Energy Harvesting – from Devices to Systems

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IEEE Distinguished Lecturer Program
Austin, May 10, 2011

Outline

• Motivation & Application Areas

• Energy Conversion
  ➢ Solar
  ➢ Thermoelectric
  ➢ Motion, Vibration (Piezoelectric, Electromagnetic, Capacitive)
  ➢ Application Specific Design
  ➢ (Bio) Fuel Cells

• Energy Storage

• Energy Management
  ➢ Energy Allocation
  ➢ Conversion Efficiency
  ➢ Adaptive Interface for Generators
Application areas of distributed embedded microsystems

- Automotive
  - Tire pressure monitoring system
- Industrial
  - Machine monitoring & control
- Building & home automation
  - Wireless switches & sensors
- Environmental monitoring
  - Agriculture monitoring
- Medical
  - Pacemaker, implants
- Consumer
  - Battery chargers

Embedded Microsystems

What do such systems look like?

But where does the energy come from?
Line powered systems

Problems
- Infrastructure (Jacks, Cables)
- Installation costs
- Extension costs
- Maintenance costs

3 km of cables!

Battery powered autonomous systems

Problems
- Limited lifetime
- Limited application (Temperature, …)
- Replacement costs
- Environmental problems

2008: > 33,000 tons of batteries sold in Germany!
© GRS Batteries

Sales quantity in metric tons.
Secondary cells
Primary cells
Energy autonomy …
Are batteries and cables the only options?

… in microscale?

Energy supply by Energy Harvesting

- Total autonomy
- “Unlimited” lifetime
- Less maintenance
- Easy installation
- Operation at not easily accessible places

**System power**

- Energy Source
- Energy Harvester
- Energy Management
- Energy Storage
- Sensor Input
- Sensors
- Signal Processing
- Wireless RX / TX
- Wireless Data

**Energy management**

**Energy conversion**

**Energy storage**
Ambient forms of energy and conversion mechanisms

- Kinetic Energy
- Optical Energy
- Electrical Energy
- Thermal Energy
- Piezoelectric-Capacitive-Inductive
- Fuel cells
- Antenna
- Chemical Energy
- RF Energy

Light energy

- Thin Film Solar Cell:
  - 1cm² active Area
  - “Quick Start”

Power, from low cost thin film solar cells

![](chart.png)
Solar cells

Hybrid solar cell based on CdSe nanocrystals and conjugated polymers

Yunfei Zhou, IMTEK

Si thin film cell on polymer carrier © Flexcell

Characteristics

- DC voltage source
- Open circuit voltage: ~0.6 V
- Efficiency: ~2-3%
- Sunlight: ~3 mW/cm²
- Condition: Illumination intensity of 100 mW/cm²

Thermoelectric converters

Seebeck coefficients of relevant material couples:

\[ \alpha [\text{µV/K}] \]

<table>
<thead>
<tr>
<th>Material Couple</th>
<th>( \alpha ) [µV/K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al / p-Poly-Si</td>
<td>195</td>
</tr>
<tr>
<td>Al / n-Poly-Si</td>
<td>110</td>
</tr>
<tr>
<td>p-Poly-Si / n-Poly-Si</td>
<td>190...320</td>
</tr>
<tr>
<td>p-Bi(<em>{0.5})Sb(</em>{1.5})Te(<em>3) / n-Bi(</em>{0.87})Sb(_{0.13})</td>
<td>200...420</td>
</tr>
</tbody>
</table>

Characteristics

- Generation of DC current
- Polarity changes with direction of temperature gradient!
- Output voltage: around 100 mV
- Output power: some µW - mW
Examples of thermoelectric converters

Micro-TEG of Seiko (1994)

$P = 3 \mu W/cm^2$
$\Delta T = 1..3 K$

„Seiko Thermic“ (limited production in 1998)

$P = 1 \mu W/cm^2 @ \Delta T = 5 K$

Micro-TEG in CMOS technology © Infineon, 2003

Micro Peltier cooler in 3D silicon technology © MicroPelt

Power from thermoelectric converters depending on size and temperature difference

www.imtek.de/mikroelektronik
IEEE Distinguished Lecturer Program, Yiannos Manoli
Kinetic / Vibration energy

\[ E \sim m \]

Power from vibrations depending on mass and frequency

Problems:
- Small amplitudes (10 µm)
- Unknown frequency (10…1000 Hz)
- Unknown direction of vibration

