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 $\mu$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

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.

<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>
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<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>
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</table>
Wireless Sensors

Wireless technology allows sensors to be placed in remote locations.

Self powered wireless sensors require technological advancement in energy harvesting.

GRC Sensors
- Temperature
- Heat Flux

J. Wrbanek & G. Fralick

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

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

Nanotechnology

Low \(\Delta T\) - Low Efficiency

Conversion Efficiency (%)

Average ZT

YEAR

FUTURE OF MERIT (ZT)_{max}

0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0

\(\Delta T=20 \degree \text{C}\)
\(\Delta T=15 \degree \text{C}\)
\(\Delta T=10 \degree \text{C}\)
\(\Delta T=5 \degree \text{C}\)
\(\Delta T=1 \degree \text{C}\)
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>
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</thead>
<tbody>
<tr>
<td>TiSi₂</td>
<td>V₃Si ( V_{3Si} ) ( V_{5Si} ) ( Vs_{2} )</td>
<td>Cr₃Si ( Cr_{3Si} ) ( Cr_{5Si} ) ( CrSi₂ )</td>
<td>MnSi₁.₇ ( \alpha−FeSi₂ ) ( \beta−FeSi₂ )</td>
<td>Co₂Si ( CoSi ) CoSi₂</td>
<td>Ni₂Si ( NiSi ) NiSi₂</td>
<td>Cu₃Si</td>
</tr>
<tr>
<td>YSi₂</td>
<td>ZrSi₂</td>
<td>Nb₃Si ( Nb_{3Si} ) NbSi₂</td>
<td>Ru₂Si₃ ( Ru_{2Si} )</td>
<td>RhSi₂</td>
<td>Pd₂Si</td>
<td></td>
</tr>
<tr>
<td>HfSi₂</td>
<td>TaSi₂</td>
<td>ReSi₁.₇ ( OsSi₂ )</td>
<td>OsSi₂ ( IrSi ) IrSi₃</td>
<td>PtSi</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<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>( \rho ) ( 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>
<td>11-14</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>
<td>16</td>
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<tr>
<td>CoSi</td>
<td>------</td>
<td>N</td>
<td>----</td>
<td>14.3</td>
<td>-50</td>
<td>0.2</td>
<td>11.1</td>
</tr>
</tbody>
</table>
Compact geometry permits parallel connection of modules for reduced series resistance.
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
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**
- **Deposition Rate vs. RF Power (Watts)**
  - Distance 13 cm
  - B doped Si
  - Sb doped Si

- **Deposition Rate vs. Power (watts)**
  - Distance 13 cm
  - Pressure 5 mT
  - Ge, Si, Cr, Mn, Co, CrSi₂
Y$_2$O$_3$ Stabilized ZrO$_2$ Substrate

Surface Roughness 500 nm

Deposit film retains the substrate surface roughness

YSZ $\sim$ 2.5 W/mK  Thermal Conductivity

$11 \times 10^{-6}$/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

ZEM-3

6-25 °C/Furnace RT-1000 °C

ΔT 0-50 °C/Furnace RT-1000 °C

Hall Measurement

Capability-RT-527 °C/Field-2 Telsa

Carrier Mobility & Density

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

Power Factor

\[
S^2 \sigma
\]

≈ 10^{19}

Carrier concentration [cm^{-3}]

Silicide

Ag Electrodes

Film
Silicon Films

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

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

Metal Induced Crystallization

Silicon Film

Substrate

Pre-layer

Ni, Cr

Lower Crystallization Temperature

Seebeck~0

Ni 10nm
B/Si 1.8 μm

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

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>
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<tbody>
<tr>
<td>As Deposit</td>
<td>14.1</td>
<td>$2 \times 10^{21}$</td>
<td>0.25</td>
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<tr>
<td>600°C-4 hrs</td>
<td>31</td>
<td>$5 \times 10^{20}$</td>
<td>0.5</td>
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<td>800°C-2 hrs</td>
<td>242</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 $(1/cm^3)$</th>
<th>Mobility $(cm^2/VS)$</th>
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<tr>
<td>As Deposit</td>
<td>280.1</td>
<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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<tr>
<td>800°C-2 hrs</td>
<td>50</td>
<td>$2 \times 10^{19}$</td>
<td>7.3</td>
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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

Seebeck Coefficient ($\mu$V/K)

Electrical Conductivity (S/m)

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

Open Symbols 2nd Measurement
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>$5 \times 10^{20}$</td>
<td>11</td>
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<tr>
<td></td>
<td>600°C-4 hrs 0.8</td>
<td>$5 \times 10^{20}$</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>800°C-2 hrs 1.9</td>
<td>$7 \times 10^{20}$</td>
<td>4</td>
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<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>73/27 %</td>
<td>As Deposit 0.3</td>
<td>$1 \times 10^{22}$</td>
<td>2.5</td>
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<tr>
<td></td>
<td>600°C-4 hrs 0.1</td>
<td>$1.5 \times 10^{22}$</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>800°C-2 hrs 0.1</td>
<td>$1 \times 10^{22}$</td>
<td>3</td>
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<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>
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<td>$5 \times 10^{21}$</td>
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<td></td>
<td>600°C-4 hrs 0.9</td>
<td>$2 \times 10^{22}$</td>
<td>5</td>
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<tr>
<td></td>
<td>800°C-2 hrs 0.2</td>
<td>$3 \times 10^{22}$</td>
<td>2</td>
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</table>

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

Deposition Temperature – 450 °C
XRD – Target CrSi$_2$ - Poorly Crystallized
Co-sputtered – Crystalline CrSi$_2$
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>$\rho$</th>
<th>Carrier</th>
<th>Mobility</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>($10^{-5}\ \Omega\cdot m$)</td>
<td>$(1/cm^3)$</td>
<td>(cm²/VS)</td>
</tr>
<tr>
<td>As Deposit</td>
<td>9.2</td>
<td>$1.5 \times 10^{20}$</td>
<td>1.4</td>
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<tr>
<td>600°C-4 hrs</td>
<td>37.3</td>
<td>$1.7 \times 10^{20}$</td>
<td>1</td>
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<tr>
<td>800°C-2 hrs</td>
<td>775.4</td>
<td>$6 \times 10^{17}$</td>
<td>10</td>
</tr>
</tbody>
</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>$\rho$</th>
<th>Carrier</th>
<th>Mobility</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>($10^{-5}\ \Omega\cdot m$)</td>
<td>$(1/cm^3)$</td>
<td>(cm²/VS)</td>
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<tr>
<td>As Deposit</td>
<td>428</td>
<td>$1.5 \times 10^{21}$</td>
<td>0.1</td>
</tr>
<tr>
<td>600°C-4 hrs</td>
<td>$2.69 \times 10^5$</td>
<td>$2 \times 10^{17}$</td>
<td>1</td>
</tr>
<tr>
<td>800°C-2 hrs</td>
<td>219</td>
<td>$3.2 \times 10^{18}$</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 $\leq 10^{-12}$ watts

Load=2.2 KΩ

Voltage (10⁻⁶ V)

\[ \Delta T \]
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.