Nanotechnology has provided a new interest in thermoelectric technology. A thermodynamically driven process is one approach in achieving nanostructures in bulk materials. TiO$_2$/SnO$_2$ system exhibits a large spinodal region with exceptional stable phase separated microstructures up to 1400 °C. Fabricated TiO$_2$/SnO$_2$ nanocomposites exhibit n-type behavior with Seebeck coefficients greater than -300 V/K. Composites exhibit good thermal conductance in the range of 7 to 1 W/mK. Dopant additions have not achieved high electrical conductivity (<1000 S/m). Formation of oxygen deficient composites, TixSn1-xO$_{2-y}$, can change the electrical conductivity by four orders of magnitude. Achieving higher thermoelectric ZT by oxygen deficiency is being explored. Seebeck coefficient, thermal conductivity, electrical conductance and microstructure will be discussed in relation to composition and doping.
Thermoelectric Properties in the TiO$_2$/SnO$_2$ System

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Heat to Electric Power Generation

Waste Heat to Power

Objective: High Conversion Efficiency
- Reduces Mass, Volume & Cost

Space Power Generation

- Waste Heat is a under utilized energy resource
- U.S.-energy consumption ~29 tera-kWh \( \times 10^{12} \)
  Barrels of Oil – 170 giga-barrels \( \times 10^9 \)
- World-energy consumption ~120 tera- kWh \( \times 10^{12} \)
- 20-65 percent is lost in the form of heat
- Maximizes efficiency
- Reduces CO\(_2\) emission

- High temperature
- Oxidizing environment
- Low mass
- Low cost
Nanotechnology

Figure of Merit

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

- \( S \) - Seebeck coefficient
- \( \sigma \) – electrical conductivity
- \( \kappa \) – thermal conductivity

Efficiency

\[ \eta_{\text{max}} = \frac{\Delta T}{T_{\text{hot}}} \frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} + T_{\text{cold}}/T_{\text{hot}}} \]

Phonon Scattering:
- Atom disorder
- Superlattices
- Alloying
- Crystal Structures
- Anharmonic vibrations
- Nano-technology

Fleurial/Chen – JPL/MIT

Si/Ge

Alloy Limit
Spinodal Decomposition

**Desired Features**
- ~50 nm grains
- High Temperature Stability
- Wide Composition Range
- Large $\Delta$ Mass

**Transparent Conducting Oxides**

*Insulator/Semiconductor/Conductor*
- Large Bandgap 2.4-3.8 ev
- N-type – Degenerate Semiconductor

**Electrical Conductivity**

<table>
<thead>
<tr>
<th>TCO</th>
<th>$\sigma$(S/m)</th>
<th>@ RT</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITO</td>
<td>8x10$^5$</td>
<td></td>
</tr>
<tr>
<td>In$_2$O$_3$</td>
<td>1x10$^6$</td>
<td></td>
</tr>
<tr>
<td>SnO$_2$</td>
<td>2.5x10$^5$</td>
<td></td>
</tr>
<tr>
<td>ZnO</td>
<td>8.3x10$^5$</td>
<td></td>
</tr>
<tr>
<td>ZnO:Al</td>
<td>7.7x10$^4$</td>
<td></td>
</tr>
<tr>
<td>CdSnO$_2$</td>
<td>7.7x10$^5$</td>
<td></td>
</tr>
<tr>
<td>CdO:In</td>
<td>1.7x10$^6$</td>
<td></td>
</tr>
</tbody>
</table>

**ZnO:Al**
ZT~0.6 @ 1000 °C

Fig. 10. TEM image of (Ti$_{50}$/Sn$_{50}$)$_2$O$_3$ ceramics annealed for 48 h.
Shultz & Stubican, JACS, 53, 1970
Experimental

SnO₂
- Purity: 99.9%
- APS: 50 nm
- SSA: 14.2 m²/g

TiO₂ Rutile
- Purity: 99.99%
- APS: 20 nm,
- SSA: > 30 m²/g

Dopants
- CoO, MnO₂
- Ta₂O₅, In₂O₃

TiO₂/SnO₂
- 50/50 mol %
- 75/25 mol %
- 25/75 mol %

Powder Mixing
Compaction Die Press
Reactive Sintering 1250-1550 °C
Anneal 72 Hrs

Seebeck/Resistivity

• Laser Flash Method- Thermal Diffusivity
• Standard
• Specific Heat- C_p - Laser Flash
• Thermal Conductivity (K = αρC_p)

ΔT 0-50 °C/Furnace RT-1000 °C
Sintering

50/50 TiO₂/SnO₂  1625 °C

75/25 TiO₂/SnO₂  1550 °C

SnO₂ Sintering-Inhibited
• Surface Diffusion <1100 °C
• Evaporation >1100 °C
SnO₂ → SnO + ½O₂(g)