Conversion:
- Capacitive (Electret)
- Piezoelectric
- Inductive (Coil & Perm. magnet)

Capacitive converters

Variable overlapping area
\[ \Rightarrow \text{Variable capacitor between } C_{\text{min}} \text{ and } C_{\text{max}} \]

\[ i(t) = \frac{dC(t)}{dt} \cdot V_{\text{bias}} \]

Characteristics
- Generation of AC current by dynamic capacitance variation
- Miniaturized (accelerometers)
- Bias voltage necessary
- Active control necessary
- Output voltage: some V
- Output power: some µW
### Examples for capacitive converters

- **Power:** 0.8 to 10 µW/cm²
- **Frequency:** 50 to 1.9 kHz
- **Size:** from 18x16 mm² to 6x5 mm²

### Piezoelectric converters

**Characteristics**

- **Materials:** PZT, LiNbO₃, PVDF
- **Charge based converter**
- **Generation of AC current by dynamic mechanical stress**
- **Output voltage:** 1V…100 V
- **Output power:** µW…mW

**Vertical mode**

- An external force F produces a voltage V due to charge separation.

**Transversal mode**

**Bimorph**

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**IMEC-NL, Netherlands, 2009**

**Vertical capacitor design, Imperial College, London, UK, 2003**

**National Chiao Tung University, Taiwan, 2008**
Examples of piezoelectric converters

In-shoe piezoelectric generator,
$P_{\text{max}} = 8 \text{ mW}$, N. Schenck, MIT, 1999

Wafer with MEMS Piezo generators,
Siemens, 2009

Electromagnetic (inductive) converters

\[ U = -N \cdot \frac{d \Phi}{dt} \]

Induction by alternating field

Electromechanical generator: $\frac{d \Phi}{dt} = f(v, \omega)$

Characteristics
- Generation of AC current by alternating field or relative motion
- Output voltage: mV…V
- Output power: µW…mW
Examples of electromagnetic converters

Rotatory converter
From Seiko Kinetic

Perpetuum
PMG17 ATEX/IECEx

$P = 5 \mu W$

$P = 50 \text{ mW} @ 1g$ acceleration

The size of an apple!

$P = 800 \mu W$

Multimodal oscillating converter
University of Hongkong, 2002

Wireless – Cost effective solution for Asset Management

- Annual maintenance spend 5-7% of Replacement Asset Value - Best in Class: 2-3% ($5$ trillion in US)
- High expense & production loss
- Avoid “run to failure” to reduce cost - more data from sensors
- Very expensive to add sensors by conventional wiring
- Energy harvesting and wireless is great opportunity for easily installing sensors at low cost

Ormen Lange Gas Field (Shell)
Wireless Light Switch

- Contact nipples for switch rocker identification
- Rotation axis for push buttons or switch rockers
- Power converter, Processor, HF radio and antenna
- Energy bow on both device sides
- Electrodynamic Energy Converter

© EnOcean

Wiring: Expensive & Invasive

Conventional Wired Solutions:

- Time consuming
- Building chaos
- Environmentally unfriendly
- Inflexible & expensive over lifespan

Solution:

- Wireless & battery-less light switches
- Occupancy & daylight sensors
- Savings:
  - Kilometers of cable
  - Lighting energy costs
  - Cost of retrofitting

© EnOcean
Application Specific Vibration Converters

Types of electromechanical coupling

Power density
Power-management
Packaging
Costs

D. Spreemann
Power and voltage optimization approach

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geometry</strong></td>
<td></td>
</tr>
<tr>
<td>Volume (coil/magnet)</td>
<td>cm³</td>
</tr>
<tr>
<td>Gap</td>
<td>mm</td>
</tr>
<tr>
<td>Maximum displacement</td>
<td>mm</td>
</tr>
<tr>
<td><strong>Magnet</strong></td>
<td></td>
</tr>
<tr>
<td>Remanence</td>
<td>T</td>
</tr>
<tr>
<td>Density of magnet</td>
<td>g/cm³</td>
</tr>
<tr>
<td><strong>Coil</strong></td>
<td></td>
</tr>
<tr>
<td>Copper filling factor</td>
<td>1</td>
</tr>
<tr>
<td>Wire diameter</td>
<td>μm</td>
</tr>
<tr>
<td>Resistance per length</td>
<td>Ω/m</td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td></td>
</tr>
<tr>
<td>Excitation amplitude</td>
<td>m/s²</td>
</tr>
<tr>
<td>Vibration frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>Mechanical damping</td>
<td>N/m/s</td>
</tr>
</tbody>
</table>

