Flexible thermoelectric energy harvesters using bulk thermoelectric materials and low-resistivity liquid metal interconnects

Mehmet C. Ozturk and M. Dickey
Yasaman Sargolzaeiaval, Viswanath Padmanabhan Ramesh & Taylor Neumann

North Carolina State University
Advanced Self-Powered Systems of Integrated Sensors and Technologies (ASSIST) Nanosystems Engineering Research Center
ASSIST vision of health and wellness is enabled by its disruptive system features

ASSIST’s vision of health and wellness is enabled by its disruptive system features

Motion - Piezoelectric
Heat - Thermoelectric

Long-term monitoring of personal health & environment enabled by always-on platforms

Self-Powered/Ultra Low Power
Wireless
Hassle-Free/Comfortable
Medically Validated
Non-invasive/minimally invasive
Multi-modal health and environmental sensors

Sophisticated picture of health via correlation of multiple sensors

Enable a pathway towards personalized medicine
ASSIST Roadmap

Health and Environmental Tracker

ASSIST Low-Power Sensor Technologies
- Ozone
- VOC
- PPG
- ECG

Detection
- Wheeze / Cough

Critical Data Correlation
- Ozone / Respiratory & Cardiac Health

ASSIST Low-Power Detection Technologies

HET 1
- Asthma Management
  - Long term monitoring of environmental exposures & health

HET 2
- Diet Management & Wound Healing
  - Non-Invasive Glucose/Lactate & Wound Health Monitoring
  - ASSIST Zero-Power Extraction and Transportation Technologies
    - Sweat
    - ISF
    - Wound Fluid
  - ASSIST Low-Power Detection Technologies
    - Glucose
    - Lactate
    - Uric Acid
    - Breathable Materials

Critical Data Correlation
- Food Intake - Glucose / Lactate Levels & Uric Acid - Wound Health

HET 3
- Medication Adherence
  - Non-Invasive Medication Detection
    - ASSIST Zero-Power Extraction and Transportation Technologies
      - Sweat
      - ISF
    - ASSIST Low-Power Detection Technologies
      - Monitoring of Medication Intake

Critical Data Correlation
- Medication Intake & Physiological Parameters from HET 1.0 & 2.0

ASSIST Zero-Power Extraction and Transportation Technologies

SAP 1
- Cardiac Health
  - Vigilant ECG (R-R) and Motion

SAP 2
- Cardiac Health, Blood Pressure & Asthma
  - SAP 1.0 + HET 1.0

SAP 3
- Cardio-Metabolic Health
  - SAP 2.0 + HET 2.0

ASSIST Energy Harvesting and Low-Power Circuit Technologies

Energy Harvesting
- Supercapacitors
- SoC & Radio
- ECG AFE

Critical Data Correlation
- A-Fib and Activity Identification Optimized for Low-Power

Critical Data Correlation
- HET 1.0 and Pulsed Transit Time Blood Pressure

ASSIST Energy Harvesting, Sensor & Low-Power Circuit Technologies

Energy Harvesting
- PPG
- ECG
- Ozone

ASSIST Energy Harvesting, Sensor & Low-Power Circuit Technologies

Energy Harvesting
- VOC
- Ozone
- BP Biomarkers < Sweat/ISF
- ECG
- PPG

Critical Data Correlation
- Metabolic Changes & Cardiac Health

Self-Powered Adaptive Platform
Harvesting Heat from the Body

Flexible thermoelectric generators (TEGs) are desirable:

- Conformal to the body
  - Better contact with the skin
- Large area harvesting
  - Simple Integration
  - Electrical resistance
  - Aesthetics

The application imposes large thermal resistances
Harvesting Heat from the Body

Key Challenge: Small $\Delta T$ across the harvester
Our approach to Flexible Thermoelectrics

- Bulk thermoelectric materials
  - Best materials used in rigid TEGs
  - No new material development
- Pick-and-Place Tooling
  - Standard technique
- Flexible packaging
  - Material Innovations

A flexible approach with a low cost-of-ownership that can rival the performance of rigid TEGs
Eutectic Gallium Indium (EGaIn)

Gallium + Indium = Liquid

- Low viscosity
- Low toxicity
- Near-zero vapor pressure

Can be encapsulated by an elastomer

Gallium 30 °C
Indium 157 °C
Liquid 16 °C

TEG Fabrication with EGaIn Interconnects

TEG with liquid interconnects

PDMS Encapsulation

Suarez at. Al, Flexible thermoelectric generator using bulk legs and liquid metal interconnects for wearable electronics, Applied Energy, 2017
Testing on the Human Body

Promising performance despite
- No heat spreaders
- No heatsink
- Thick PDMS encapsulation
Mechanical Testing
Mechanical Testing

