

Si-Ge Nano-structured with Tungsten Silicide Inclusions

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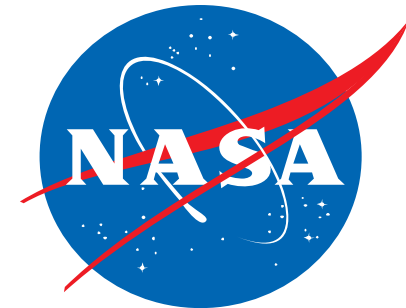
Materials Science and Engineering,
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RXC, NASA Glenn Research Center

NASA Cooperative Agreement: NNX08AB43A

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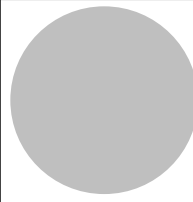
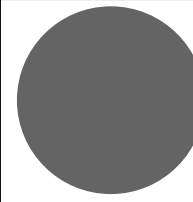
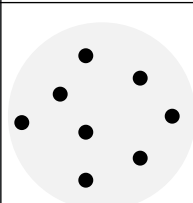
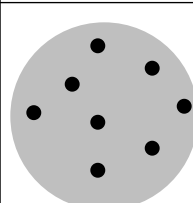
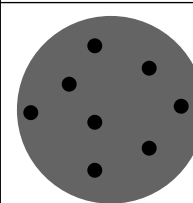
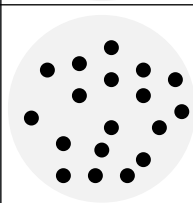
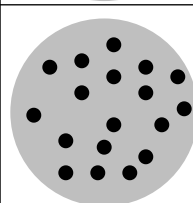
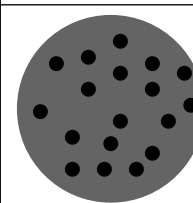
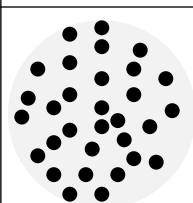
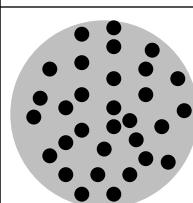
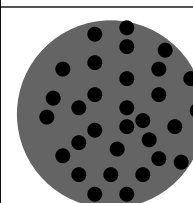
Objectives

- Investigate composite strategies with proven Si/Ge thermoelectrics.
- Validate theoretical modeling for silicide inclusion in Si/Ge, requires 10nm inclusions.
- Develop reliable uncertainty analysis for thermoelectric transport properties.
- Study thermal stability of composites.

$$\text{Material } ZT = \frac{\alpha^2 \sigma}{\lambda} T$$

$$\lambda = \lambda_{Elec.} + \lambda_{Lattice}$$

Test Matrix

		Si/Ge at% Ratio		
		70/30	80/20	90/10
Tungsten Silicide Volume Fraction	2% Dopant P-Type, B N-Type, P	0%	1%	2%
	0%			
	1%			
	2%			
5%				

Objectives

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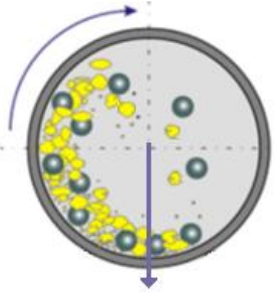
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	0%			
	1%			
	2%			
5%				

Powder Processing

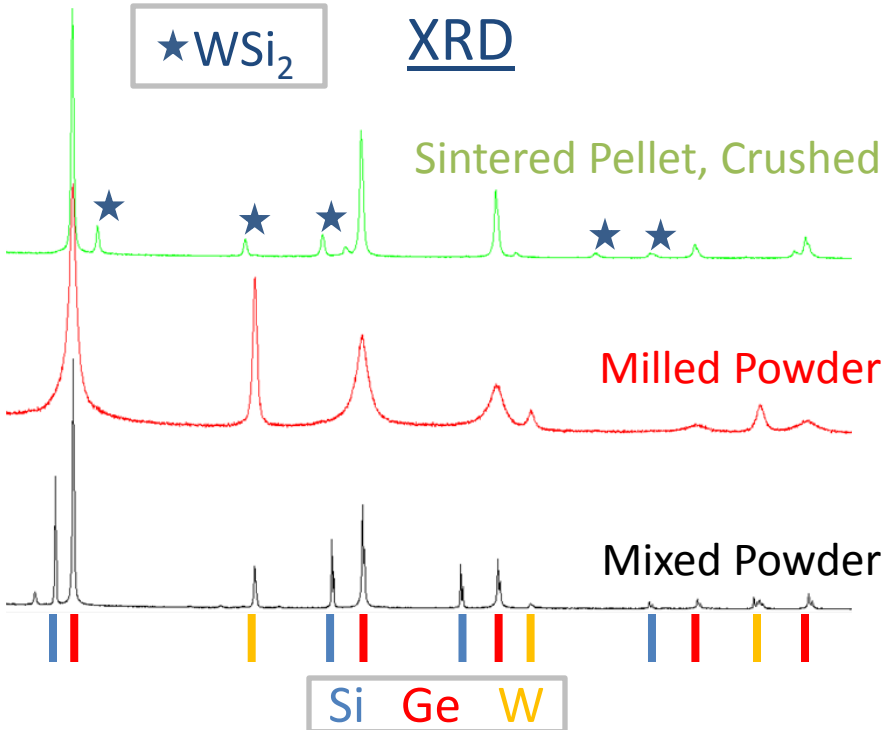


- Planetary Milling
 - 8 Hours @ 300-580 rpm
 - Ball to powder ratio 3-5
- Spark Plasma Sintering (AFRL)
 - 800-1100°C @ 70-90 MPa
 - 5-10 min Hold

