Voltage Piezoelectric Energy Harvesting With Residual Charge Inversion," IEEE Trans. Power Electron., vol. 31, no. 2, pp. 1263–1274, Feb. 2016.

SECE with Residual Charge Inversion

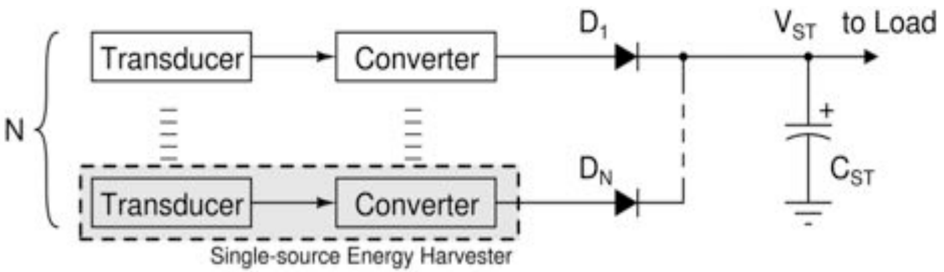
- A voltage flipping circuit can be added in parallel to the transducer
- At the end of every energy transfer the residual voltage V_R is flipped to $-V_R$
- $-V_R$ becomes the new starting point for the next peak-to-peak elongation
- As a consequence the rectified voltage reaches $V_R + V_{PP}$
- The harvested power increases of ≃60% with input voltages in the order of 1V with typical components



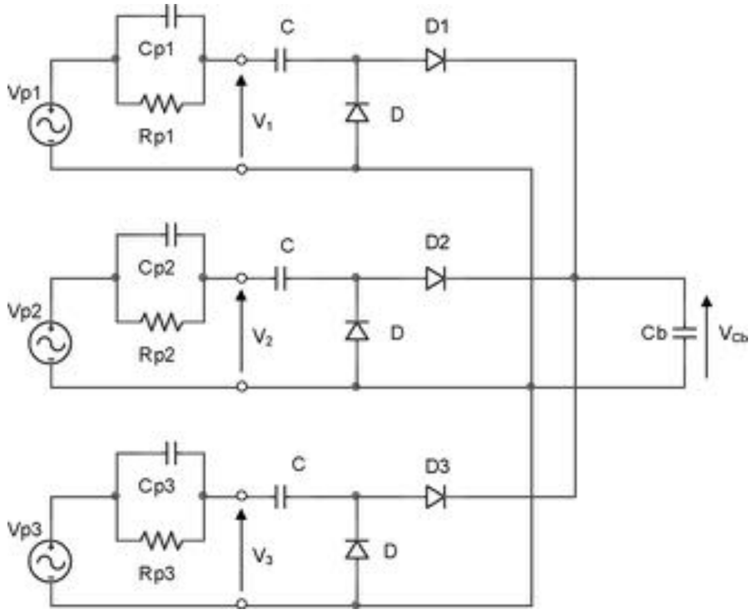
M. Dini, A. Romani, M. Filippi, and M. Tartagni, "A Nanopower Synchronous Charge Extractor IC for Low-Voltage Piezoelectric Energy Harvesting With Residual Charge Inversion," IEEE Trans. Power Electron., vol. 31, no. 2, pp. 1263–1274, Feb. 2016.

Multi-Source Harvesting

- Combining the power generated by multiple transducers is strategic in many applications
- The simplest technique is the so-called '**Power OR-ing**', which can be easily applied to DC voltages and to piezoelectric transducers,
- The main drawback is efficiency: different sources are not likely to operate in the MPP at the same time given that they share the same loading condition



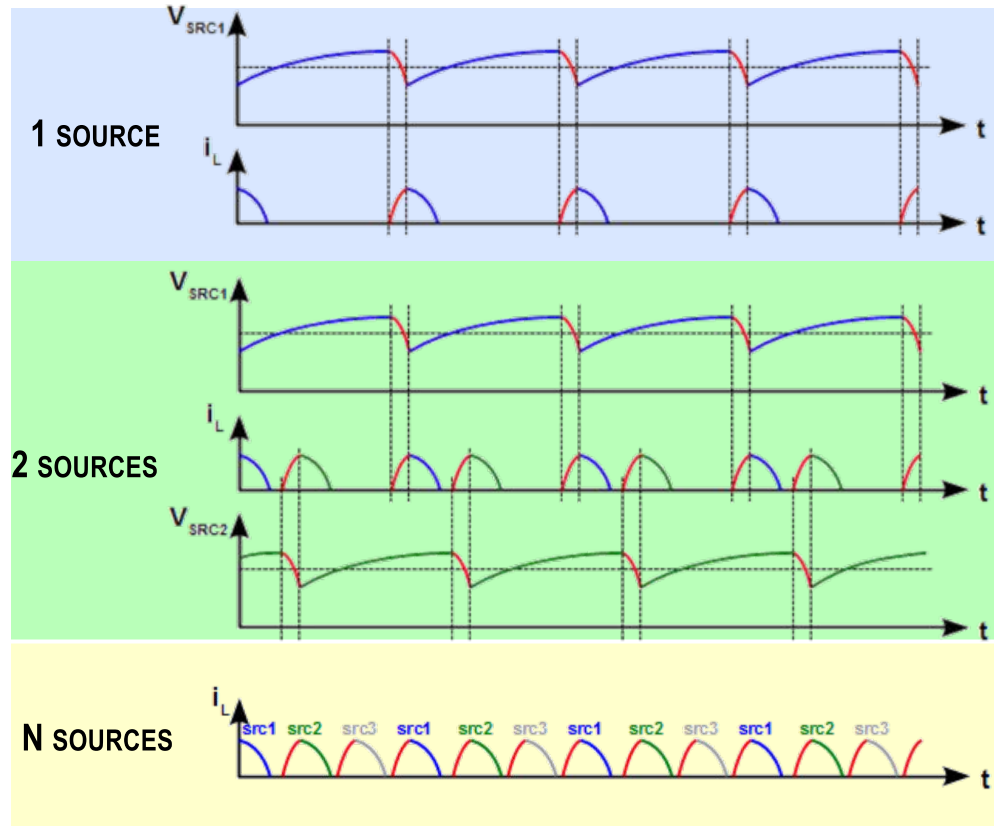
M. Dini, A. Romani, M. Filippi, V. Bottarel, G. Ricotti, and M. Tartagni, "A Nano-current Power Management IC for Multiple Heterogeneous Energy Harvesting Sources," IEEE Trans. Power Electron., vol. 30, no. 10, pp. 5665–5680, 2015.

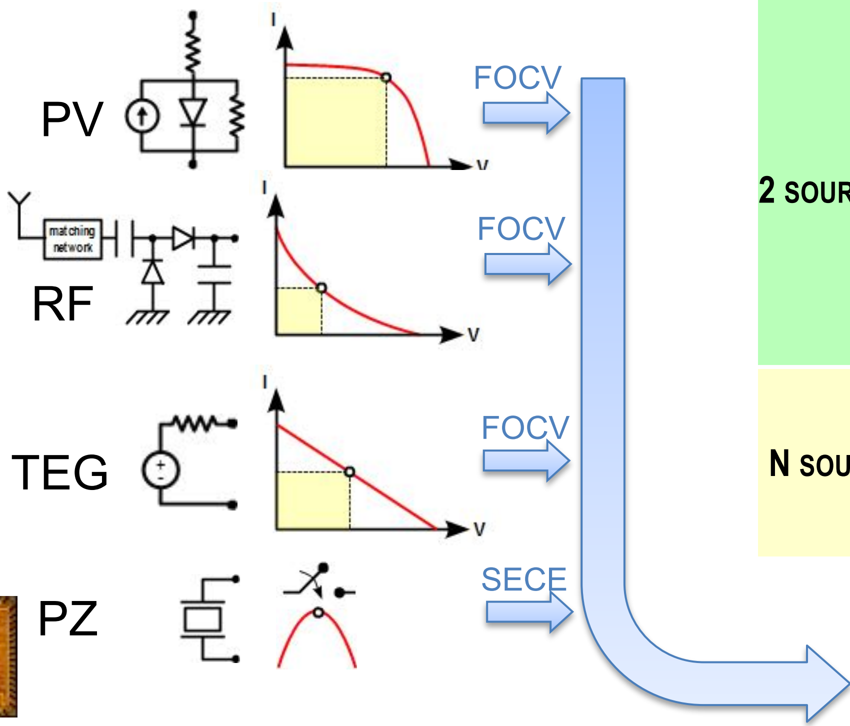


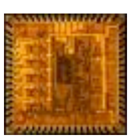
M. Ferrari, V. Ferrari, M. Guizzetti, D. Marioli, and A. Taroni, "Piezoelectric multifrequency energy converter for power harvesting in autonomous microsystems," Sensors Actuators A Phys., vol. 142, no. 1, pp. 329–335, Mar. 2008.