Evolution optimization strategy

**Initialization**
- Random distribution of individuals (geometry and fitness) in the search space
- Low fitness
- Best individuals are selected for reproduction

**Stop criterion fulfilled**
- Individuals are very similar
- Only negligible increase of fitness for further generations
Maximum performance for architectures with and without back iron

Voltage Output

Power Output

D. Spreemann

Energy Autonomous Systems in Cars

Air temperature sensor in AC
Solar rooftop
Wireless switches and controls
Rain sensor
Alarm
Inclination sensor
Glass breakage
Fluid level sensor
Tire pressure sensors
Keyless entry
Coolant temperature sensor
Exhaust pipe thermal energy
Oil quality sensors
Transducers on Motor Block

Transducer for intelligent fluid quick connector

Transient simulation with measured acceleration as excitation
(virtual operation of vibration transducer)

<table>
<thead>
<tr>
<th>Threshold (V)</th>
<th>City</th>
<th>Country</th>
<th>Highway</th>
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<tbody>
<tr>
<td>300mV</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>700mV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000mV</td>
<td></td>
<td></td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>Mean Power</th>
<th>Mean Power</th>
<th>Mean Power</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>290µW</td>
<td>473µW</td>
<td>275µW</td>
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<tr>
<td></td>
<td>270µW</td>
<td>464µW</td>
<td>264µW</td>
</tr>
<tr>
<td></td>
<td>266µW</td>
<td>451µW</td>
<td>248µW</td>
</tr>
</tbody>
</table>
Transducer for intelligent fluid quick connector

Ongoing Research: Anti-Theft Sensor

Questions:

Does the vibration have enough energy to:

- Sense the signal
- Process the data
- Transmit info

What is the conversion efficiency?
Frequency tunable converters

Frequency shift by axial preload

D. Spreemann

Bio fuel cells

Characteristics

• Generation of DC current by catalytic oxidation of biofuel (e.g. glucose)
• Use of different (bio)catalyzers (enzymes, microbes, metals)
• Output voltage: 0.1…0.5 V
• Output power: µW…mW

IMTEK, Laboratory for MEMS applications
Direct glucose fuel cell

S. Kerzenmacher, R. Zengerle, IMTEK

The „self-feeding“ Robot!

„Autonomous“ robot „EcoBot II“ with 8 microbial fuel cells

- Max. speed: 10…30 cm/h
- Typical “consumption”: 8 flies within 5 days

University of Bristol
Hybrid Harvesting System

Use different harvesters to complement energy supply

- e.g. vibration and heat in a motor
- e.g. vibration and light in an industrial application

Energy aware power management unit
Energy Aware Hierarchy of Functions

- Energy Conversion
  - Power Management
  - Band Limiting
  - Amplification
  - Compensation
  - Linearization
  - Filtering
  - Calibration
  - Compression
  - Storage
  - Analysis

Power Requirements

- Sensor
  - Low Power Interface
  - ADC
    - Digital Sig. Proc. & Control
    - Data Transmit & Protocol

Power Needed:
- Data Acquisition and A/D Conversion: 1nJ / sample
- Computation: (32bit Instructions) 1nJ / Instruction
- RF-Link: (10-100m) 100nJ / bit

Compute before transmitting!
For every transmitted bit we can afford 100 computations
Who is consuming how much current?

80%-90% of energy goes to transmission
(EnOcean, 2003)

Interfaces for AC generators
One-Way and Full-Wave Bridge Rectifier

Only every second half-wave is rectified → large energy loss

Both half-waves are rectified → smaller energy loss, but double voltage drop

Low-Voltage Rectification

MOSFETs as switches
- Full-Bridge with only 1 “diode” voltage loss
- Integration in standard CMOS is easy
- Diodes prevent excessive reverse leakage

\[ V_{\text{loss}} \approx V_{\text{th}} + IR_{DS,\text{on}} \]

small

Cross-coupled Inverters
- No significant voltage drop
- Integration in standard CMOS is easy
- But bidirectional functionality
Active Rectifier

Two stage approach:

- First stage:
  - Negative voltage converter
- Second stage:
  - Diode part

Active Rectifier – Active Diode

Second Stage – Active Diode

- Concept:
  - pMOS switch driven by a comparator
- Very small voltage drop
  - $V_{\text{drop}} = R_{DS} \times I$
- But: Active elements
  - Permanent current consumption
  - Reduced bandwidth
Active Rectifier – Results

Implementation:
- CMOS 0.35μm process
- No special process options needed
- ~30% more output power!

