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

Fred Dynys & Ali Sayir
NASA Glenn Research Center
Cleveland, OH
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

Repair

Proactive Maintenance

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

MEMS Device

- Sensor
- Processor
- Actuator

Physical Event

- Memory
- Radio
- Controller
- Sensor/Actuator

Power Supply

Energy Storage

Physical Response
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.

<table>
<thead>
<tr>
<th>Source</th>
<th>μW/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>15 -15000</td>
</tr>
<tr>
<td>Air Flow</td>
<td>~380</td>
</tr>
<tr>
<td>Biological</td>
<td>~330</td>
</tr>
<tr>
<td>Vibration</td>
<td>100 - 400</td>
</tr>
<tr>
<td>Thermal</td>
<td>&lt;100</td>
</tr>
<tr>
<td>Pressure</td>
<td>&lt;100</td>
</tr>
</tbody>
</table>

MEMS Technology

- Size
  - 300 cm³
  - 10 cm³

Power Supply

- Battery
- Energy Harvesting
- Fuel Cells

Power

- 1 mW
- 500 mW

MEMS Power
Wireless Sensors

Wireless technology allows sensors to be placed in remote locations.

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

GRC Sensors

Temperature  Heat Flux

J. Wrbanek & G. Fralick

Self powered wireless sensors require technological advancement in energy harvesting.
Thermoelectric Converters

Seebeck Effect

ΔT

ΔV

ΔT

Heat

Cold Side

Low Efficiency (<7%) – Niche Markets

Radioisotope Thermoelectric Generator

Proven Technology

• Long Life-Continuous Power- 20+ years
• Durable in Harsh Environments
• No Moving Parts

Hot Shoe (Mo-Si)

B-doped \(Si_{0.78}Ge_{0.22}\)

B-doped \(Si_{0.63}Ge_{0.36}\)

P-doped \(Si_{0.78}Ge_{0.22}\)

P-doped \(Si_{0.63}Ge_{0.36}\)

\(p\)-type leg

\(n\)-type leg

Cold Shoe
Thermoelectrics

Figure of Merit

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

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 (%) vs. Average ZT

\(\Delta T\) values: 20 °C, 15 °C, 10 °C, 5 °C, 1 °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>VIIIa</th>
<th>IB</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiSi₂</td>
<td>V₃Si</td>
<td>V₃Si₂</td>
<td>V₅Si₃</td>
<td>VSi₂</td>
<td>MnSi₁.₇</td>
<td>Cr₃Si</td>
</tr>
<tr>
<td>YSi₂</td>
<td>ZrSi₂</td>
<td>Nb₃Si</td>
<td>NbSi₂</td>
<td></td>
<td></td>
<td>Ru₂Si₃</td>
</tr>
<tr>
<td>HfSi₂</td>
<td>TaSi₂</td>
<td>ReSi₁.₇</td>
<td>OsSi₂</td>
<td>IrSi</td>
<td>IrSi₃</td>
<td>PtSi</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Band Gap</th>
<th>Type</th>
<th>Mobility Cm²/SV</th>
<th>K W/mK @300 K</th>
<th>S mV/K @500K</th>
<th>ρ 10⁻⁵ Ω·m @500K</th>
<th>TE 10⁻⁶/°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>CrSi₂</td>
<td>~0.35 ev</td>
<td>P</td>
<td>15</td>
<td>6.8</td>
<td>220</td>
<td>7.2</td>
</tr>
<tr>
<td>MnSi₁.₇</td>
<td>~0.7 ev</td>
<td>P</td>
<td>40</td>
<td>2.9</td>
<td>160</td>
<td>3.1</td>
</tr>
<tr>
<td>CoSi</td>
<td>------</td>
<td>N</td>
<td>----</td>
<td>14.3</td>
<td>-50</td>
<td>0.2</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

![Micro-Cooler Image]

![Plot Image]

**ZT vs Substrate Thickness (μm)**
- Insulator
- Glass
- Silicon
- 10 μm film
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

JPL TEMD

252 Legs

ΔT
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

![Graph showing deposition rate vs. RF power and RF power vs. power](image-url)
**Y$_2$O$_3$ Stabilized ZrO$_2$ Substrate**

Surface Roughness 500 nm

Deposit film retains the substrate surface roughness

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

**11 x 10^{-6}/K Thermal Expansion**

**Total Film Stress = $\sigma_{TE} + \sigma_{process} + \sigma_{external}$**

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

Seebeck/Resistivity

ZEM-3

6-25 °C/Furnace RT-1000 °C

ΔT 0-50 °C

4-8 mm

Silicide
Film

Ag Electrodes

Hall Measurement

Capability-RT-527 °C/Field-2 Telsa

Carrier Mobility & Density

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

Power Factor
\[ S^2 \sigma \]

\( \approx 10^{19} \)

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

Electrical Resistivity ($10^4 \, \Omega \cdot m$)

Temperature (°C)

