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 \( \mu \text{V/K} \) 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

Repair

Proactive Maintenance

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

Physical Event: Sensor -> Processor -> Actuator

Physical Response

MEMS Device

Memory

Radio -> Controller -> Sensor/Actuator

Power Supply

Energy Storage
MEMS Power

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.

### Power Supply

- Battery
- Energy Harvesting
- Fuel Cells

### Energy Sources

<table>
<thead>
<tr>
<th>Source</th>
<th>μW/cm³</th>
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<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>
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

\[ \Delta T \]

\[ \Delta V \]

Low Efficiency (<7%) – Niche Markets

Radioisotope Thermoelectric Generator

Proven Technology

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

B-doped \( \text{Si}_{0.78} \text{Ge}_{0.22} \)

P-doped \( \text{Si}_{0.78} \text{Ge}_{0.22} \)

B-doped \( \text{Si}_{0.63} \text{Ge}_{0.36} \)

P-doped \( \text{Si}_{0.63} \text{Ge}_{0.36} \)

n-type leg

p-type leg

Hot Shoe (Mo-Si)

Cold Shoe

Heat

Cold Side

\( \Delta T \)
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 (%)

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

Average ZT

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 3.5 4.0
Standard Thermoelectric Materials

Operational Conditions
- Temperatures 300 - 600 °C
- Environment – Varying P_O2

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>
</tr>
</thead>
<tbody>
<tr>
<td>TiSi₂</td>
<td>V₃Si</td>
<td>V₃Si₂</td>
<td>V₅Si₃</td>
<td>VS₁₂</td>
<td>MnSi₁.₇</td>
<td>α−FeSi₂</td>
</tr>
<tr>
<td>YSi₂</td>
<td>ZrSi₂</td>
<td>Nb₃Si</td>
<td>NbS₁₂</td>
<td>Ru₂S₁₃</td>
<td>RhSi₂</td>
<td>Pd₂S₁</td>
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<tr>
<td>HfS₁₂</td>
<td>TaS₁₂</td>
<td>ReSi₁.₇</td>
<td>OsS₁₂</td>
<td>IrS₁</td>
<td>IrS₁₃</td>
<td>PtS₁</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>III A</strong></th>
<th><strong>IV A</strong></th>
<th><strong>V I A</strong></th>
<th><strong>VII A</strong></th>
<th><strong>VIII A</strong></th>
<th><strong>I B</strong></th>
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</thead>
<tbody>
<tr>
<td>CrSi₂</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<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></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<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></td>
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</tr>
</tbody>
</table>

- **Band Gap**: The energy gap between the valence and conduction bands.
- **Type**: P for p-type, N for n-type.
- **Mobility**: Cm²/SV.
- **K**: W/mK @300 K.
- **S**: mV/K @500K.
- **ρ**: 10⁻⁵ Ω⋅m @500K.
- **TE**: 10⁻⁶/°C.
Thermoelectric Module I

**TE Materials**
- Thickness ~ 10’s μm
- Electrical conductivity $\geq 10^4 \, \Omega^{-1} \text{m}^{-1}$
- Larger $\Delta T$
- 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

![Graph of ZT vs. Substrate Thickness](image)

- Silicon
- Insulator
- Glass

Micro-Cooler
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
Magnetron Sputtering

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

3 RF Guns
600 W

Sample Rotation
Heater
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

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**Graphs**
- **Distance 13 cm**
  - B doped Si
  - 5 mT
  - 10 mT
  - 20 mT
  - 40 mT
- **Sb doped Si**

- **Deposition Rate vs. RF Power**
  - Distance 13 cm
  - Pressure 5 mT

- **Deposition Rate vs. Power**
  - Distance 13 cm
  - Pressure 5 mT
Y$_2$O$_3$ Stabilized ZrO$_2$ Substrate
Surface Roughness 500 nm

Deposit film retains the substrate surface roughness

<table>
<thead>
<tr>
<th>YSZ</th>
<th>2.5 W/mK Thermal Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>11 x 10^{-6}/K Thermal Expansion</td>
</tr>
</tbody>
</table>

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

Film Failure is a Concern-Thickness $> 1$ μm
TE Property Measurements

Seebeck/Resistivity

ZEM-3

6-25 °C/Furnace RT-1000 °C

ΔT 0-50 °C/Furnace RT-1000 °C

Silicide

Ag Electrodes

Film

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}]
Silicon Films

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

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

Metal Induced Crystallization

![Graph showing electrical resistivity vs. temperature for different metals]

Ni 10nm
B/Si 1.8 μm

Temperature (°C)

Seebeck~0

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

Deposition Temperature – 450 °C
XRD – Crystalline Phases – Mn₁₅Si₂₆
Film Thickness – 2.4 μm & 2.6 μm

