SELF-POWERED WIRELESS SENSORS
Fred Dynys and Ali Sayir, NASA Glenn Research Center, USA

NASA’s integrated vehicle health management (IVHM) program offers the potential to improve aeronautical safety, reduce cost and improve performance by utilizing networks of wireless sensors. Development of sensor systems for engine hot sections will provide real-time data for prognostics and health management of turbo-engines. Sustainable power to embedded wireless sensors is a key challenge for prolong operation. Harvesting energy from the environment has emerged as a viable technique for power generation.

Thermoelectric generators provide a direct conversion of heat energy to electrical energy. Micro-power sources derived from thermoelectric films are desired for applications in harsh thermal environments. Silicon based alloys are being explored for applications in high temperature environments containing oxygen. Chromium based p-type Si/Ge alloys exhibit Seebeck coefficients on the order of 160 µV/K and low thermal conductance of 2.5 to 5 W/mK. Thermoelectric properties of bulk and thin film silicides will be discussed.
Self-Powered Wireless Sensors

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Integrated Vehicle Health Monitoring

Real Time Health Diagnostics From Remote Airplane

Wireless Sensor Network to Monitor Vehicle System

Examine Sensor Data for Early Detection of Component Failure

Airport

Repair

Proactive Maintenance

Future airplanes will have a wireless sensor network for monitoring vehicle system health, flight environment and structural integrity.
Energy Harvesting

• Reduction in MEMS energy consumption is the key to enabling energy harvesting
• Looking for renewable energy sources in the application environment.
• Infinite power source.

MEMS Power

<table>
<thead>
<tr>
<th>Power Supply</th>
<th>Battery</th>
<th>Energy Harvesting</th>
<th>Fuel Cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>Air Flow</td>
<td>Vibration</td>
<td>Solar</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>Thermal</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Biological</td>
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<table>
<thead>
<tr>
<th>Source</th>
<th>( \mu W/cm^3 )</th>
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<tbody>
<tr>
<td>Solar</td>
<td>15 - 15000</td>
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<tr>
<td>Air Flow</td>
<td>~380</td>
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<tr>
<td>Biological</td>
<td>~330</td>
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<tr>
<td>Vibration</td>
<td>100 - 400</td>
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<tr>
<td>Thermal</td>
<td>&lt;100</td>
</tr>
<tr>
<td>Pressure</td>
<td>&lt;100</td>
</tr>
</tbody>
</table>

Size

- 300 cm\(^3\)
- 10 cm\(^3\)
Wireless Sensors

Wireless technology allows sensors to be placed in remote locations

Self powered wireless sensors require technological advancement in energy harvesting

Sensors/power supply fabricated from materials that are operational in high temperature environments

GRC Sensors

Temperature

Heat Flux

J. Wrbanek & G. Fralick
Thermoelectric Converters

Seebeck Effect

Low Efficiency (<7%) – Niche Markets

Radioisotope Thermoelectric Generator

Proven Technology
- Long Life-Continuous Power- 20+ years
- Durable in Harsh Environments
- No Moving Parts
Thermoelectrics

Figure of Merit

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

Desired Properties of TE’s
- High Seebeck coefficient (S)
- High electrical conductivity (\(\sigma\))
- Low thermal conductivity (\(\kappa\))

Efficiency

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

Nanotechnology

Low \(\Delta T\) - Low Efficiency

Conversion Efficiency (%)

Average ZT

Year

0.0 0.5 1.0 1.5 2.0 2.5 3.0

0.0 0.5 1.0 1.5 2.0 2.5 3.0

\(\Delta T = 20 \degree C\)
\(\Delta T = 15 \degree C\)
\(\Delta T = 10 \degree C\)
\(\Delta T = 5 \degree C\)
\(\Delta T = 1 \degree C\)
Standard Thermoelectric Materials

Operational Conditions
• Temperatures 300 - 600 °C
• Environment – Varying P_{O_2}

Silicides
• Environmental/Chemical Stability
• Low Electrical Resistance
• Low Formation Temperature
## Electrical Transport