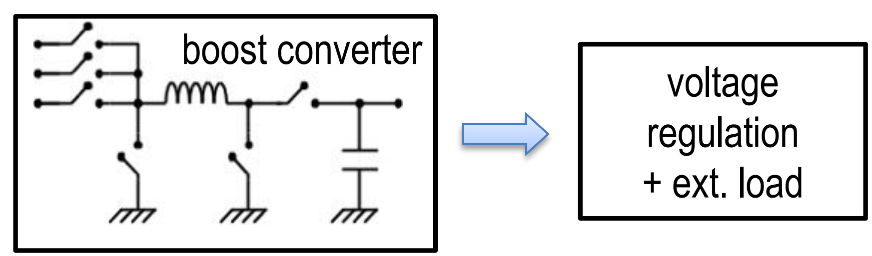
Multi-Source Harvesting

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









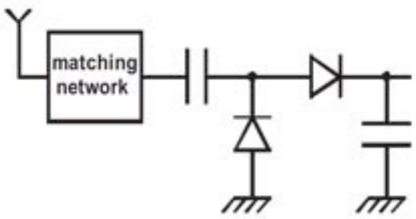
Dini et al., IEEE TPEL 2015

Bandyopadhyay et al., JSSC 2012

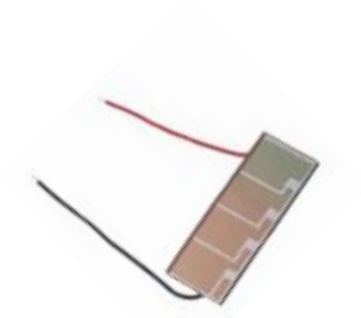
Romani et al., IEEE TPEL, 2014

Ultra-low voltage energy harvesting

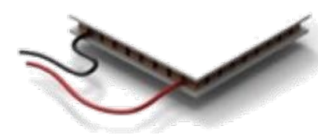
- Voltages available from energy transducers are very low in many practical cases



rectenna
≈ 0.8 V with
$P_{IN}\cong 100uW$[1]



PV cell
≈ 200 mV under
indoor illumination[2]



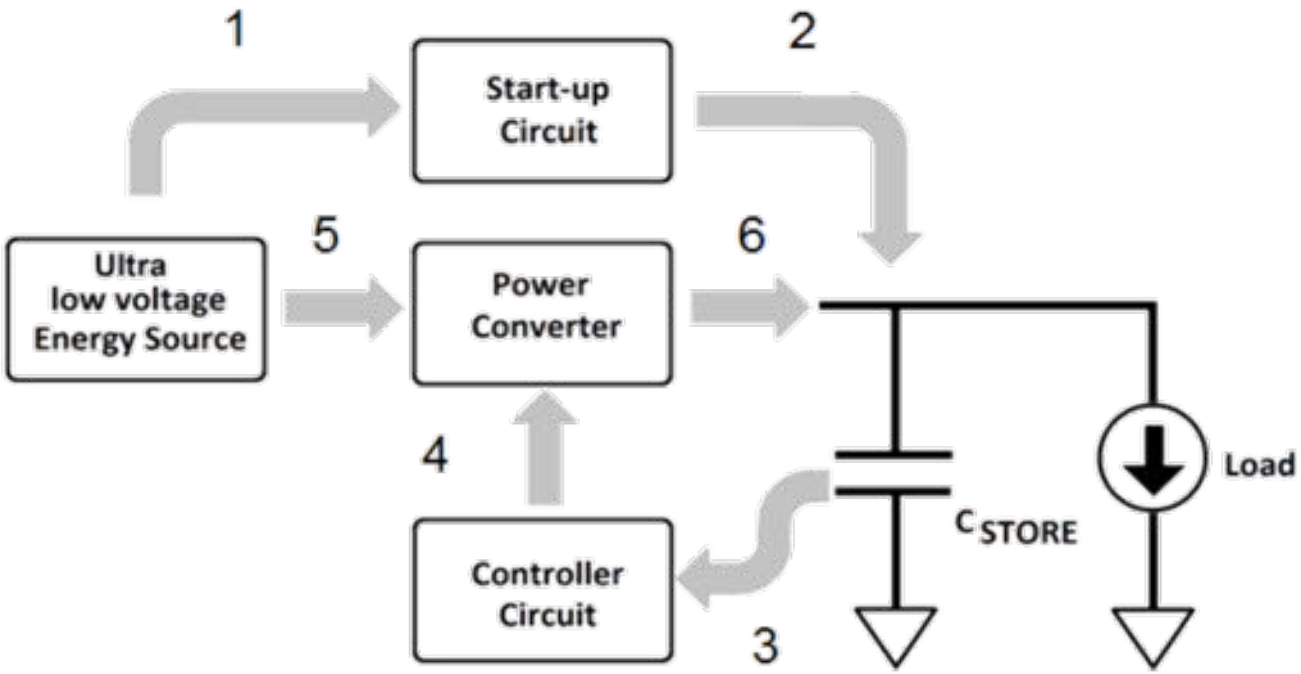
TEG
≈ 50 mV under thermal
gradients of a few °C [3]

- **Target: battery-less energy harvesting systems**
- Application circuits and power converters require higher V_{DD}
- Switching boost converters and charge pumps cannot operate when $V_{SRC} \ll V_{TH}$

[1] *A. Costanzo et al., Sensors and Actuators, 2012* [2] *M. Dini, ESSCIRC 2014* [3] *A. Camarda, Eurosensors, 2014*

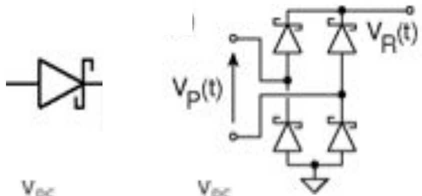
Role of start-up circuit

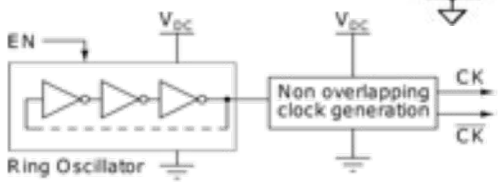
- The start-up circuit is enabled **only** in discharged states
- It boosts initially the voltage on the storage capacitor up to the **minimum operating voltage** of active circuits
- After this, it is **disabled**, and the power converter is enabled

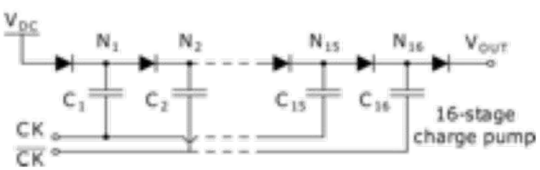


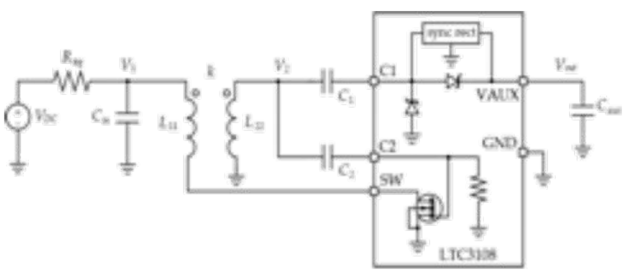
Types of passive start-up circuits

- **Ways to provide the initial voltage V_{DD} required by the active converter:**