Ni 10nm

B/Si 1.8 μm

Seebeck~0

Knaepen et al., Thin Solid Films, 516, 4946, 2008

www.nasa.gov
Mn-Si

Deposition Temperature – 450 °C
XRD – Crystalline Phases –Mn<sub>15</sub>Si<sub>26</sub>
Film Thickness – 2.4 μm & 2.6 μm

800 °C Anneal

No Adhesion Failures – Tape Test

Open Symbols
2nd Measurement

*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 $(1/cm^3)$</th>
<th>Mobility $(cm^2/VS)$</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>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B-Si/Ge/Mn 61/37/2 %</th>
<th>$\rho$ $(10^{-5} , \Omega \cdot m)$</th>
<th>Carrier $(1/cm^3)$</th>
<th>Mobility $(cm^2/VS)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>As Deposit</td>
<td>280.1</td>
<td>$6 \times 10^{19}$</td>
<td>0.3</td>
</tr>
<tr>
<td>600°C-4 hrs</td>
<td>40.8</td>
<td>$6 \times 10^{19}$</td>
<td>2.6</td>
</tr>
<tr>
<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

Open Symbols
2nd Measurement
Co-Si

Hall Measurement

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Si/Co</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50/50 %</td>
<td>$\rho$ (10^{-5} \Omega\cdot m)</td>
<td>Carrier (1/cm³)</td>
<td>Mobility (cm²/VS)</td>
</tr>
<tr>
<td>As Deposit</td>
<td>0.8</td>
<td>$5 \times 10^{20}$</td>
<td>11</td>
</tr>
<tr>
<td>600°C-4 hrs</td>
<td>0.8</td>
<td>$5 \times 10^{20}$</td>
<td>14</td>
</tr>
<tr>
<td>800°C-2 hrs</td>
<td>1.9</td>
<td>$7 \times 10^{20}$</td>
<td>4</td>
</tr>
</tbody>
</table>

| Sb-Si/Co  |               |                |              |
| 73/27 %   | $\rho$ (10^{-5} \Omega\cdot m) | Carrier (1/cm³) | Mobility (cm²/VS) |
| As Deposit| 0.3           | $1 \times 10^{22}$ | 2.5          |
| 600°C-4 hrs| 0.1           | $1.5 \times 10^{22}$ | 5            |
| 800°C-2 hrs| 0.1           | $1 \times 10^{22}$ | 3            |

| Sb-Si/Co  |               |                |              |
| 62/37 %   | $\rho$ (10^{-5} \Omega\cdot m) | Carrier (1/cm³) | Mobility (cm²/VS) |
| As Deposit| 0.4           | $5 \times 10^{21}$ | 1.5          |
| 600°C-4 hrs| 0.9           | $2 \times 10^{22}$ | 5            |
| 800°C-2 hrs| 0.2           | $3 \times 10^{22}$ | 2            |

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

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

800 °C Anneal
No Adhesion Failures – Tape Test
**CrSi<sub>2</sub> Target**

- **Co-Sputtered**

**Cr-Si**

**Hall Measurement**

<table>
<thead>
<tr>
<th></th>
<th>CrSi&lt;sub&gt;2&lt;/sub&gt;</th>
<th>ρ (10&lt;sup&gt;-5&lt;/sup&gt; Ω·m)</th>
<th>Carrier (1/cm&lt;sup&gt;3&lt;/sup&gt;)</th>
<th>Mobility (cm&lt;sup&gt;2&lt;/sup&gt;/VS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As Deposit</td>
<td>9.2</td>
<td>1.5 x 10&lt;sup&gt;20&lt;/sup&gt;</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>600°C-4 hrs</td>
<td>37.3</td>
<td>1.7 x 10&lt;sup&gt;20&lt;/sup&gt;</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>800°C-2 hrs</td>
<td>775.4</td>
<td>6 x 10&lt;sup&gt;17&lt;/sup&gt;</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

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

**Hall Measurement**

<table>
<thead>
<tr>
<th>B-Si/Ge/Cr</th>
<th>ρ (10&lt;sup&gt;-5&lt;/sup&gt; Ω·m)</th>
<th>Carrier (1/cm&lt;sup&gt;3&lt;/sup&gt;)</th>
<th>Mobility (cm&lt;sup&gt;2&lt;/sup&gt;/VS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As Deposit</td>
<td>428</td>
<td>1.5 x 10&lt;sup&gt;21&lt;/sup&gt;</td>
<td>0.1</td>
</tr>
<tr>
<td>600°C-4 hrs</td>
<td>269 x 10&lt;sup&gt;5&lt;/sup&gt;</td>
<td>2 x 10&lt;sup&gt;17&lt;/sup&gt;</td>
<td>1</td>
</tr>
<tr>
<td>800°C-2 hrs</td>
<td>219</td>
<td>3.2 x 10&lt;sup&gt;18&lt;/sup&gt;</td>
<td>8.8</td>
</tr>
</tbody>
</table>
Simple Module

Shadow Mask

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

N-leg Pt Si\Mn\Ge

Load=2.2 KΩ

Power ≤ 10^{-12} watts

Voltage (10^{-6} V)
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.