### Semiconductor/Metallic Behavior

<table>
<thead>
<tr>
<th>IIIA</th>
<th>IVA</th>
<th>VA</th>
<th>VIA</th>
<th>VIIA</th>
<th>VIII A</th>
<th>IB</th>
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<tbody>
<tr>
<td>TiSi$_2$</td>
<td>V$_3$Si</td>
<td>V$_3$Si$_2$</td>
<td>V$_5$Si$_3$</td>
<td>VSi$_2$</td>
<td>Cr$_3$Si</td>
<td>MnSi$_{1.7}$</td>
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<tr>
<td>YSi$_2$</td>
<td>ZrSi$_2$</td>
<td>Nb$_3$Si</td>
<td>NbSi$_2$</td>
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<td></td>
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<tr>
<td>HfSi$_2$</td>
<td>TaSi$_2$</td>
<td></td>
<td>ReSi$_{1.7}$</td>
<td>OsSi$_2$</td>
<td>IrSi</td>
<td>IrSi$_3$</td>
</tr>
</tbody>
</table>

### Band Gap

<table>
<thead>
<tr>
<th>Material</th>
<th>Type</th>
<th>Mobility</th>
<th>K @300 K</th>
<th>S @500K</th>
<th>ρ @500K</th>
<th>TE @300K</th>
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</thead>
<tbody>
<tr>
<td>CrSi$_2$</td>
<td>P</td>
<td>15</td>
<td>6.8</td>
<td>220</td>
<td>7.2</td>
<td>11-14</td>
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<tr>
<td>MnSi$_{1.7}$</td>
<td>P</td>
<td>40</td>
<td>2.9</td>
<td>160</td>
<td>3.1</td>
<td>16</td>
</tr>
<tr>
<td>CoSi</td>
<td>N</td>
<td>-</td>
<td>14.3</td>
<td>-50</td>
<td>0.2</td>
<td>11.1</td>
</tr>
</tbody>
</table>
Thermoelectric Module I

**TE Materials**
- Thickness ~ 10’s μm
- Electrical conductivity ≥10^4 Ω^{-1}m^{-1}
- Larger ΔT
- Thick film stresses

**Substrate**
- Thickness
- Low thermal conductivity
- Electrically insulating

**Interconnect Technology**
- Low contact resistance

Compact geometry permits parallel connection of modules for reduced series resistance.

Source: P.M. Martin et al., PNNL
Thermoelectric Module II

TE Materials
• Thickness ~ 100’s μm
• Small ΔT – Limited TE Thickness
• Electrical Conductivity

Substrate
• Good thermal conductivity
• Electrically insulating

Interconnect Technology
• Low contact resistance

ΔT

252 Legs

JPL TEMD

4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0

P (μW)

V (mV)

I (mA)

4 strings
1.0 Ω/string
Magnetron Sputtering

- Lower Deposition Pressure
- Reduces Contamination
- Increases Deposition Rate
- Complex Alloys

3 RF Guns 600 W

Sample Rotation RT – 800 °C
Magnetron Sputtering

Deposition Rate
- Distance – $1/(d)^{1/2}$
- Material
- Pressure

Targets
- Commercial Sources
- Single Crystal – B-Si, Sb-Si

Co-Sputtering
Adjust Deposition Rate To Control Composition

Deposition Rate
- Distance – $1/(d)^{1/2}$
- Material
- Pressure

Targets
- Commercial Sources
- Single Crystal – B-Si, Sb-Si

Co-Sputtering
Adjust Deposition Rate To Control Composition

Graphs showing deposition rate as a function of RF power and pressure for different materials and conditions.
**Y\textsubscript{2}O\textsubscript{3} Stabilized ZrO\textsubscript{2} Substrate**

Surface Roughness 500 nm

Deposit film retains the substrate surface roughness

**YSZ ~ 2.5 W/mK Thermal Conductivity**

11 x 10\textsuperscript{-6}/K Thermal Expansion

Total Film Stress = \(\sigma_{\text{TE}} + \sigma_{\text{process}} + \sigma_{\text{external}}\)

**Film Failure is a Concern-Thickness > 1 \mu m**
TE Property Measurements

Seebeck/Resistivity

ΔT 0-50 °C/Furnace RT-1000 °C

6-25 mm

4-8 mm

ZEM-3

Silicide Film

Ag Electrodes

Hall Measurement

Capability-RT-527 °C/Field-2 Telsa

Carrier Mobility & Density

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

\[ \approx 10^{19} \]