Sintering Aids-SnO₂
• MnO, CoO, CuO, ZnO
CoO → Co"Ti,Sn + V'O

Ta₂O₅ & In₂O₃
Ineffective Sintering Aids

Ta₂O₅ → 2Ta₆Ti,Sn + 2e⁺ + ½O₂
In₂O₃ → 2In₆Ti,Sn + 2V'O
**75/25 TiO$_2$/SnO$_2$**

- **Undoped**
- **1% Ta$_2$O$_5$**

- Large Grain
- Small Grain

- Nano-ppts

- Diffuse Composition Fluctuation

Sn rich

Ti rich
Thermal Conductivity

Compositions

- 1% MnO-50 TiO₂
- 1% CoO-50 TiO₂
- 1% MnO-75 TiO₂
- 1% CoO-75 TiO₂
- 1% MnO-25 TiO₂
- 1% CoO-25 TiO₂
- 1% Ta₂O₅/0.5% CoO-25 TiO₂

- Compositions exhibit low $\kappa$ – 1.7 to 6.8 W/mK
- Observe no dependence on composition or post treatments
- Spinodal Decomposition – $\kappa$ reduction?
- Best ZT ~ 0.05
Electrical Conductivity
75/25 TiO₂/SnO₂

- Ta₂O₅ & Nb₂O₅ - Increases σ
  \[ M_2O_5 = 2M^{Ti_{,Sn}} + 2e^- + \frac{1}{2}O_2 + 4O^X_O \]
- No further σ increase above 2% dopant.
- In₂O₃, MnO & CoO – No σ increase

Activation Energy

<table>
<thead>
<tr>
<th></th>
<th>Undoped</th>
<th>1% Nb₂O₅</th>
<th>0.5% Ta₂O₅</th>
<th>1% Ta₂O₅</th>
<th>2% Ta₂O₅</th>
<th>4% Ta₂O₅</th>
<th>1% In₂O₃</th>
<th>1% CoO</th>
<th>1% MnO</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ (ev)</td>
<td>0.97 ev</td>
<td>0.25 ev</td>
<td>0.49 ev</td>
<td>0.22 ev</td>
<td>0.30 ev</td>
<td>0.26 ev</td>
<td>0.99 ev</td>
<td>1.6 ev</td>
<td>7.9 ev</td>
</tr>
</tbody>
</table>

\[ ZT = \frac{S^2 \sigma}{\kappa} \]

σ to low
Seebeck Coefficient
75/25 TiO₂/SnO₂

• N-type
• Large Seebeck coefficients at low σ
• Increase Ta₂O₅ conc. reduces Seebeck coefficient
• Nb₂O₅ doping most effective in Seebeck reduction
Semiconductor

• Improve electrical conductivity by forming oxygen deficient material \((Ti_xSn_{1-x})O_{2-y}\)
\((Ti_{0.5}Sn_{0.5})O_{2-y}\)

- H₂ Reduction from \(10^3\) to \(10^4\) x

- \(~0\) Seebeck Coefficient

• Control the oxygen stoichiometry to increase \(\sigma\) and maintain a good Seebeck coefficient?
Effects of reducing conditions

$\text{(Ti}_{0.75}\text{Sn}_{0.25})\text{O}_{2-x}$

4% Ta

1% Ta
Mechanical Robustness

Undoped – 800 °C

1% Ta doped – 900 °C

4% Ta doped – 900 °C
4% Ta$_2$O$_5$-800 °C

$$\text{PF} = S^2 \sigma$$
In Summary

- TiO$_2$/SnO$_2$ compositions exhibit low thermal conductivity. Nanostructured phases are observed.
- Improved electrical conductivity is observed for Ta$_2$O$_5$ doped (Ti$_{0.75}$Sn$_{0.25}$)O$_{2-x}$ reduced at 800 °C.
- Reduction of doped samples retained a low thermal conductivity (≈2W/mK).
- 800 °C reduction increases the power factor by 1.69 – 2.76 for 4% Ta$_2$O$_5$ doping. However, ZT is <0.1.

Dense specimens with Sn-rich compositions need to be evaluated.

Acknowledgements
Thomas Sabo
Raymond Babuder
Electrical Conductivity

$\text{(Ti}_{0.75}\text{Sn}_{0.25})\text{O}_{2-x}$

- $\geq 800 \, ^\circ\text{C}$ treatment is required to enhance $\sigma$.
- 4% Ta$_2$O$_5$ produces the highest $\sigma$.
- Significant effect on low temperature $\sigma$.