Interfaces for AC generators
Interface for inductive generators

Switch Capacitor Array between Rectifier and Buffer

• Provides the opportunity of
  ➢ Decoupling of generator and buffer cap.
  ➢ Matching the impedance of the generator
  ➢ Immediate voltage conversion

Parallel - Stack Operation

D. Maurath, ESSCIRC 2009
Implementation – 0.35 µm CMOS

![Image of a circuit diagram]

**Comparison of Harvesting Efficiencies $\eta_{hvst}$**

**Less peak efficiency**
- but ideal load condition rarely occurs (e.g. in a sensor network node)
- Medium load (e.g. active - measure state of a sensor node)

**High harvesting efficiency for**
- Low load (e.g. sleep state of a sensor node)
- High load (e.g. transmit state of a sensor node)

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**Table:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMOS</td>
<td>0.35 µm</td>
</tr>
<tr>
<td>Area</td>
<td>4.56 mm²</td>
</tr>
<tr>
<td>$V_{pp,min}$</td>
<td>&gt; 1.1 V</td>
</tr>
<tr>
<td>$V_{pp,max}$</td>
<td>7.2 V</td>
</tr>
<tr>
<td>$P_{out,typ}$</td>
<td>300-700 µW</td>
</tr>
<tr>
<td>$P_{control}$</td>
<td>27 µW</td>
</tr>
<tr>
<td>$f_{gen}$</td>
<td>&lt; 500 Hz</td>
</tr>
<tr>
<td>$R_i$</td>
<td>1-10 kΩ</td>
</tr>
</tbody>
</table>
**Principle of operation - SECE**

- Synchronous electric charge extraction (SECE)
- Pulsed operation, triggered by peak of $V_{\text{RECT}}$
- Temporary energy storage in coil
- Energy accumulated in large storage capacitor, unregulated output voltage $V_{\text{CAP}}$
- Duration of transfer process (phases B+C) much shorter than half-period of excitation
- Challenge: Generation of control signals for S1, S2, S3

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**SECE CMOS implementation**

- 0.35 µm CMOS process with high voltage option
- 5 V input transistors
- Bidirectional “rectifier”: Reverse current blocked by S2
- Autonomous operation:
  - Gate signal generator powered by storage capacitor
  - Low average power (µW range) consumption due to dynamic enable/disable
- Timing independent from $V_{\text{CAP}}$

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T. Hehn, PowerMEMS 2010
SECE measurement results

- Best performance using the 2.2 mH coil ($R_{DC} = 5.4$ Ohm)
- Output power quite constant for $V_{CAP} = 1.5$ V ... 2.5 V, higher power consumption and higher dynamic losses with higher $V_{CAP}$
- Power gain compared to Schottky diode rectifier ($V_D = 0.2$ V):
  - $1.3x$ @ $V_{CAP} = 1.4$ V
  - $1.7x$ @ $V_{CAP} = 2.1V$
  - $5x$ @ $V_{CAP} = 2.7$ V

Minimum Supply Voltage of Digital Blocks

Supply voltage reduction beyond minimum energy per operation point for...

- Energy harvesting devices delivering low VDD
- Always-on circuits with low speed requirements
  - Standby power reduction
- BUT: On- to off-current ratio degrades with decreasing VDD
Leakage Quenching in Schmitt Trigger

Feedback: Node X close to $V_{DD}$

$V_{DS}$ of middle transistor close to zero

$V_{GS}$ of middle transistor below zero

$\Rightarrow$ Leakage Quenching

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Speed / Energy / Power

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![Graph showing Frequency, Active Energy per Operation, and Leakage Power vs. Supply Voltage]
Minimum Supply Voltage – Temperature Dependence

Conclusions

• Energy Harvesting provides new opportunities
  ➢ Sensor applications
  ➢ Condition monitoring
  ➢ Remote areas

• Codesign of generator and interface electronics
  ➢ More than More than Moore

• Power efficient adaptive interfaces
  ➢ Impedance matching
  ➢ Frequency matching

• Ultra low-power sensor electronics
  ➢ Digital and analog subthreshold design

• Hybrid Systems
  ➢ More than one generator type for reliable supply