Carrier concentration [cm\(^{-3}\)]

\[ \approx 10^{19} \]
Silicon Films

Si, B-Si, Sb-Si & Si/Ge Films

- Amorphous Films
- Deposition Temperatures – up to 750 °C
- High Resistivity – $10^9 \, \Omega \cdot m$
- Anneal – 800 °C - Resistivity – $10^6 \, \Omega \cdot m$

Metal Induced Crystallization

Silicon Film

Substrate

Pre-layer
Ni, Cr

Lower Crystallization Temperature

Graphs showing electrical resistivity and temperature for different metals:
- Ni 10nm
- B/Si 1.8 µm
- Seebeck~0

Knaepen et al., Thin Solid Films, 516, 4946, 2008
Mn-Si

Deposition Temperature – 450 °C
XRD – Crystalline Phases – Mn$_{15}$Si$_{26}$
Film Thickness – 2.4 μm & 2.6 μm

800 °C Anneal

No Adhesion Failures – Tape Test

Seebeck Coefficient ($\mu$V/K)

Temperature (°C)

Electrical Conductivity (S/m)

$1000/T$ (K$^{-1}$)

*2 Hou et al., Appl. Phys. A, 80, 1807, 2005
Mn-Si

Hall Measurements

<table>
<thead>
<tr>
<th>Si/Mn 78/22 %</th>
<th>$\rho$ (10^{-5} \Omega \cdot m)</th>
<th>Carrier (1/cm³)</th>
<th>Mobility (cm²/VS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As Deposit</td>
<td>14.1</td>
<td>$2 \times 10^{21}$</td>
<td>0.25</td>
</tr>
<tr>
<td>600°C-4 hrs</td>
<td>31</td>
<td>$5 \times 10^{20}$</td>
<td>0.5</td>
</tr>
<tr>
<td>800°C-2 hrs</td>
<td>242</td>
<td>$2 \times 10^{20}$</td>
<td>0.1</td>
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</table>

<table>
<thead>
<tr>
<th>B-Si/Ge/Mn 61/37/2 %</th>
<th>$\rho$ (10^{-5} \Omega \cdot m)</th>
<th>Carrier (1/cm³)</th>
<th>Mobility (cm²/VS)</th>
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</thead>
<tbody>
<tr>
<td>As Deposit</td>
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<td>$6 \times 10^{19}$</td>
<td>0.3</td>
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<tr>
<td>600°C-4 hrs</td>
<td>40.8</td>
<td>$6 \times 10^{19}$</td>
<td>2.6</td>
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<td>800°C-2 hrs</td>
<td>50</td>
<td>$2 \times 10^{19}$</td>
<td>7.3</td>
</tr>
</tbody>
</table>

Microstructure

- Film Cracking
- No observable Grain Structure
- Defects due to Substrate
**Co-Si**

Deposition Temperature – 450 °C & 250 °C  
Film Thickness – 1.5 μm & 1.8 μm  

800 °C Anneal  
No Adhesion Failures – Tape Test

*3 Ren et al., J. Alloys & Comp., 392, 50, 2005

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Seebeck Coefficient (μV/K)

B doped

Electrical Conductivity (S/m)

