Toward Waste Heat Recovery Using Nanostructured Thermoelectrics

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Potential for Waste Heat Harvesting

~ 57% of energy consumed in the US rejected as heat
Sources of Low Quality Waste Heat

- $T_{\text{exhaust}} \sim 400-600 \, ^\circ C$
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- $T_{\text{water}} \sim 33 \, ^\circ C$
- $T_{\text{flue}} \geq 100 \, ^\circ C$ ($\eta_{\text{furnace}} \sim 90\%$)

- $T_{\text{IN}} \sim 27 \, ^\circ C$ (ASHRAE)
- $\delta T \sim 50 – 120 \, ^\circ C$ (HD, State of art at Intel)

- $\eta_{\text{CARNOT}} (T_H=100\% \sim 20\%
- Difficult to extract work
- Fluid machines infeasible
- Transcritical CO$_2$, organic Rankine, Kalina are expensive
- Thermoelectrics?
Thermoelectric Generators

$V_{SEEBECK} = \int_{C}^{H} \nabla \phi \, d\vec{r} = -\int_{C}^{H} S(T) \nabla T \, d\vec{r} = -S \Delta T$

$S \sim k/e \times 10^4 \, V/K$

$Z = \frac{S^2 \sigma}{k}$

Thermopile (Nobili & Melloni)

~ 200 W maximum power

Patent (Yamamoto)

5% efficiency, ZT (Abraham Ioffe)

kW (Russia)

Bi-Sb-Te-Se alloys

Radioscope TEG (Pioneer, Voyager, Galileo, Cassini ...)

\section*{Thermoelectrics}

Thomas Johann Seebeck (1770-1831)

Seebeck, T.J., “Magnetische polarisation der metalle und erze durch temperaturdifferenz”, Verlag von Willhelm Engelmann, Leipzig, Germany (1895)
Thermoelectrics Applications

Refrigeration

Power Generation

Waste Heat Recovery

University of Illinois

BSST

Cassini

Amerigon

[4]
The Thermoelectric Heat Engine

\[ Q_{\text{in}} \]

\[ Q_{\text{out}} \]

\[ \Delta T \propto k^{-1} \]

\[ V = S \Delta T \]

\[ \frac{\sqrt{1 + ZT}}{\sqrt{1 + ZT} + \frac{T_C}{T_H}} \]

\[ ZT = \frac{S^2 T}{k} \]

\[ \eta = 1 - \frac{T_{\text{cold}}}{T_{\text{hot}}} \]

\[ \text{Bi}_2\text{Te}_3 \]
The Z Conundrum

$Z = \frac{S^2}{\sigma}$

- Microscopic linkage between $S$, $\sigma$ and $k$

Degenerate semiconductors

$S^2 \sigma$

Metals

Carrier concentration

$\kappa = (\kappa_{\text{Electron}} + \kappa_{\text{Lattice}})$

$\kappa_E$

$\kappa_L$

Carrier concentration

Wiedemann Franz Law

$\kappa = LT$

$\kappa \leftrightarrow \sigma \leftrightarrow S$
Conversion Efficiency

\[ h = \frac{1}{\text{CARNOT}} \times \frac{1}{\sqrt{1 + Z_T}} \times \frac{T_C}{T_H} \]

\[ Bi_2Te_3 \text{ alloys have } Z_T \sim 1 \text{ at } 300 \text{ K} \]

Scalability Issues:
- Low abundance
- ~15x expensive as Si

What about silicon?
\[ k \sim 150 \text{ W/mK (300 K)} \]

\[ \Rightarrow \text{ Bulk } Z_T \sim 0.01 \]
Thermal Conductivity

- Lattice vibrations conduct heat in Si

From Kinetic theory, $k \sim C v \Lambda$

$\Lambda$ limited by different scattering processes

Boundary Scattering

Impurity Scattering

Phonon-Phonon Scattering (Umklapp)
Boundary scattering dominates in 100 nm Si

Phonon boundary scattering is frequency dependent and tunable through roughness

$\Lambda_{\text{PHONON}} \approx 100\text{-}300 \text{ nm}$
UIUC Silicon TE Device Concept

- Hot Gas
- Cooling Water

- Rms roughness > 2nm
- Corr. Length < 100 nm
- Dia < 100 nm

- Sq. mm array
- > 25 % areal coverage
- Resistivity ~ mΩ-cm
- L > 10 µm
Wire Array Fabrication

Image Reversal via Lift-Off

Thermal Dewetting

MAC-Etch
**Device Formation**

SOG/Poly Fill & Contact Formation

Controlled Roughness Enhancement

Transfer Printing ($n$- and $p$-type)
Roughened wire still crystalline

Image Stitching Process
\( \rho \) can be reduced to \( \sim 1 \ \text{m}\Omega\cdot\text{cm} \) via controlled doping.
Single Wire Thermal Measurements

Thermal Conductivity (W/mK)

Temperature (K)

5.0kV 10.6mm x 4.00k

5.0kV 11.0mm x 25.0k

University of Illinois

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Array Seebeck and Thermal Measurements

Heater
Voltage pad
NW array
Substrate

\[ R_{\text{ox}} \]
\[ R_{\text{NW}} \]
\[ q'' \]
\[ \text{Sub f(w)} \]
\[ V_n \]
\[ V_s \]

NW sample
Reference

\[ T_{h2} \]
\[ q'' \]
\[ \text{Sub f(w)} \]
\[ V_s \]

\[ \Delta T = 0.34 \; K \]

\[ \Delta V = -60 \; \mu V \]

Frequency (Hz)

T/P (K/W)

Ref NW

V/P (uV/W)

Ref. NW array

Frequency (Hz)
Summary and Outlook

- Silicon thermoelectrics potentially enables unprecedented cost-effective waste heat recovery
- Ongoing work at UIUC seeks to fabricate the first truly nanostructured silicon thermoelectric device
- Preliminary characterization work shows promising trend and focus is now on device engineering