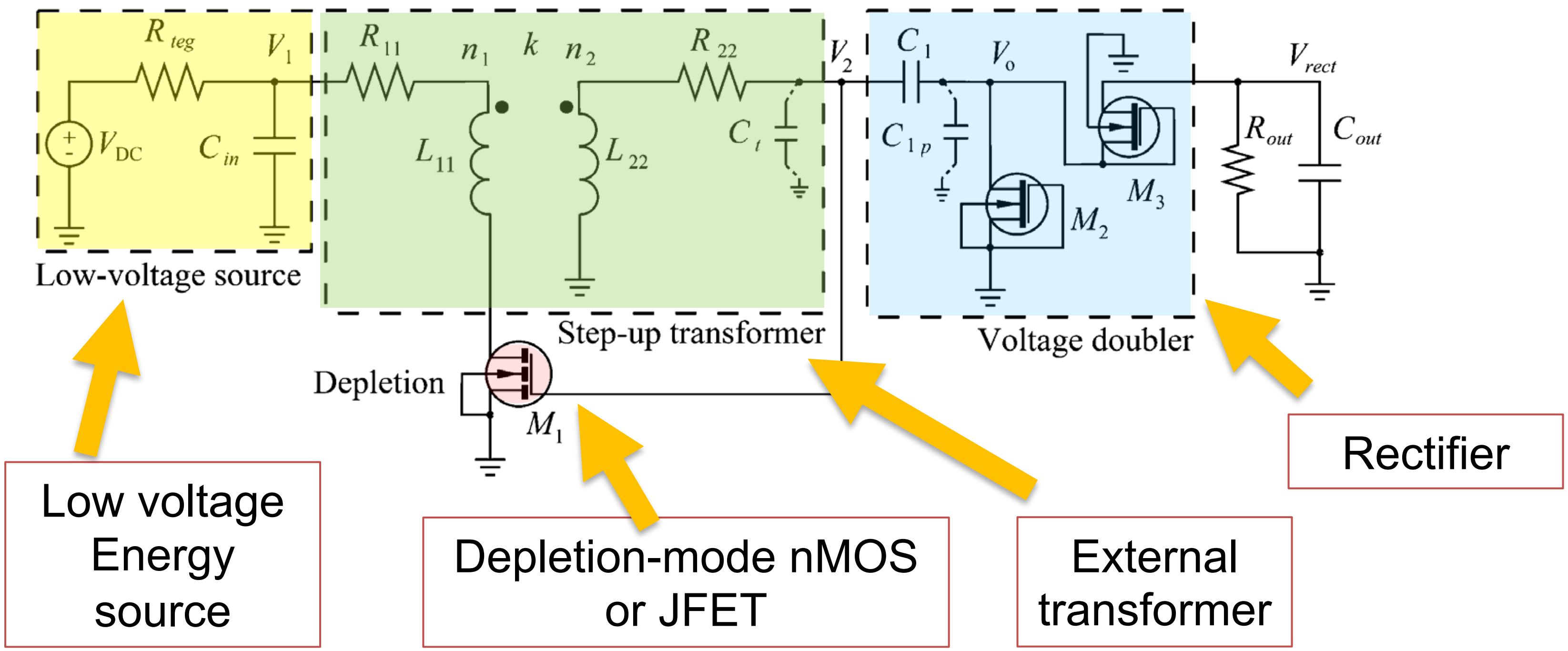


  - above V_{TH}: passive rectifiers directly charge the storage capacitor
  - around or slightly below V_{TH}: an oscillator starts driving a charge pump
  - below V_{TH}: a step-up oscillator based on a transformer steps up the output voltage

Until the minimum V_{DD} is detected by an UVLO.
Then the active (more efficient) converter is started.

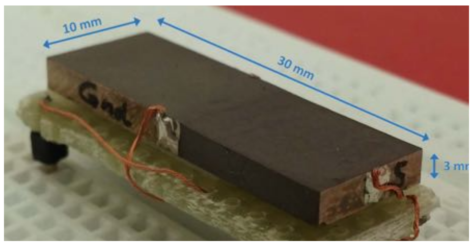
Step-up oscillators

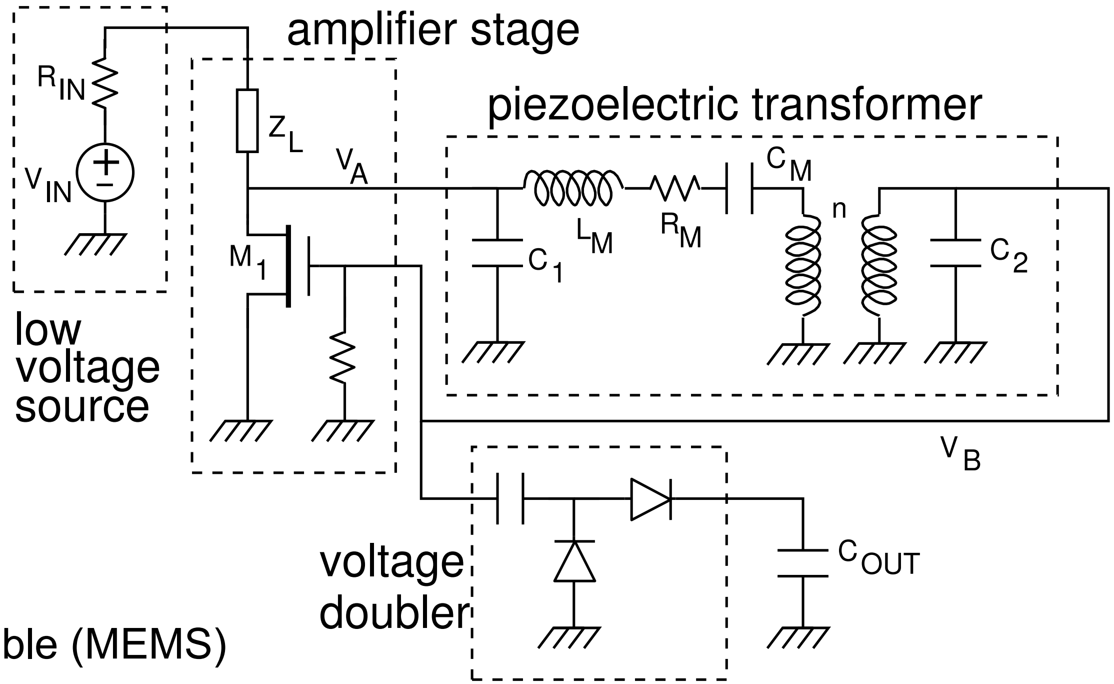
- A step-up oscillator is a circuit generating an oscillation with growing amplitude starting from an ultra-low voltage (~tens of mV)
- Low voltage step-up oscillators based on **coupled inductors** can operate as **bootstrap circuits** in discharged states.
- **Primary target:** minimum operating voltage



Step-up Oscillators

- At UNIBO we investigated novel start-up circuits based on **piezoelectric transformers**





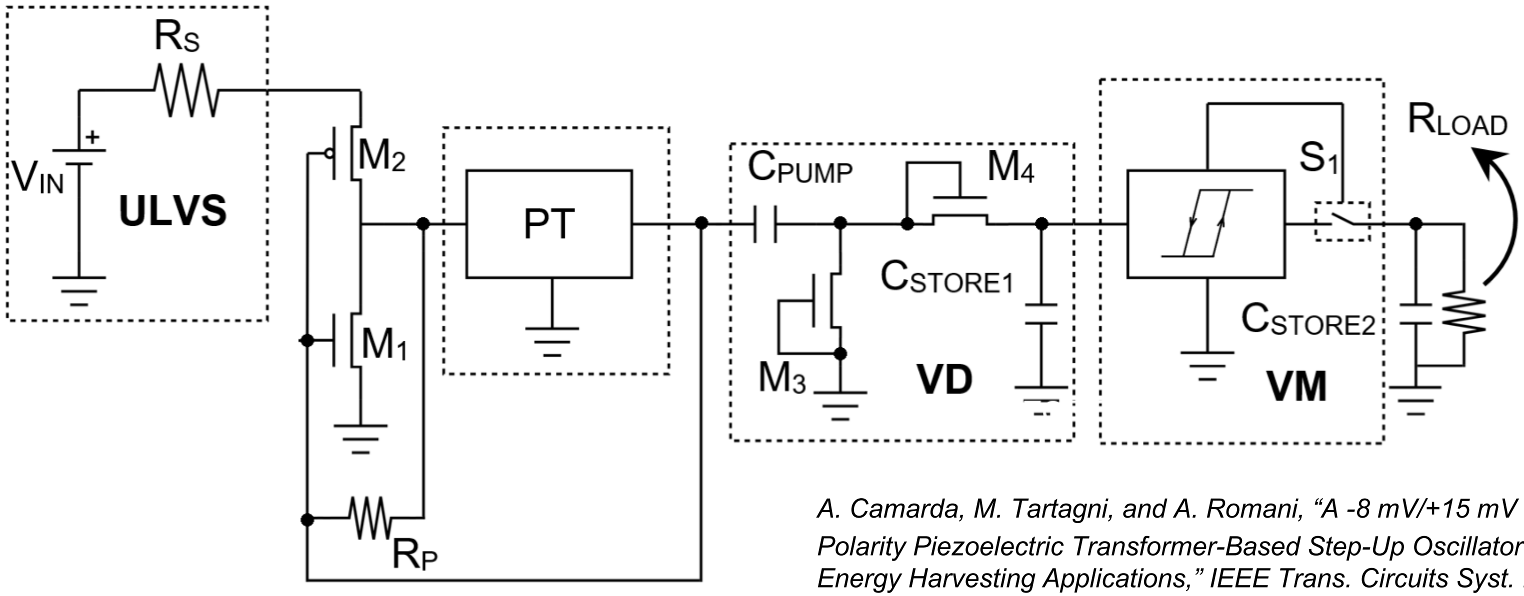
- **Advantages**
  - No EMI
  - Higher Q factors
  - Losses do not increase with frequency
  - PTs are integrable andshrinkable (MEMS)

- **Minimum measured start-up voltage**
  - **16 mV** with a series 40 µH inductor (Z_L), a Noliac PT and a discrete FET

A. Camarda et al., S&A A: Phys.I, 2015

Step-up oscillators

- **Double-polarity version**
  - CMOS inverter as amplifying element, whose phase shift depends on the polarity of the supply (180° when $V_{IN}>0$, 0° when $V_{IN}<=0$)
  - Phase shift of PT is ≃180° around anti-resonance or ≃0° below resonance
  - The high gain of PT always allows to satisfy Barkhausen criterion