800 °C Anneal

No Adhesion Failures – Tape Test

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

Open Symbols
2nd Measurement
Mn-Si

Hall Measurements

<table>
<thead>
<tr>
<th>Si/Mn</th>
<th>( \rho ) (( 10^{-5} \ \Omega \cdot m ))</th>
<th>Carrier (1/cm(^3))</th>
<th>Mobility (cm(^2)/V.S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>78/22 %</td>
<td>14.1</td>
<td>2 x 10(^{21})</td>
<td>0.25</td>
</tr>
<tr>
<td>As Deposit</td>
<td>14.1</td>
<td>2 x 10(^{21})</td>
<td>0.25</td>
</tr>
<tr>
<td>600(^\circ)C-4 hrs</td>
<td>31</td>
<td>5 x 10(^{20})</td>
<td>0.5</td>
</tr>
<tr>
<td>800(^\circ)C-2 hrs</td>
<td>242</td>
<td>2 x 10(^{20})</td>
<td>0.1</td>
</tr>
<tr>
<td>B-Si/Ge/Mn</td>
<td>( \rho ) (( 10^{-5} \ \Omega \cdot m ))</td>
<td>Carrier (1/cm(^3))</td>
<td>Mobility (cm(^2)/V.S)</td>
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<tr>
<td>61/37/2 %</td>
<td>280.1</td>
<td>6 x 10(^{19})</td>
<td>0.3</td>
</tr>
<tr>
<td>As Deposit</td>
<td>280.1</td>
<td>6 x 10(^{19})</td>
<td>0.3</td>
</tr>
<tr>
<td>600(^\circ)C-4 hrs</td>
<td>40.8</td>
<td>6 x 10(^{19})</td>
<td>2.6</td>
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<tr>
<td>800(^\circ)C-2 hrs</td>
<td>50</td>
<td>2 x 10(^{19})</td>
<td>7.3</td>
</tr>
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</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

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
Co-Si

Hall Measurement

<table>
<thead>
<tr>
<th>Si/Co</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>
<tr>
<td>50/50 %</td>
<td>As Deposit 0.8</td>
<td>5 x 10^{20}</td>
<td>11</td>
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<tr>
<td></td>
<td>600°C-4 hrs 0.8</td>
<td>5 x 10^{20}</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>800°C-2 hrs 1.9</td>
<td>7 x 10^{20}</td>
<td>4</td>
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</table>

<table>
<thead>
<tr>
<th>Sb-Si/Co</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>73/27 %</td>
<td>As Deposit 0.3</td>
<td>1 x 10^{22}</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>600°C-4 hrs 0.1</td>
<td>1.5 x 10^{22}</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>800°C-2 hrs 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</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>
<tr>
<td>62/37 %</td>
<td>As Deposit 0.4</td>
<td>5 x 10^{21}</td>
<td>1.5</td>
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<td></td>
<td>600°C-4 hrs 0.9</td>
<td>2 x 10^{22}</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>800°C-2 hrs 0.2</td>
<td>3 x 10^{22}</td>
<td>2</td>
</tr>
</tbody>
</table>

- 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
**Cr-Si**

**CrSi₂ Target**

- Co-Sputtered

**Hall Measurement**

<table>
<thead>
<tr>
<th>CrSi₂</th>
<th>( \rho ) (10⁻⁵ Ω·m)</th>
<th>Carrier (1/cm³)</th>
<th>Mobility (cm²/VS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As Deposit</td>
<td>9.2</td>
<td>1.5 x 10²⁰</td>
<td>1.4</td>
</tr>
<tr>
<td>600°C-4 hrs</td>
<td>37.3</td>
<td>1.7 x 10²⁰</td>
<td>1</td>
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<tr>
<td>800°C-2 hrs</td>
<td>775.4</td>
<td>6 x 10¹⁷</td>
<td>10</td>
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</table>

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

**Hall Measurement**

<table>
<thead>
<tr>
<th>B-Si/Ge/Cr 59/35/6 %</th>
<th>( \rho ) (10⁻⁵ Ω·m)</th>
<th>Carrier (1/cm³)</th>
<th>Mobility (cm²/VS)</th>
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</thead>
<tbody>
<tr>
<td>As Deposit</td>
<td>428</td>
<td>1.5 x 10²¹</td>
<td>0.1</td>
</tr>
<tr>
<td>600°C-4 hrs</td>
<td>269x10⁵</td>
<td>2 x 10¹⁷</td>
<td>1</td>
</tr>
<tr>
<td>800°C-2 hrs</td>
<td>219</td>
<td>3.2 x 10¹⁸</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

Power ≤ 10^{-12} watts

Load=2.2 KΩ

Voltage (10^{-6} V)

2 mm → 5 mm

32 mm

20 40 60 80 100

10 20 30 40 50 60
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.