Laser-assisted direct-writing of thermoelectric generators

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Outline

1. Motivation
2. Laser-induced forward transfer
3. Thermoelectric generator designs
4. Results
5. Comparison with existing generators
6. Conclusion
1. Motivation (I)

Thermoelectric generation (TEG) via Seebeck effect

Current thermoelectric (TE) research:
• Increasing efficiency of materials (lowering thermal conductivity & electrical resistivity, increasing Seebeck coefficient).

• New, inexpensive and non-toxic materials

• Devices with increased power density (via scaling, packaging) + novel manufacturing methods
1. Motivation (II)

- **Reduce complexity** in manufacturing (using a laser-assisted transfer technique):
  - Sequential transfer
  - Fast deposition (Single laser pulse process)
- **Combine complex materials in device**
  - Intact transfer of solid material onto polymer
  - Preserving phase of material

**Objective:** Fabricate and test working thermoelectric generator via laser-induced forward transfer
2. Laser-induced forward transfer

- Laser-induced forward transfer (LIFT)
- Additive direct-write
- Thin film technique for the fabrication of electronic devices
- Transfer solid materials in intact state
- Preserve physical properties of donor
2. Laser-induced forward transfer

Experimental:
- UV excimer laser system, 248nm
- 20ns pulses, max. 0.4J pulse energy, 3x demagnification
- Typical donor/receiver spacing of some microns or in contact.
2. Principle of LIFT

1) Absorption

Laser pulse
2. Principle of LIFT

2) Pressure build-up
2. Principle of LIFT

3) Transfer
2. Sequential transfer

Step 1)

- Laser pulse
- Carrier (fused silica)
- stage movement
- Receiver (glass)

Step 2)
3. Designs of TEG

- Lateral-lateral design: heat and current flow in substrate plane
- Design chosen as most common thermoelectric thin film device technology
- Two designs: Silver (Ag)-contacted & staggered thermocouples (TC)
Deposition of chalcogenides (Bi$_2$Se$_3$, Bi$_2$Te$_3$ and Bi$_{0.5}$Sb$_{1.5}$Te$_3$) via LIFT without intermediate release layer onto polydimethylsiloxane (PDMS)-coated glass substrate:

- Preservation of >75% of Seebeck coefficient
- Deposited areas up to 15mm$^2$ area

Substrate size: ~25mm x 20mm
4. Electrical characterisation

For single TC:
- Contact resistance (staggered TC) ~2kΩ
- Total resistance: 9kΩ
- Large TE element resistance due to non-optimised materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Resistivity [Ωm] (±10%)</th>
<th>Seebeck coefficient (donor) [μVK⁻¹] (±5%)</th>
<th>Seebeck coefficient (deposit) [μVK⁻¹] (±5%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi₂Se₃</td>
<td>0.04</td>
<td>-121</td>
<td>-93</td>
</tr>
<tr>
<td>Bi₂Te₃</td>
<td>0.003</td>
<td>-64</td>
<td>-49</td>
</tr>
<tr>
<td>Bi₀.₅Sb₁.₅Te₃</td>
<td>0.0006</td>
<td>+177</td>
<td>+142</td>
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4. Thermoelectric measurements

- Resulting max. Seebeck coefficient for a TC $\sim 170\mu V/K$ (staggered design)
- Max. output voltage $\sim 10mV$ (not shown)
4. Metallisation

- Improves junction contact, but increases reverse diode current + reduces Seebeck voltage!
- In some cases: cracking of TE elements!

![Staggered TC](image1)

![Metallised TC](image2)

**Graph:**
- **Y-axis:** Seebeck voltage (mV)
- **X-axis:** Temperature gradient (K)

**Legend:**
- **Black dots:** Staggered TC
- **Red squares:** Metallised TC

**Scale:** 200 µm
5. Comparison with conventional TEGs (I)

Francioso et al., J Power Sources (2011)

Delaizir et al., Sensor Actuat A-Phys (2012)

Jo et al., Electron Lett (2012)
## 5. Comparison with conventional TEGs (II)

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<tbody>
<tr>
<td>(Francioso et al. 2011)</td>
<td>0.23</td>
<td>3.8 x 10^3</td>
<td>409</td>
<td>0.00019</td>
<td>1.6 x 10^-5</td>
<td>~76</td>
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<td>(Delaizir et al. 2012)</td>
<td>0.88/3</td>
<td>394</td>
<td>108</td>
<td>0.05</td>
<td>1.8 x 10^-3/1.3 x 10^3</td>
<td>~33/25</td>
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<td>(Jo et al. 2012)</td>
<td>1.75/27.4</td>
<td>21.25</td>
<td>350</td>
<td>0.56</td>
<td>2.8 x 10^-3/1.0 x 10^-4</td>
<td>4.5/0.16</td>
</tr>
<tr>
<td>This study</td>
<td>1.47</td>
<td>~10^4</td>
<td>210</td>
<td>0.0013</td>
<td>1.299 x 10^-4</td>
<td>~90</td>
</tr>
</tbody>
</table>

*From: Glatz et al., J Microelectromech S (2009)*
6. Conclusions

- LIFT presented as **additive direct-write** tool for **microfabrication**
- Demonstrated **working thermoelectric generator** (TEG) on **polymer-coated** substrate
- Key results:
  - Sequentially LIFTed device elements
  - Seebeck coefficient/TC: $\sim 170 \mu V/K$
  - Performance comparable with other lateral-lateral TEGs on polymer

- **Future**: transfer of more complex TE materials, use of fully flexible substrate, Metal electrodes via LIFT
Acknowledgements

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LIFT at the University of Southampton: http://www.orc.soton.ac.uk/lift.html