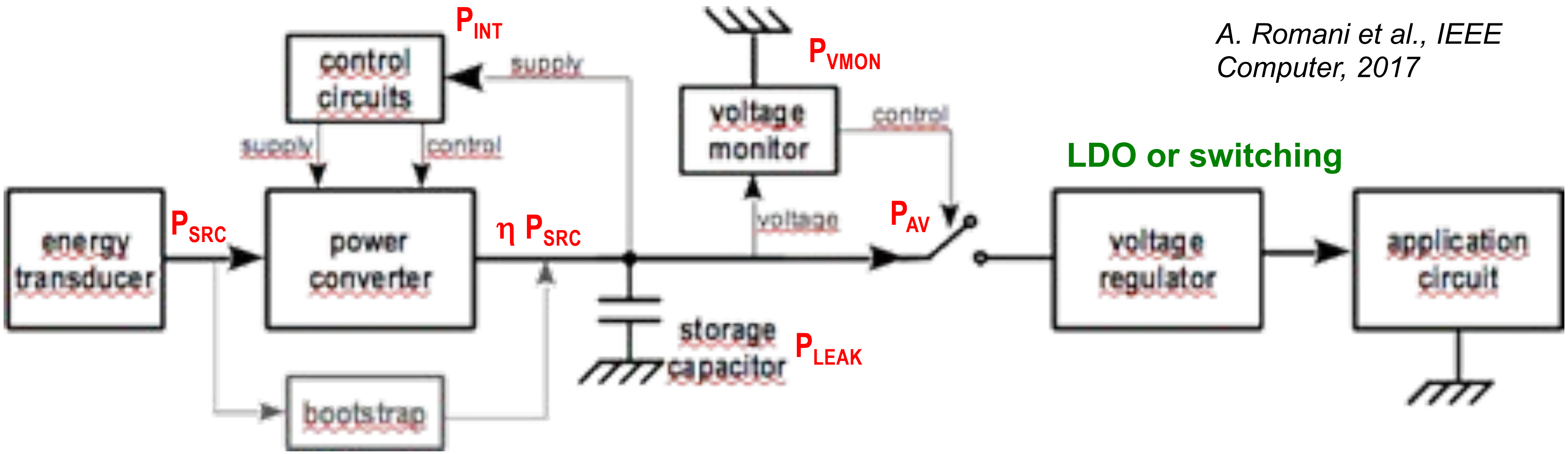


A. Camarda, M. Tartagni, and A. Romani, "A -8 mV/+15 mV Double Polarity Piezoelectric Transformer-Based Step-Up Oscillator for Energy Harvesting Applications," IEEE Trans. Circuits Syst. I Regul. Pap., 2017.

Techniques and design trade-offs for power management circuits

The importance of reducing intrinsic power

Battery-less Reference Architecture

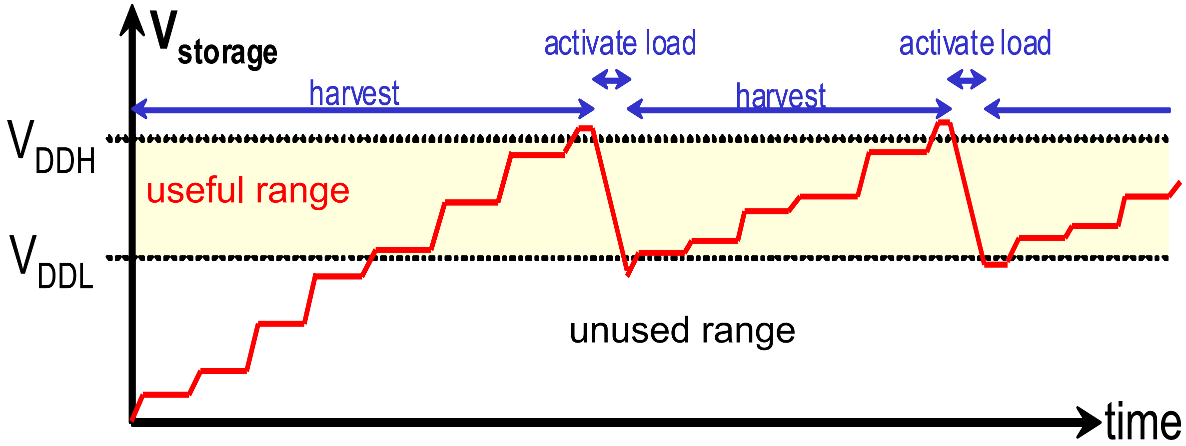


A. Romani et al., IEEE Computer, 2017

- 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

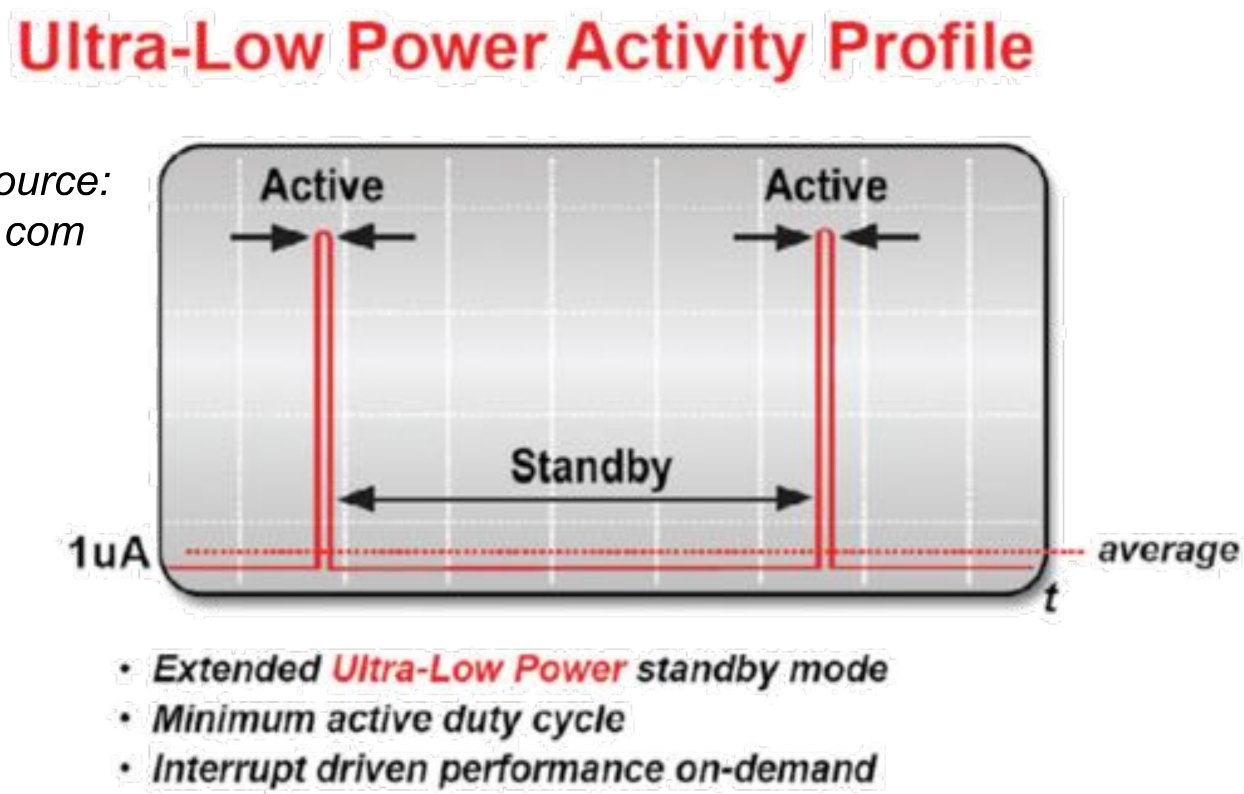
$$E_{BASE} = \frac{1}{2} C_{STORE} V_{DDL}^2$$

- When $P_{LOAD} > P_{AV}$ duty-cycled operation is necessary
- Load is activated when the output voltage is between two thresholds
  - 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 activation 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



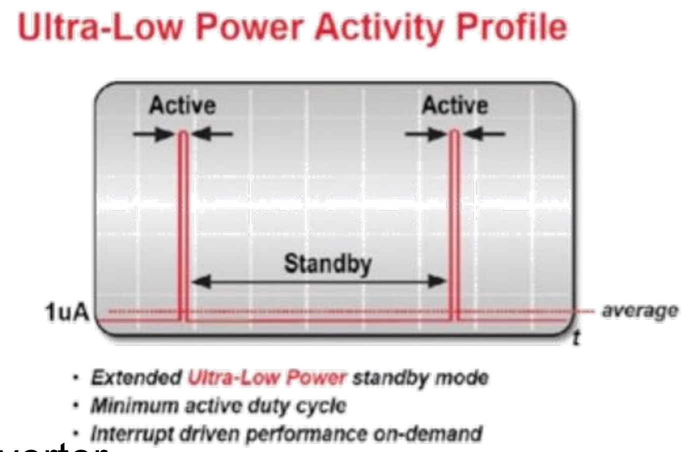
The average consumed power decreases with the duty-cycle…