Open Symbols  
2nd Measurement
Co-Si

Hall Measurement

<table>
<thead>
<tr>
<th>Co-Si</th>
<th>( \rho ) (10^{-5} , \Omega \cdot \text{m})</th>
<th>Carrier (1/cm^3)</th>
<th>Mobility (cm^2/VS)</th>
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</thead>
<tbody>
<tr>
<td>Si/Co 50/50 %</td>
<td></td>
<td></td>
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<tr>
<td>As Deposit</td>
<td>0.8</td>
<td>5 x 10^{20}</td>
<td>11</td>
</tr>
<tr>
<td>600{\degree}C-4 hrs</td>
<td>0.8</td>
<td>5 x 10^{20}</td>
<td>14</td>
</tr>
<tr>
<td>800{\degree}C-2 hrs</td>
<td>1.9</td>
<td>7 x 10^{20}</td>
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<table>
<thead>
<tr>
<th>Sb-Si/Co 73/27 %</th>
<th>( \rho ) (10^{-5} , \Omega \cdot \text{m})</th>
<th>Carrier (1/cm^3)</th>
<th>Mobility (cm^2/VS)</th>
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</thead>
<tbody>
<tr>
<td>As Deposit</td>
<td>0.3</td>
<td>1 x 10^{22}</td>
<td>2.5</td>
</tr>
<tr>
<td>600{\degree}C-4 hrs</td>
<td>0.1</td>
<td>1.5 x 10^{22}</td>
<td>5</td>
</tr>
<tr>
<td>800{\degree}C-2 hrs</td>
<td>0.1</td>
<td>1 x 10^{22}</td>
<td>3</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Sb-Si/Co 62/37 %</th>
<th>( \rho ) (10^{-5} , \Omega \cdot \text{m})</th>
<th>Carrier (1/cm^3)</th>
<th>Mobility (cm^2/VS)</th>
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<tbody>
<tr>
<td>As Deposit</td>
<td>0.4</td>
<td>5 x 10^{21}</td>
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<td>600{\degree}C-4 hrs</td>
<td>0.9</td>
<td>2 x 10^{22}</td>
<td>5</td>
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<tr>
<td>800{\degree}C-2 hrs</td>
<td>0.2</td>
<td>3 x 10^{22}</td>
<td>2</td>
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</tbody>
</table>

- Film Cracking
- No observable Grain Structure
- Defects due to Substrate
- Segregation?
Cr-Si

Deposition Temperature – 450 ºC
XRD – Target CrSi₂ - Poorly Crystallized
Co-sputtered – Crystalline CrSi₂
Film Thickness – 2.3 μm & 2.5 μm

800 ºC Anneal
No Adhesion Failures – Tape Test

Electrical Conductivity (S/m)

Seebeck Coefficient (μV/K)

Temperature (ºC)

1000/T (K⁻¹)
Cr-Si

CrSi$_2$ Target

- Film Cracking
- No observable Grain Structure
- Defects due to Substrate

Co-Sputtered

Hall Measurement

<table>
<thead>
<tr>
<th>CrSi$_2$</th>
<th>$\rho$ (10$^{-5}$ $\Omega\cdot$m)</th>
<th>Carrier (1/cm$^3$)</th>
<th>Mobility (cm$^2$/VS)</th>
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</thead>
<tbody>
<tr>
<td>As Deposit</td>
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<td>1.5 x 10$^{20}$</td>
<td>1.4</td>
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<td>1.7 x 10$^{20}$</td>
<td>1</td>
</tr>
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<td>800$^\circ$C-2 hrs</td>
<td>775.4</td>
<td>6 x 10$^{17}$</td>
<td>10</td>
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</table>

Hall Measurement

<table>
<thead>
<tr>
<th>B-Si/Ge/Cr 59/35/6 %</th>
<th>$\rho$ (10$^{-5}$ $\Omega\cdot$m)</th>
<th>Carrier (1/cm$^3$)</th>
<th>Mobility (cm$^2$/VS)</th>
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<tbody>
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<td>1.5 x 10$^{21}$</td>
<td>0.1</td>
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<tr>
<td>600$^\circ$C-4 hrs</td>
<td>269 x 10$^5$</td>
<td>2 x 10$^{17}$</td>
<td>1</td>
</tr>
<tr>
<td>800$^\circ$C-2 hrs</td>
<td>219</td>
<td>3.2 x 10$^{18}$</td>
<td>8.8</td>
</tr>
</tbody>
</table>
Simple Module

- Shadow Mask
- 2.2 KΩ Load
- Voltage (10^-6 V) vs. Temperature (ΔT)

- Si\Mn\Ge
- Large internal Ω
- Legs ~ 40 MΩ
- 650 °C Anneal

- N-leg Pt
- Power ≤ 10^{-12} watts
Summary

- Low resistive Si & Si/Ge difficult to achieve by magnetron sputtering.
- Low resistive films achieved with silicides of Co, Mn and Cr.
- Good Seebeck coefficients achieved for Mn & Cr silicides with P-type behavior.
- Moderate Seebeck coefficients achieved for Co silicides with N-type behavior.
- Silicide films exhibit low carrier mobility.
- Extensive film cracking is a problem.