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.
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.

<table>
<thead>
<tr>
<th>Source</th>
<th>μW/cm³</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>
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<tr>
<td>Thermal</td>
<td>&lt;100</td>
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<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

ΔT  

ΔV  

Cold Side

Heat

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**

![Graph showing the development of ZT over years with various materials and their respective ZT values.](image)

**Low \( \Delta T \) - Low Efficiency**

![Graph showing conversion efficiency vs. average ZT with different \( \Delta T \) values.](image)
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>
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<td>V₃Si</td>
<td>V₃Si₂</td>
<td>Cr₃Si</td>
<td>MnSi₁.₇</td>
<td>α−FeSi₂</td>
<td>CrSi²</td>
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<td>V₅Si₃</td>
<td>V₅Si₃</td>
<td>Cr₅Si₃</td>
<td>CrSi₂</td>
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<td>β−FeSi₂</td>
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<td>VSi²</td>
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<td>NiSi</td>
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<td>TaSi²</td>
<td>ReSi₁.₇</td>
<td>OsSi₂</td>
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<td></td>
<td>PtSi</td>
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<table>
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<tr>
<th>Band Gap</th>
<th>Type</th>
<th>Mobility Cm²/SV</th>
<th>K W/mK @300K</th>
<th>S mV/K @500K</th>
<th>ρ 10⁻⁵ Ω−m @500K</th>
<th>TE 10⁻⁶/°C</th>
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<tr>
<td>CrSi₂</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>MnSi₁.₇</td>
<td>P</td>
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<td>16</td>
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<td>CoSi</td>
<td>N</td>
<td>----</td>
<td>14.3</td>
<td>-50</td>
<td>0.2</td>
<td>11.1</td>
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Thermoelectric Module I

TE Materials
• Thickness ~ 10’s μm
• Electrical conductivity ≥10⁴ Ω⁻¹m⁻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

![Graph showing ZT vs. Substrate Thickness for different materials](image_url)
**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

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
- Deposition Rate (nm/min) vs. RF Power (Watts)
  - B doped Si
  - Sb doped Si
  - Distance 13 cm
  - Pressure 5 mT

- Deposition Rate (nm/min) vs. Power (watts)
  - Ge
  - Si
  - Cr
  - Mn
  - Co
  - CrSi$_2$
  - Distance 13 cm
  - Pressure 5 mT
**Y₂O₃ Stabilized ZrO₂ Substrate**

Surface Roughness 500 nm

Deposit film retains the substrate surface roughness

YSZ $\sim 2.5$ 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 μm
TE Property Measurements

Seebeck/Resistivity

ZEM-3

6-25 °C/Furnace RT-1000 °C

ΔT 0-50 °C/Furnace RT-1000 °C

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 – 10⁹ Ω-m
- Anneal – 800 °C - Resistivity – 10⁶ Ω-m

Metal Induced Crystallization

Silicon Film

Substrate

Pre-layer
Ni, Cr

Lower Crystallization Temperature

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

Open Symbols
2nd Measurement

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

Hall Measurements

<table>
<thead>
<tr>
<th>Si/Mn</th>
<th>( \rho ) ((10^{-5} \text{ } \Omega \cdot \text{m}))</th>
<th>Carrier ((1/\text{cm}^3))</th>
<th>Mobility ((\text{cm}^2/\text{V} \cdot \text{S}))</th>
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<tbody>
<tr>
<td>As Deposit</td>
<td>14.1</td>
<td>2 x 10^{21}</td>
<td>0.25</td>
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<td>600°C-4 hrs</td>
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<td>5 x 10^{20}</td>
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<td>800°C-2 hrs</td>
<td>242</td>
<td>2 x 10^{20}</td>
<td>0.1</td>
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<table>
<thead>
<tr>
<th>B-Si/Ge/Mn</th>
<th>( \rho ) ((10^{-5} \text{ } \Omega \cdot \text{m}))</th>
<th>Carrier ((1/\text{cm}^3))</th>
<th>Mobility ((\text{cm}^2/\text{V} \cdot \text{S}))</th>
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<td>600°C-4 hrs</td>
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<td>800°C-2 hrs</td>
<td>50</td>
<td>2 x 10^{19}</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

Open Symbols
2nd Measurement

*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 $\Omega$−m)</th>
<th>Carrier (1/cm$^3$)</th>
<th>Mobility (cm$^2$/VS)</th>
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<td>50/50 % As Deposit</td>
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<td>800°C-2 hrs</td>
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<td>Sb-Si/Co</td>
<td>$\rho$ (10^-5 $\Omega$−m)</td>
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<td>73/27 % As Deposit</td>
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<td>800°C-2 hrs</td>
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<td>1 x 10$^{22}$</td>
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<td>Sb-Si/Co</td>
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<td>Carrier (1/cm$^3$)</td>
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<td>800°C-2 hrs</td>
<td>0.2</td>
<td>3 x 10$^{22}$</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 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>ρ ((10^{-5} \ \text{Ω} \cdot \text{m}))</th>
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<th>Mobility ((\text{cm}^2/\text{V}\cdot\text{s}))</th>
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<td>6 \times 10^{17}</td>
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- Film Cracking
- No observable Grain Structure
- Defects due to Substrate

### Hall Measurement

<table>
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<tr>
<th>B-Si/Ge/Cr</th>
<th>(\rho) ((10^{-5} \ \text{Ω} \cdot \text{m}))</th>
<th>Carrier ((1/\text{cm}^3))</th>
<th>Mobility ((\text{cm}^2/\text{V}\cdot\text{s}))</th>
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<td>3.2 \times 10^{18}</td>
<td>8.8</td>
</tr>
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Simple Module

Shadow Mask

Si\Mn\Ge
Large internal $\Omega$
Legs $\sim 40$ M$\Omega$
650 °C Anneal

N-leg Pt

Power $\leq 10^{-12}$ 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.