- Low Resistance - negligible contribution from interconnects
- Spikes recovered due to “self-healing” nature of EGaIn
Further Improvements

- Thinner Top and Bottom Elastomers & Higher Thermal Conductivity
- Taller Legs
- Thin Metal Spreaders
- Reduction of Filler Thermal Conductivity
Printing and Spray Coating of EGaIn

- Printing provides faster and more reliable interconnects on TEGs with large leg count
- Spray coating of encapsulation provides a much thinner encapsulation
Flexible TEG with 256 legs & Spray Coated Encapsulation
**Al₂O₃, AlN, and BN Doped PDMS**

Increasing the thermal conductivity of the encapsulating layer

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity</th>
<th>Powder size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al₂O₃ Powder</td>
<td>~35 W/mK</td>
<td>≤10 µm</td>
</tr>
<tr>
<td>AlN Powder</td>
<td>~150 W/mK</td>
<td>~10 µm</td>
</tr>
<tr>
<td>BN Powder</td>
<td>~30 W/mK</td>
<td>~1 µm</td>
</tr>
</tbody>
</table>

3X enhancement can be achieved in the thermal conductivity of PDMS
Output Power – Device characterization on the wrist – *Impact of time on the wrist*

- Refrigerator (1 °C)
  - Immediate
  - 1 minute
  - 5 minutes

- Room Temperature (22 °C)
  - Immediate
  - 1 minute
  - 5 minutes

- Outdoor (~32 °C)
  - Immediate
  - 1 minute
  - 5 minutes

3X improvement in performance with
- Thin PDMS encapsulation
- Al$_2$O$_3$ doped PDMS top/bottom layers

Still... No heatsink or heat spreaders
Device characterization on the wrist
Voltage, Temperature Differential and Power

![Graphs showing output power, measured load voltage, and temperature differential vs. air velocity at different temperatures.](image-url)
## Benchmarking (w/o Air Flow)

<table>
<thead>
<tr>
<th>Output Power (µW/cm²)</th>
<th>Author/Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>S.E. Jo et al/25</td>
</tr>
<tr>
<td>0.178</td>
<td>M.K. Kim et al/15</td>
</tr>
<tr>
<td>1</td>
<td>S.J. Kim et al/15</td>
</tr>
<tr>
<td>0.224</td>
<td>M.K. et al/15</td>
</tr>
<tr>
<td>0.25</td>
<td>S.L. Kim et al/15</td>
</tr>
<tr>
<td>0.084</td>
<td>S.E. Jo et al/20</td>
</tr>
<tr>
<td>3</td>
<td>Trung et al/15</td>
</tr>
<tr>
<td>3.2</td>
<td>Our work/22</td>
</tr>
<tr>
<td>4.5</td>
<td>Our work/15</td>
</tr>
</tbody>
</table>

### Authors and Techniques:
- **PDMS + Dispensing printing of TE legs, Yonsei University (Korea)/2012**
- **Flexible fabric+ Dispensing printing of TE legs, Yonsei University (Korea)/2014**
- **CNT TE legs/ No encapsulation, Texas A&M University/2014**
- **PDMS + Dispensing printing of TE legs, Yonsei University (Korea)/2015**
- **CNT TE legs/ No encapsulation, Texas A&M University/2014**
- **PDMS + Dispensing printing of TE legs, Yonsei University (Korea)/2015**
- **Multi stage TEG/ PDMS+ Electrochemical deposition of TE legs, Tohoko University (Japan)/2017**

### Temperature Conditions:
- **T_{amb} = 15°C**
- **T_{amb} = 22°C**
- **T_{amb} = 1°C**
Further Improvements – COMSOL simulation
A low thermal conductivity elastomer between the legs can increase the power by ~ 2X
Graphene/EGaIn Doped Elastomer

- Our approach was elastomer doping with high thermal conductivity particles
- We have tried
  - Al2O3, AlN, BN, Graphene and EGaIn
- Best results were obtained with EGaIn + Graphene Doping
  - 0.85 W/mK (5.6X improvement)
- We can increase the encapsulating thickness to 200 um without paying significant penalty
Improved TEG design

- High Thermal Conductivity Elastomer
- Low-Resistivity EGaIn Interconnects
- Nanocomposite BiTe Legs
- Spray Coated Thin Elastomer
- Low Thermal Conductivity Elastomer
- Copper Heat Spreader
- Titanium
- Gold
Conclusions

- EGaIn provides
  - Printable, low-resistivity, stretchability
  - Self-healing, reliability
  - Room-temperature bonding to TE legs
- There is still much room for improvement
  - Thermal management - Device packaging and materials

There is potential for producing flexible TEGs that rival the performance of rigid TEGs
Wearable Energy Harvesting and Storage Devices

Guest Editor
Prof. Dr. Mehmet C Ozturk

Deadline
30 September 2018