Thermoelectricity: From Atoms to Systems

Week 4: Thermoelectric Systems
Lecture 4.3: Microrefrigerator on a chip

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High Cooler Power Density Micro Peltier Coolers

4"-6" wafer technology
Microelectronics compatible

H. Bottner
Cooling Power Density

Conventional Thermoelectric Cooling

Net Cooling:

\[ Q = S_{pn} T_C I - \frac{1}{2} I^2 R - \beta \Delta T; \]

Peltier Cooling  Joule Heating  Heat Conduction

Coefficient of Performance:

\[ COP = \frac{Q}{W} = \frac{S_{pn} T_C I - \frac{1}{2} I^2 R - \beta \Delta T}{S_{pn} (\Delta T) I + I^2 R} \]

The coefficient of performance, COP, of a TE cooler is the ratio of cooling capacity to the amount of input power.
Superlattices/ Quantum Dot Thermoelectrics

Quaternary: $ZT = 2$
$\Delta T = 43.7$ K

T.C. Harman, Science, 2002

$\Delta T = 32.2$ K, $ZT \approx 2-2.4$

Actual $ZT \approx 1$
(see papers by C. Vineis et al.)

<table>
<thead>
<tr>
<th>PbTe/PbSeTe Nanostructure</th>
<th>Bulk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Factor ($\mu W/cmK^2$)</td>
<td>25.5</td>
</tr>
<tr>
<td>Thermal Conductivity (W/mK)</td>
<td>0.5</td>
</tr>
</tbody>
</table>

In-plane geometry

<table>
<thead>
<tr>
<th>Bi$_2$Te$_3$/Sb$_2$Te$_3$ Superlattice</th>
<th>Bulk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Factor ($\mu W/cmK^2$)</td>
<td>40</td>
</tr>
<tr>
<td>Thermal Conductivity (W/mK)</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Cross-plane geometry

(From M. S. Dresselhaus, Rohsenow Symposium, 2003)
Thin Film Peltier Coolers

Microrefrigerators on a chip


Performance of microrefrigerators

- Monolithic integration on silicon
- $\Delta T_{\text{max}} \sim 4^\circ\text{C}$ at room temp. (7$^\circ\text{C}$ at 100$^\circ\text{C}$)
- Cooling power density > 500 W/cm$^2$


*Featured in Nature Science Update, Physics Today, AIP April 2001*
SiGe superlattice microrefrigerators

Nanoscale heat transport and microrefrigerators on a chip; A. Shakouri, Proceedings of IEEE, July 2006
Microrefrigerator with integrated heater

Thin film heater and thermistor fabricated on top of microrefrigerator

Device Area dependence

Fig. 13. The maximum cooling power density at zero net cooling (solid circles) and the maximum cooling temperature at zero heat load (open squares) versus device size for the SiGe superlattice microrefrigerator (see Fan [101] and Zang et al. [96]).

Nanoscale heat transport and microrefrigerators on a chip; A. Shakouri, Proceedings of IEEE, July 2006
Ultra Fast Co-Planar Peltier Coolers

B. Vermeersch, J. Bahk et al. JAP 2013

return contacts

tapering maintains 50Ω

probe contact pads

coplanar waveguides

directional current flow

not to scale

direction of metal deposition

constriction

current flow
Ultra Fast Peltier Cooling

B. Vermeersch et al. JAP 2013
# Superlattice vs. Alloy Thin Film SiGe Cooler

<table>
<thead>
<tr>
<th>Material</th>
<th>Seebeck Coefficient, $S$ (µV/K)</th>
<th>Electrical Conductivity, $\sigma$ (Ωcm$^{-1}$)</th>
<th>Thermal Conductivity, $\beta$ (W/mK)</th>
<th>Power Factor, $S^2\sigma$ (10$^{-3}$ W/K$^2$m)</th>
<th>Figure-of-Merit, $ZT = S^2\sigma T/\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical Bi$_2$Te$_3$ alloy</td>
<td>200-220</td>
<td>1000</td>
<td>1.5</td>
<td>4.0</td>
<td>0.8-1.0</td>
</tr>
<tr>
<td>Si (p-type) (Micro</td>
<td>325</td>
<td>330</td>
<td>150</td>
<td>3.5</td>
<td>0.007</td>
</tr>
<tr>
<td>refrigeration $\Delta T_{\text{max}}= 1.1\text{K}$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Si (optimized p-doping)</td>
<td>450</td>
<td>285</td>
<td>150</td>
<td>5.8</td>
<td>0.012</td>
</tr>
<tr>
<td>Si$<em>{0.9}$Ge$</em>{0.1}$ alloy</td>
<td>9.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Si$<em>{0.8}$Ge$</em>{0.2}$ alloy</td>
<td>210</td>
<td>367</td>
<td>5.9</td>
<td>1.6</td>
<td>0.08</td>
</tr>
<tr>
<td>Superlattice Si/Si$<em>{0.7}$Ge$</em>{0.3}$ (10nm/5nm) (Micro refrigeration $\Delta T_{\text{max}}= 3.5\text{K}$)</td>
<td>200 (∥)</td>
<td>300 (∥)</td>
<td>10.7-12.9 (⊥)</td>
<td>1.8 (⊥, estimated)</td>
<td>0.07 (⊥, estimated)</td>
</tr>
<tr>
<td>Superlattice Si/Si$<em>{0.75}$Ge$</em>{0.25}$ (3nm/12nm) (Micro refrigeration $\Delta T_{\text{max}}= 4.2\text{K}$)</td>
<td>200-220 (⊥)</td>
<td>300 (∥)</td>
<td>6.8-8.7 (⊥)</td>
<td>2.2 (⊥, estimated)</td>
<td>0.085 (⊥, estimated)</td>
</tr>
</tbody>
</table>


