Energy Harvesting
Power from the People!
Christopher D. Rahn
The Pennsylvania State University
Standard Quartz Watch
< 10 uW

Jawbone UP4
• Battery: 38 mAh, 3.6 V = 137 J
• Lasts “up to 7 days”.
• 225 – 500 uW average power draw

Apple Watch (38 mm version)
• Battery: 205 mAh, 3.6 V = 738 J
• Lifetime: 5 – 18 hrs → 14 – 41 mW
• 14 – 41 mW average power draw

Energy harvesting technologies
- Thermal
- Solar
- Vibration
- Human Power

Energy Harvesting Market
Energy Harvesting Publications by Year

Thermal Energy Harvesting

  - $\Delta T = 5$ °C, 25 rows in series
  - Output
    - 88 mA, 0.75 V
    - 33 mW with matched load
Flexible thermoelectrics

Wearable devices

Photovoltaic

• Thermoelectric energy harvesters from the Holste Center (IMEC)
• Able to achieve about 50 uW/cm² on wearable devices
  • http://www.holstcentre.com/PartneringinResearch/SharedPrograms/WAST/MicroPowerGeneration.aspx

• ~ 15 mW/cm² outside in direct sunlight
  – 15% efficiency, 100 mW/cm²

<table>
<thead>
<tr>
<th>Distance</th>
<th>Power (μW/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 cm</td>
<td>503</td>
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<tr>
<td>30 cm</td>
<td>236</td>
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<tr>
<td>45 cm</td>
<td>111</td>
</tr>
<tr>
<td>Office Light</td>
<td>7.2</td>
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</tbody>
</table>
DSSC / Perovskite Solar Cells and Modules

<table>
<thead>
<tr>
<th>Samples</th>
<th>Voc (V)</th>
<th>Jsc (mA cm⁻²)</th>
<th>FF (%)</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>One-step deposition</td>
<td>0.84</td>
<td>18.48</td>
<td>48.45</td>
<td>7.52</td>
</tr>
<tr>
<td>Two-step deposition</td>
<td>0.88</td>
<td>19.36</td>
<td>63.12</td>
<td>11.01</td>
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<tr>
<td>Solvent engineering</td>
<td>1.06</td>
<td>20.4</td>
<td>73.91</td>
<td>15.99</td>
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</tbody>
</table>

- Close to highest efficiency reported in literature.
- One of the first demonstrations of the ferroelectric nature.
- Large area flexible module development.

Shashank Priya et al.

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Power Potential from Human Motion

<table>
<thead>
<tr>
<th>Joint/Motion</th>
<th>Power [W]</th>
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</thead>
<tbody>
<tr>
<td>Foot/Toes</td>
<td>2</td>
</tr>
<tr>
<td>Ankle</td>
<td>70</td>
</tr>
<tr>
<td>Knee</td>
<td>50</td>
</tr>
<tr>
<td>Hip</td>
<td>39</td>
</tr>
<tr>
<td>Elbow</td>
<td>2</td>
</tr>
<tr>
<td>Shoulder</td>
<td>2</td>
</tr>
<tr>
<td>Center of Mass</td>
<td>1</td>
</tr>
</tbody>
</table>


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Electromechanical Energy Harvesting.

- Inductive
- Capacitive
- Piezoelectric

Vs Vs Rs
Vs Lc Rc Load
Vibrations

Clamped => Reliable connection
Tunable stiffness

State of the art mechanical harvester

Experimental Setup
Heel Strike - Shoes

Krupenkin and Taylor. 2011 Nature Communications

“few mW”

See also http://www.instepnanopower.com/

Heel Strike - Shoes

Bramhanand et. al., 2012. Hilton Head

7.3 mW

Prof. Hanseup Kim’s group.

Energy harvesting backpacks

Rome et. al., 2005 Science.

7.4 watts

80 lb backpack
Energy harvesting from knee rotation

~ 3.5 watts / leg
~ 2.4 watts / leg – regenerative braking mode

Wrist worn piezoelectric energy harvester

Photos by Susan Trolier-McKinstry group, Penn State.
Flex circuits by Tom Jackson group, Penn State.
Device design/integration by Shad Roundy group, U. Utah.

Energy harvesting from breathing
Energy harvesting technologies

- Thermal
- Solar
- Vibration
- Human Power

Thank You