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

Input power can't 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:

$$P_{AV} = \eta P_{SRC} - P_{INT} = \eta \eta_{MPP} P_{SRC,MAX} - P_{INT}$$

← **need for trade-offs with η, η_{MPP} and P_{INT}!**

Evolution & Trends in Power Management Circuits for Energy Harvesting Applications

Advantages of ICs

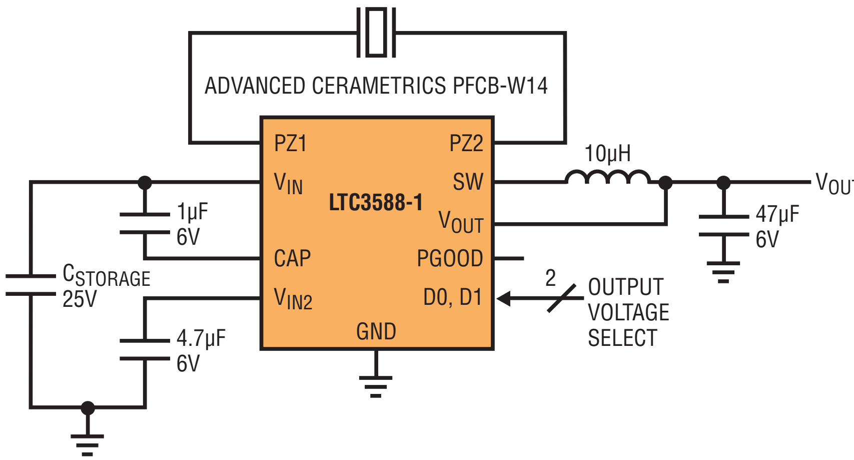
- **Why ASICs for energy harvesting?**
  - Very low parasitics and leakage currents → extremely low intrinsic power (at least 10x with respect to discrete components)
  - Possibility of fine tuning of all design parameters
  - Size is also reduced, but usually is not an issue (transducers, inductors 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

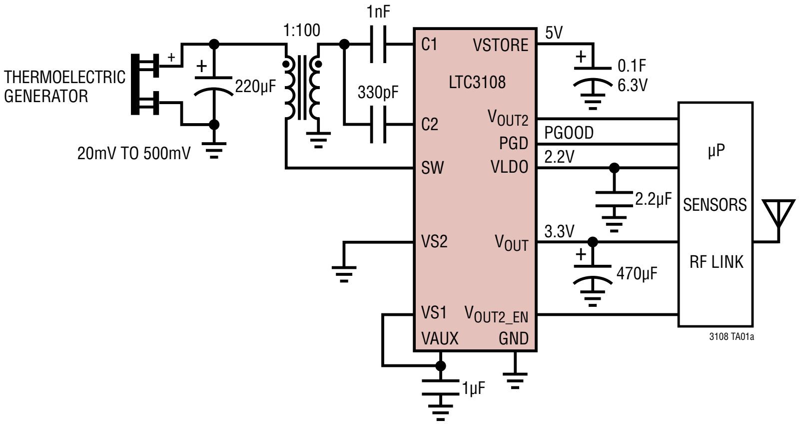
Commercial devices

- 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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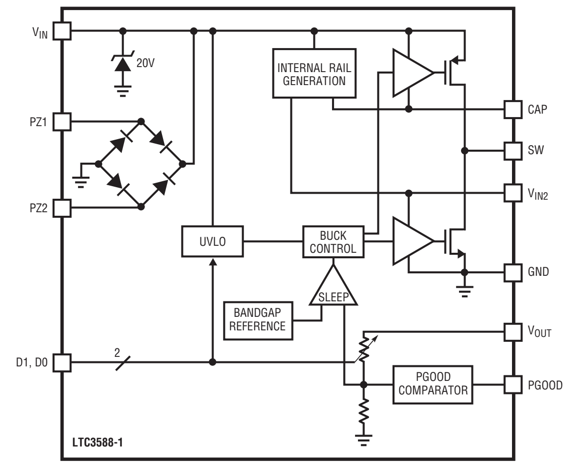
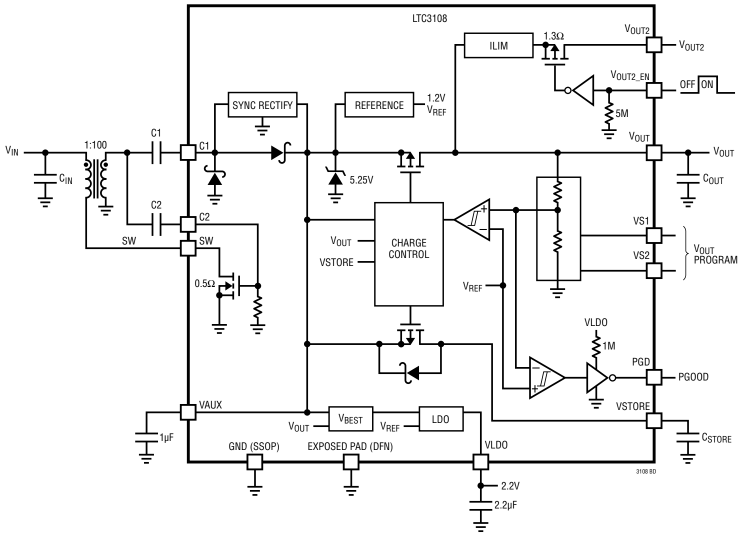
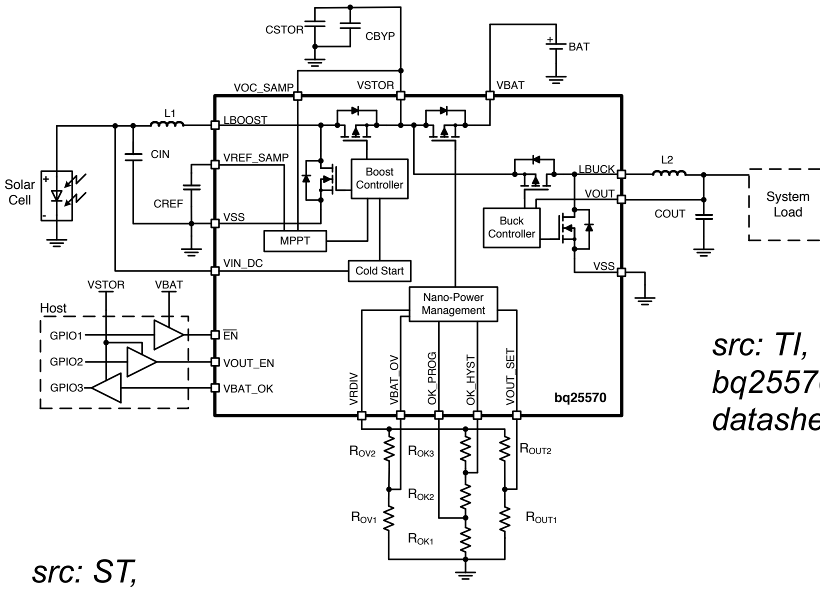