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**Table 1** Material Parameters for BiTe Alloy, p-Type Silicon, SiGe Alloys and Si/SiGe Superlattices. Maximum Cooling Temperature of Microrefrigerator Devices Based on Some of the Material Is Also Given. Typical Microrefrigerator Device Size is $60 \times 60 \mu$m square and Alloy or Thin-Film Thickness Is $\sim 3 \mu$m. (∥) Refers to In-Plane Material Properties and (⊥) Refers to Cross-Plane Material Properties. The Estimated Cross-Plane Power Factors and ZTs for Superlattices are Based on the Measured Maximum Cooling of Microrefrigerators and the Comparison With Identical Thin-Film Devices Based on Alloy Material.
10 microns thick, 50x50µm² monolithic microrefrigerator with ZT~0.5 can cool a 1000W/cm² hot spot by >15°C.

Younes Ezzahri, Ali Shakouri et al. InterPACK07, Vancouver, Canada
Peak Temperature anywhere on a chip must be $<85\degree C$ ($T_{j_{\max}}$)

$$Q_{\text{hotspot}} \approx 1.5\text{W on } 500\times500\mu\text{m}^2 (600 \text{ W/cm}^2), \text{ the uniform background is } 100\text{W/cm}^2$$

Total heat [W] = $Q_{\text{uniform}} + Q_{\text{hotspot}}$

Electrical power to pump coolant (FC72)

$1\times1 \text{ cm}^2$ Chip

K. Yazawa et al. ITherm 2012

Microchannel with FC72 coolant

<table>
<thead>
<tr>
<th>delta</th>
<th>55 \text{um}</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>45 \text{um}</td>
</tr>
<tr>
<td>H</td>
<td>330 \text{um}</td>
</tr>
</tbody>
</table>
Solid-state cooling impact on hot spot

K. Yazawa, et al.
ITHERM2012

$q_h = q_{\text{spot}} + q_0$, $q_{\text{spot}} = 0 \sim 1000 \text{ W/cm}^2$, $q_0 = 100\text{ W/cm}^2$

$A = 500\mu\text{m} \times 500\mu\text{m}$ (hot spot & TE cooler size)

$A_0 = 1\text{ cm}^2$ (Die size)

A: area of hot spot

F: fractional area ratio of the TE leg

$d$: leg thickness (length)

$S$: Seebeck coefficient

$\sigma$: electrical conductivity

$\beta$: thermal conductivity

(If only one element is used. Current can be reduced by using multiple n- and p-elements electrically in series and thermally in parallel)

$$T_h = -\frac{\psi_c S d^2 I^3 + \left(\beta FA \psi_c + \frac{1}{2} d\right) \frac{d}{\sigma FA} I^2 - \psi_c Q_h S d I + Q_h d + \beta FA \psi_c Q_h + T_m}{\left(\beta FA + d SI - \psi_c d S^2 I^2\right)}$$
Global optimization of active cooling methods to remove both background heat and hot spot: minimum electric power for cooling

K. Yazawa, Y. Joshi, et al. ITherm 2012

Substrate thickness 500µm

ZT=0.5

~10x efficient
Lecture 4.3: Summary

- Thin film Peltier coolers
- Microrefrigerator on a chip
  - SiGe coolers can achieve 7°C cooling at 100°C ambient and cooling power density >500W/cm²
  - In application for localized cooling, significant impact is possible even with ZT~0.5 if fully integrated inside the chip (ΔT~15°C, cooling power density >1kW/cm²)
- Selective cooling of hot spots can significantly reduce cooling power requirements for the whole chip