Performance Improvement of Thin-Film Thermoelectric Devices for Energy Harvesting and Cooling Applications

Dave Koester
Nextreme Thermal Solutions
3908 Patriot Drive, Durham, NC 27709

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Introduction to Nextreme Thermal Solutions

• Founded December, 2004
• Financing
  – Series A Venture Financing: $14M
  – Series B Venture Financing: $13M (July ‘08)
    • Chart Ventures, RedShift Ventures, Harris & Harris, In-Q-Tel, RTI, Itochu Corporation, Itochu Technology Ventures
  – Two Strategic Investments: $8M (‘09)
• 35 employees
• Located in Durham, NC
Why Thin-Film?

- **Form Factor**
  - Reduce thickness
  - Reduce footprint
  - Reduce weight

- **Integration**: directly into components

- **Performance**: pump more heat per unit area

- **Cost**:
  - Reduce manufacturing costs
  - Reduce use of TE material
Today’s Core Products
Cooling Performance

ΔT vs Qc at 25°C

HV14

I=0.12 A
I=0.24 A
I=0.43 A
I=0.67 A
I=1.22 A

ΔT vs Qc at 25°C

UPF40

I=0.46 A
I=0.92 A
I=1.61 A
I=2.54 A
I=4.61 A
HV14 Thermoelectric Generator (TEG)

At 120°C DT
- 20 W/g
- 2.6 W/cm²
- 43 W/cm³
UPF40 Thermoelectric Generator (TEG)

At 120°C DT
• 13 W/g
• 1.6 W/cm²
• 27 W/cm³
UPF40 – TEG Evaluation Kit

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TEG Efficiency Improvement
North Carolina Green Business Fund

• Nextreme awarded one year program to improve TEG efficiency
• Synthesized n-type BiTeSe and p-type BiSbTe epitaxial films in excess of 30 um thick
  – Double typical thickness
  – Retained all material specifications
• Doubled conversion efficiency of baseline devices for given heat flux.
Improving Output Voltage
$V_{oc}/Q$ vs Contact Area

![Graph showing $V_{oc}/Q$ vs Relative Contact Area for Std Thickness and Double Thickness with specific points labeled Current HV14]
Applications
Semiconductor Hot-spot Cooling

- Servers & Workstations
- High-performance PCs
- Cellular infrastructure
- Set-Top Boxes

Intel validation (Saguaro TTV)
Applications: Industrial Equipment
Thermal Cycling--PCR

2 UPF 40s

--- Independent testing of thermal cycling showed TFTEC to be 9.5x more efficient & 2.5x faster than traditional solutions
Applications: Photonics
Telecom—Laser Diode

Nextreme has demonstrated necessary size & performance as well as 4x efficiency in laser diode cooling

Meeting New Challenges
Smallest Size

Highest Pumping Power

TO56
Applications: Photonics

LED Cooling

2 UPF40 Modules

Top view w/o LED

Side view of complete assembly

• TEC cooling lowers the LED junction temperature by ~20°C
  → Increased LED intensity and/or efficiency
  → Increased long-term reliability

High Power White LED Junction Temperature

I_{LED} (A)  T_{j} (°C)

0.2 0.3 0.4 0.5 0.6 0.7 0.8
20 30 40 50 60 70 80 90 100 110 120
Performance Headroom
Material Property Distributions from Module Extractions

Thermal Conductivity ($k$)
- Frequency
- Values: 0.55, 0.6, 0.65, 0.7, 0.75, 0.8, 0.85, 0.9, 0.95, 1, 1.05, 1.1, 1.15, 1.2, 1.25

Electrical Resistivity ($\rho$)
- Values: 0.7, 0.75, 0.8, 0.85, 0.9, 0.95, 1, 1.05, 1.1, 1.15, 1.2, 1.25

Couple Seebeck ($\alpha$)
- Values: 300, 325, 350, 400, 425, 450, 475, 500, 525, 550, More

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Thermal Conductivity Measurements
Data Extractions Corroborated by Through-Plane $k$ Measurements

- Method: Time-resolved Thermoreflectance
- Conducted by Dr. David Cahill, University of Illinois, Urbana-Champaign

  N-type thermal conductivity: 0.78 W/mK
  P-type thermal conductivity: 0.68 W/mK
Extracted Intrinsic and Measured Extrinsic ZT

Histogram Comparing Recent Extrinsic and Intrinsic ZT values (at rm T)
Effect of Parasitic Losses

Thin film device performance is dominated by contacts to the device.

\[ Z_e T = \frac{Z_i T}{\left(1 + 2 \frac{\rho_c}{L_m \rho_m}\right) \left(1 + 2 \frac{L_c}{L_m} \frac{k_m}{k_c}\right)} = \frac{Z_i T}{(1 + \Gamma_e)(1 + \Gamma_i)} = \eta_e \cdot \eta_t \cdot Z_i T \]

\[ \eta_t \approx 90\% \]
\[ \eta_e \approx 35\% \]
Effect of Contact Resistance on Device ZT

Increase ZT by:
- Reducing electrical contact resistance $\rho_c$
- Increasing thickness (t) of TE elements
TEG Efficiency Improvements

\[ \eta_{\text{max}} \text{ at } \Delta T_{\text{op}}=120, 150, 200 \text{ K, } T_C=300\text{K}, \text{ vs. } \rho_c/\rho \text{ for matched } P/N, \rho_n=14, \rho_p=9 \]

\( \eta \Delta T_{\text{op}}=120, T_f=420 \)
\( \eta \Delta T_{\text{op}}=150, T_f=450 \)
\( \eta \Delta T_{\text{op}}=200, T_f=500 \)
Summary

• Thin film TE devices offer unique size, weight, performance and cost opportunities

• Applications vary widely
  – Micro-power
    • scalable to macro scale
  – Semiconductor hot spot cooling
  – Photonics cooling

• Improvements in performance being driven through
  – Contact resistance reduction
  – Film thickness increase
  – Contact area reduction
Thank You