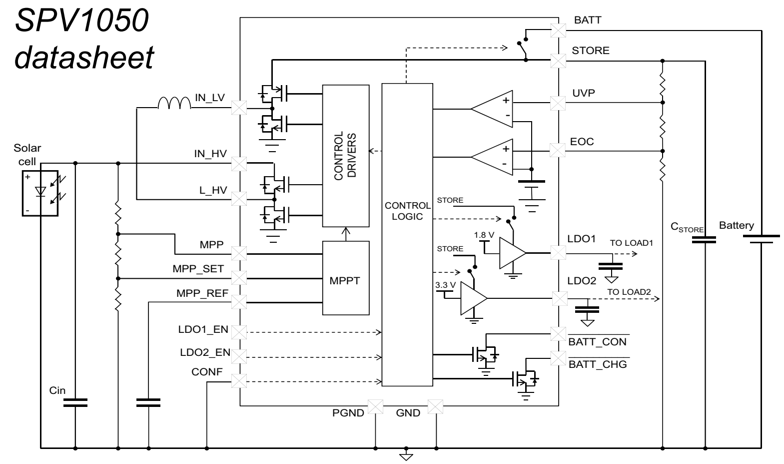
TI and STM

- 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

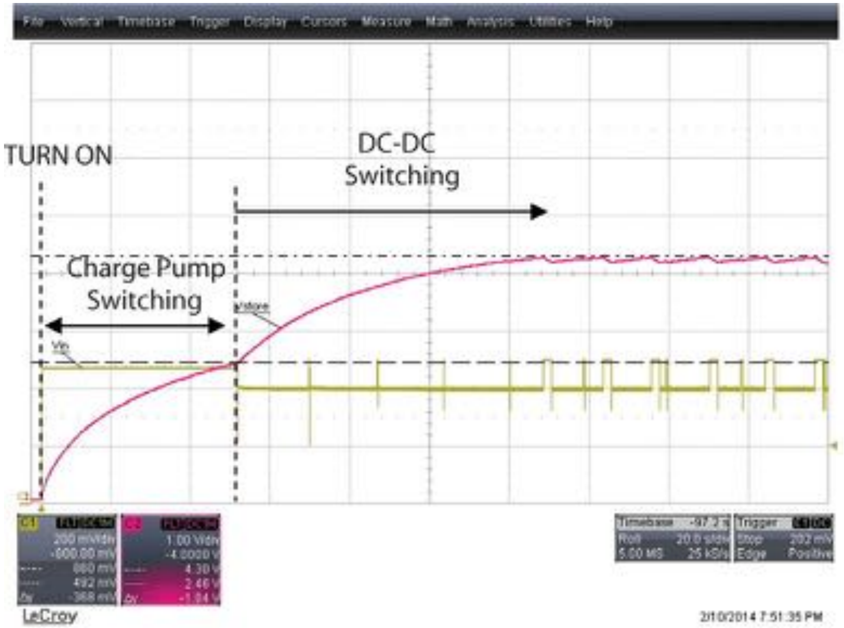
src: ST, SPV1050 datasheet



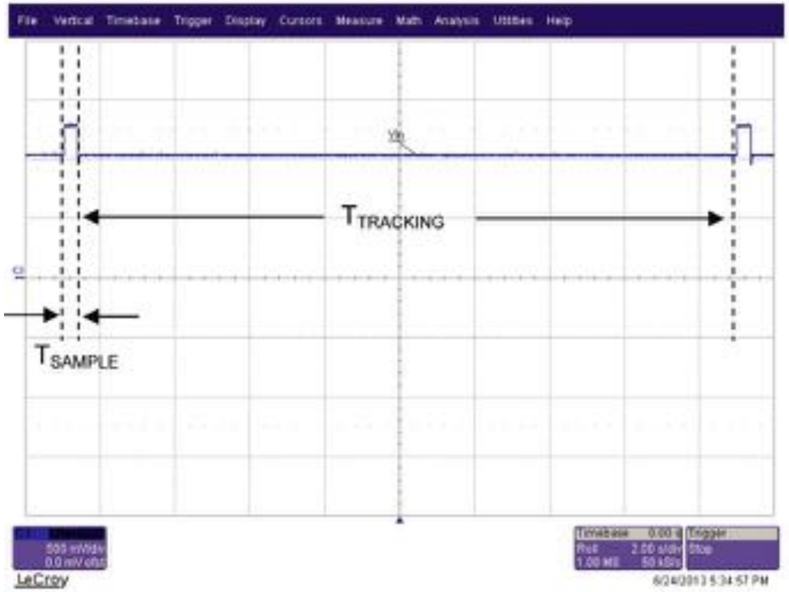
ST SPV1050

- Typical operation

source: SPV1050 datasheet



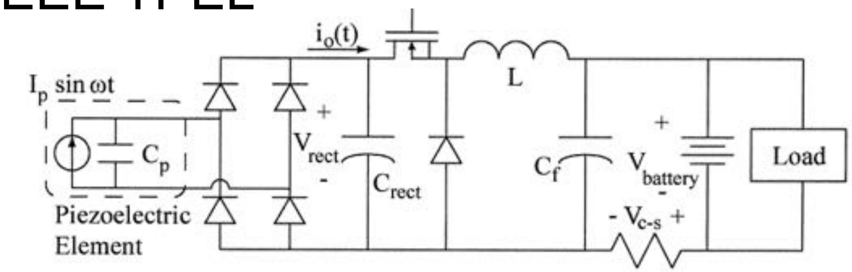
cold start-up

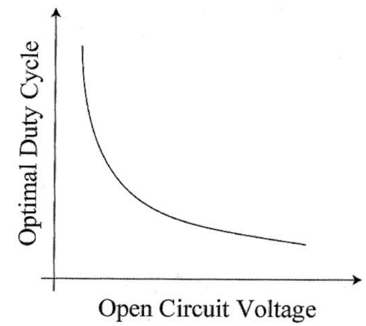


FOCV sampling

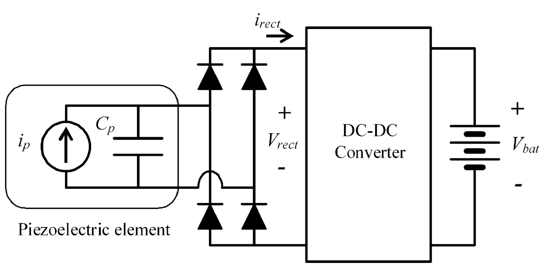
Meanwhile in scientific literature…

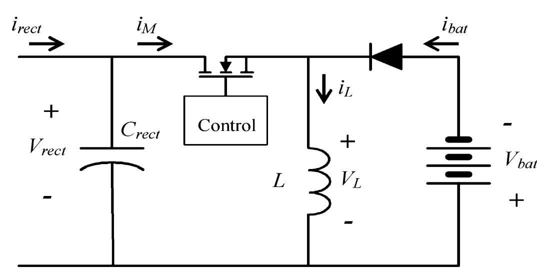
- **2003**.G. Ottman et al., Optimized Piezoelectric energy harvesting circuit using step-down converter in discontinuous conduction mode, IEEE TPEL





- **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

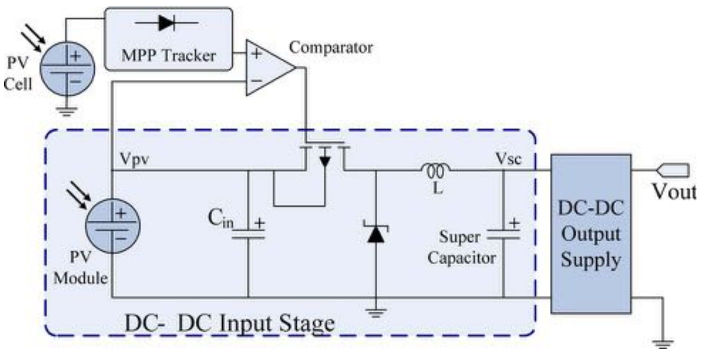




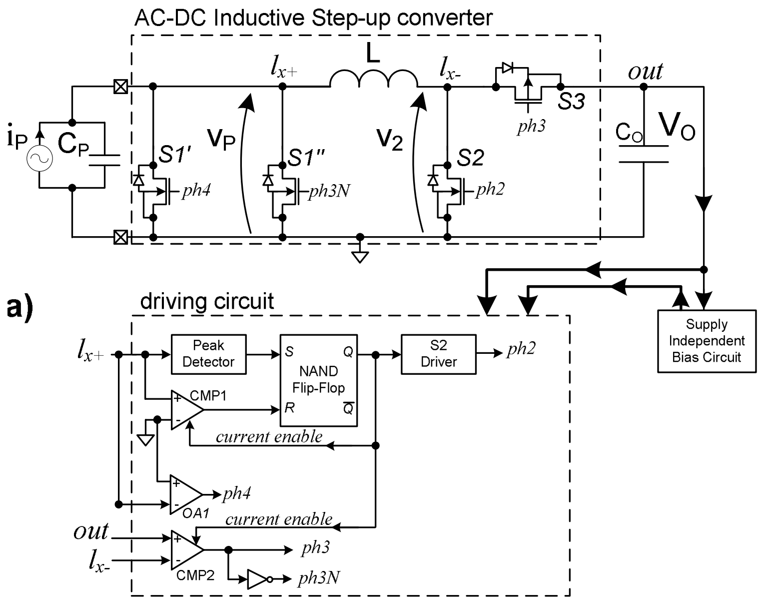
- Similar approach as first product (rectifier + DC/DC)

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

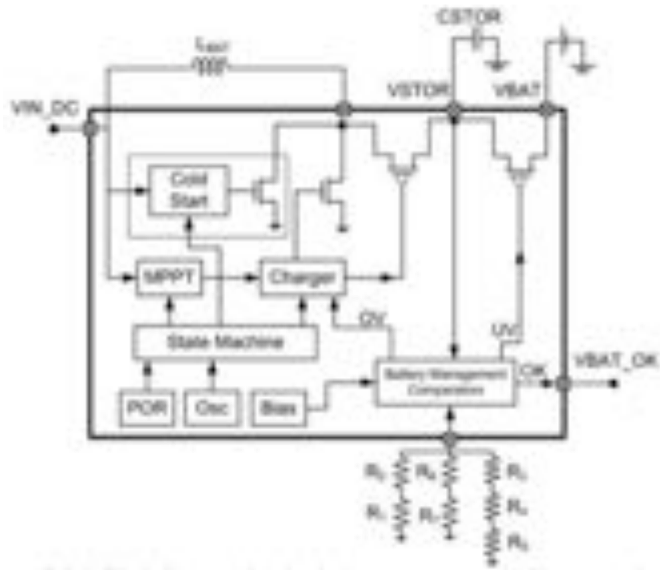


- **2009**. E. Dallago et al., Electronic interface for piezoelectric energy scavenging system
  - CMOS implementation of SECE
  - 700 nA quiescent current
  - 5V maximum voltage



Meanwhile in scientific literature…

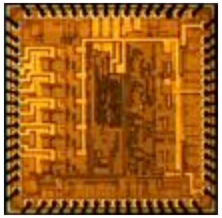
- **2012**. K. Kadirvel et al., *A 330 nA energy-harvesting charger with battery management for solar and thermoelectric energy harvesting*, IEEE ISSCC
  - Nanopower implementation of FOCV MPPT
  - 150 nA quiescent current
  - Minimum V_{IN}=330 mV and P_{IN}=5 µW.
  - efficiency >80% for V_{IN}=500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



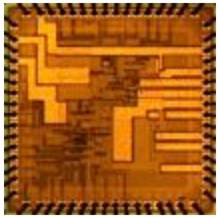
- **2014.** E. Aktakka, K. Najafi, *A micro inertial energy harvesting platform with self-supplied power management circuit for autonomous wireless sensor nodes*, IEEE JSSC
  - All components in a single package
  - SSHI on a miniature piezo source
  - 0.5 µW consumption in active mode, 10 pW in sleep-mode

Meanwhile in scientific literature…

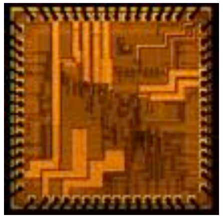
- **2013-2015.** M. Dini et al. (UNIBO), Developed a series of nanopower ASICs for DC, piezoelectric, and heterogeneous energy harvesting sources, IEEE TPEL, ESSCIRC, PRIME



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%



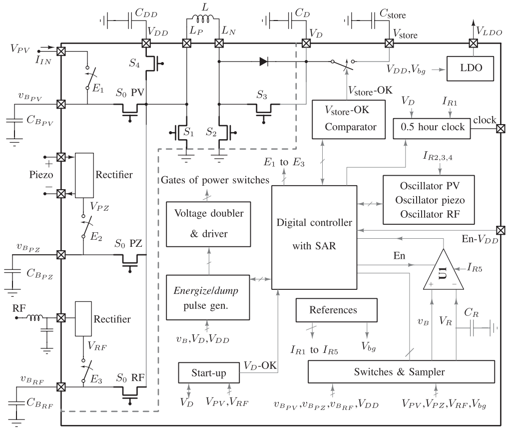
0.32 µm STM technology
Implements SECE-RCI
Separate IC/load supplies
P_{MIN} = 296 nW (@7 Hz, 0.5V_{PK})



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

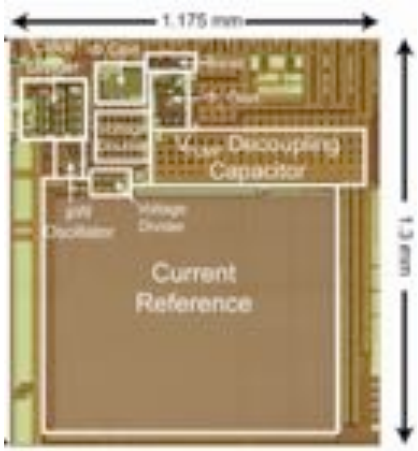
- **2015-2016**. A. Camarda et al. (UNIBO), developed an integrated ultra-low voltage dual-polarity bootstrap circuit (-8/+15 mV) based on a piezoelectric transformer

- **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

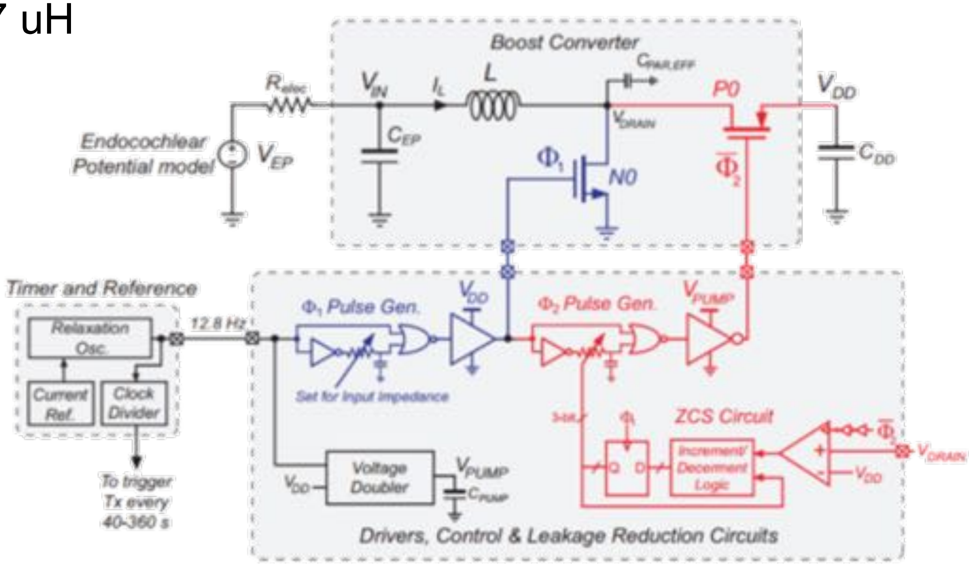


State of the art of nano-power PMICs

- S. Bandyopadhyay et al., *A 1.1 nW energy harvesting system with 544pW quiescent power for next-generation implants*, IEEE JSSC 2014

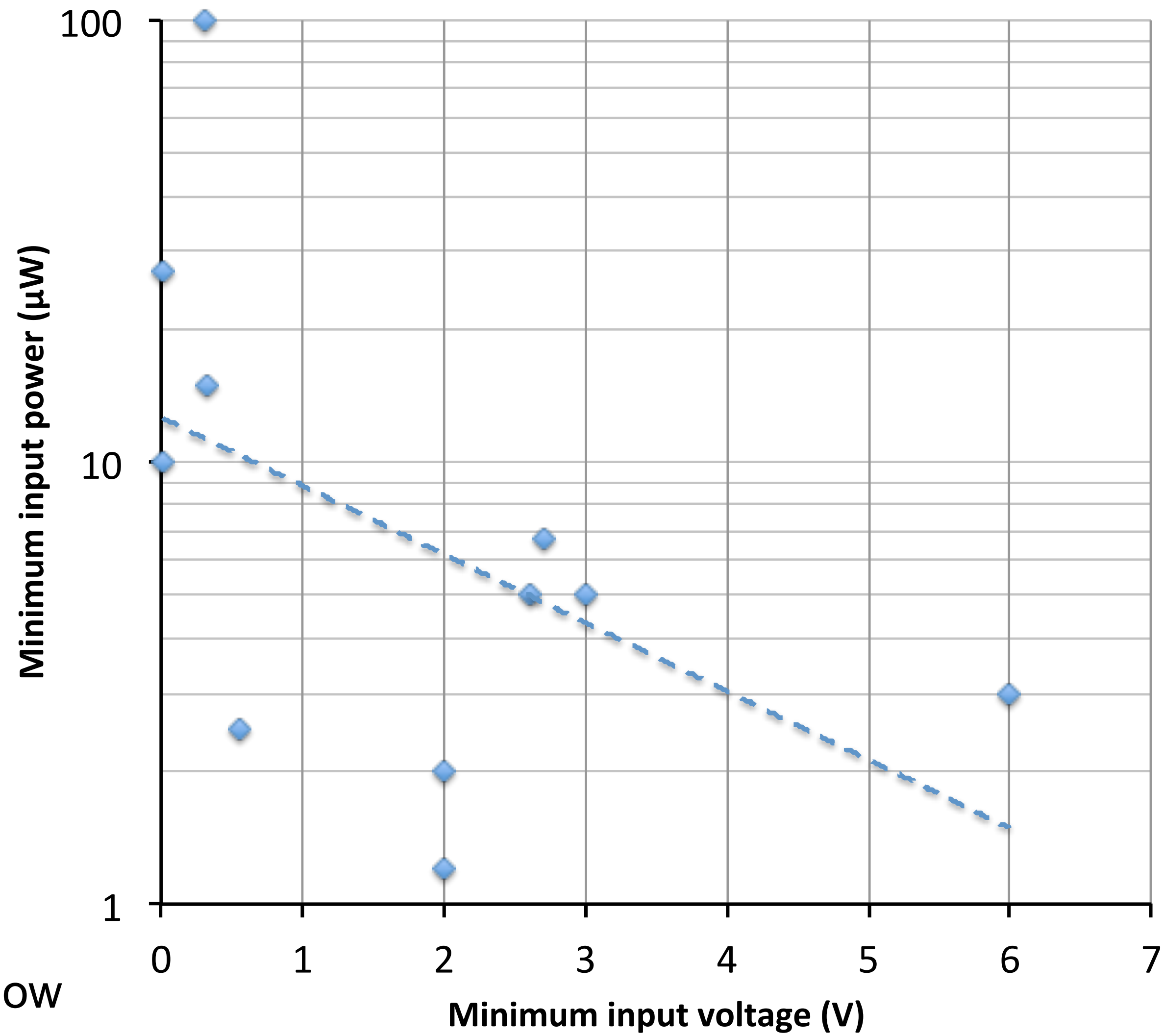


- **Features**
  - 70-100 mV input from endo-cochlear bio-potential inside ear
  - Efficiency > 53% @ V_{DD}=0.9V, L=47 uH
  - Boost converter topology with 12 Hz switching frequency
  - Trade-off between switching frequency, FET sizes and power losses carefully investigated
  - 0.18 µm CMOS
  - Cannot self-start
  - **The lowest intrinsic consumption reported up to now**



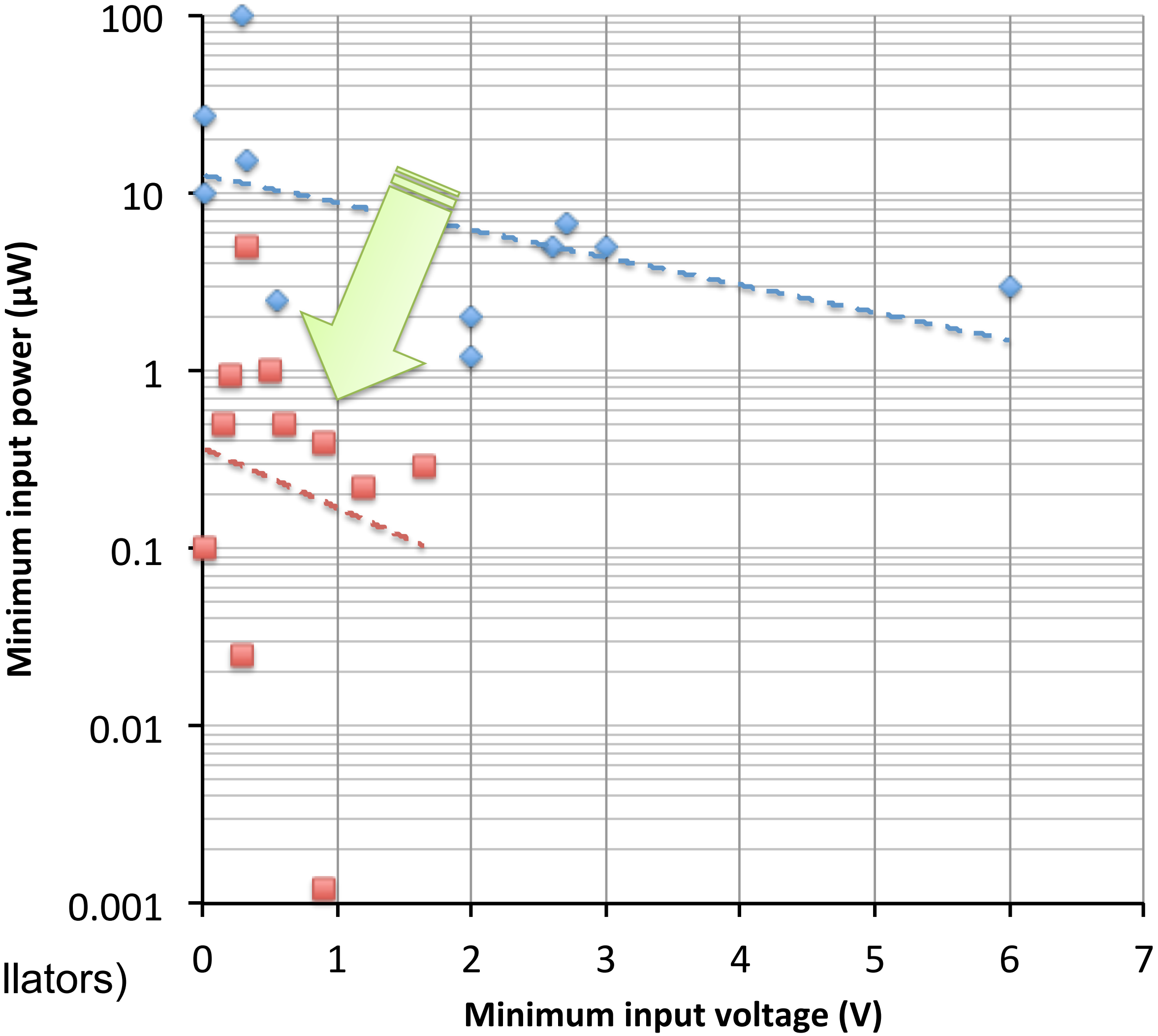
Trends: Commercial PMICs

- 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

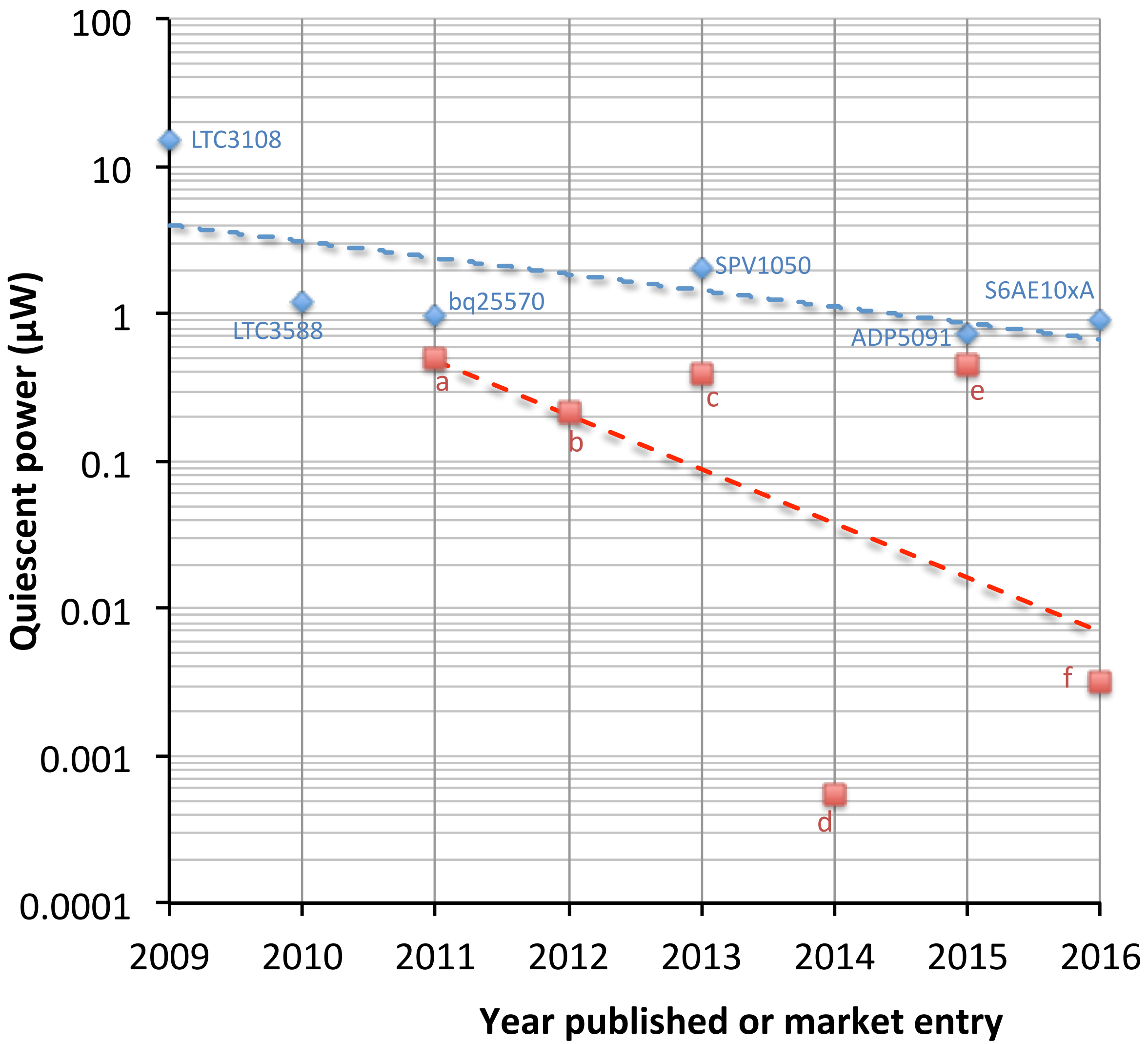
- Commercial PMICs stay on the ‘safe’ side
  - reliability
  - higher output current required by external circuits
- Research is keeping on pushing the limits towards lower power and voltages
  - Very good trade-offs on power can be found
  - Voltage is practically limited by $V_{GS,TH}$ (sub-100mV typically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



a: E. E. Aktakka et al., *IEEE ISSCC 2011;*
b: T. Huang et al., *IEEE JSSC, 2012*
c: N.K. Pour et al., *IEEE ISCAS 2013*
d: S. Bandyopadhyay et al., *IEEE JSSC, 2014*
e: M. Dini et al., *IEEE TPEL, 2016*
f: D. El-Damak et al., *IEEE JSSC, 2016.*

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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ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA
CAMPUS DI CESENA

Aldo ROMANI
Advanced Research Center on Electronic Systems “E. De Castro”
University of Bologna, Campus of Cesena

aldo.romani@unibo.it