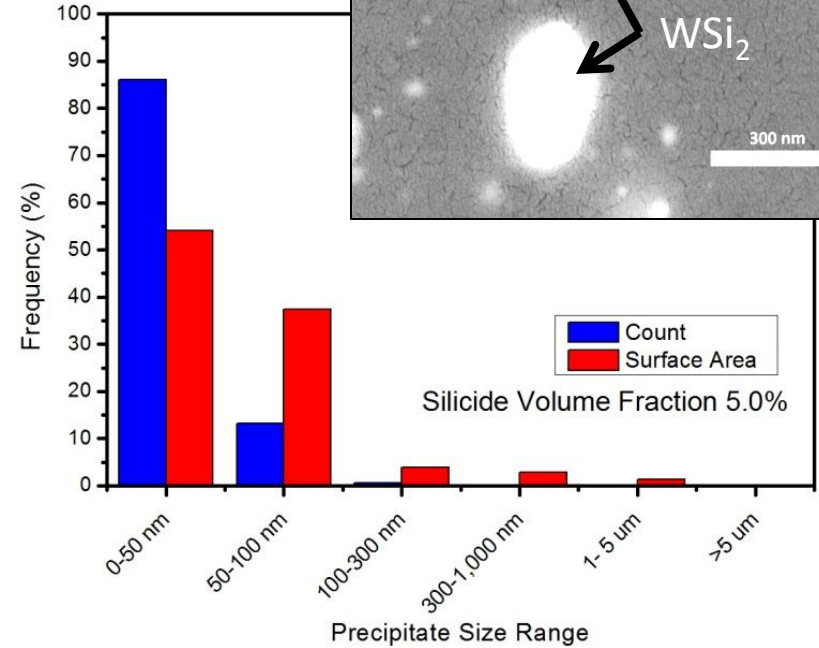
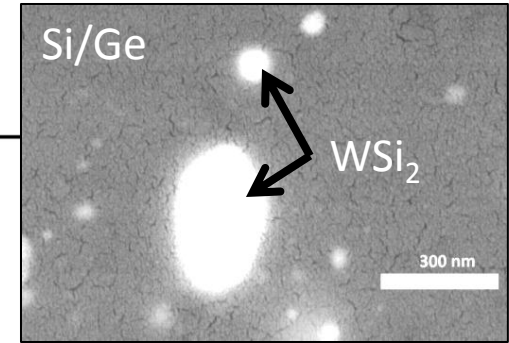
XRD

★ WSi₂

Sintered Pellet, Crushed



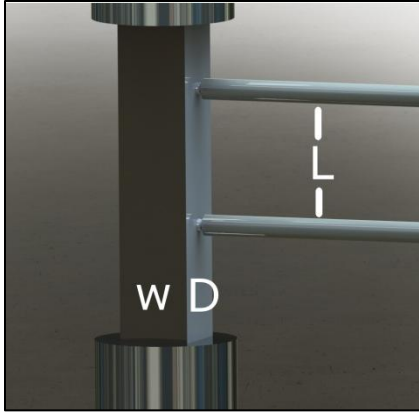
SEM



1" Diameter



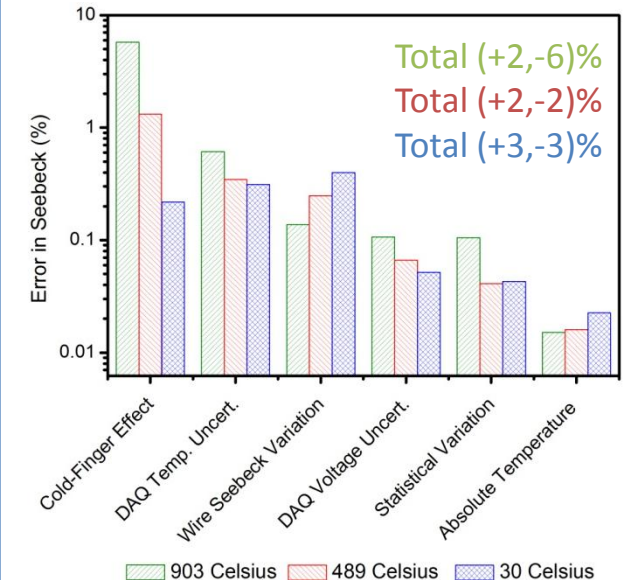
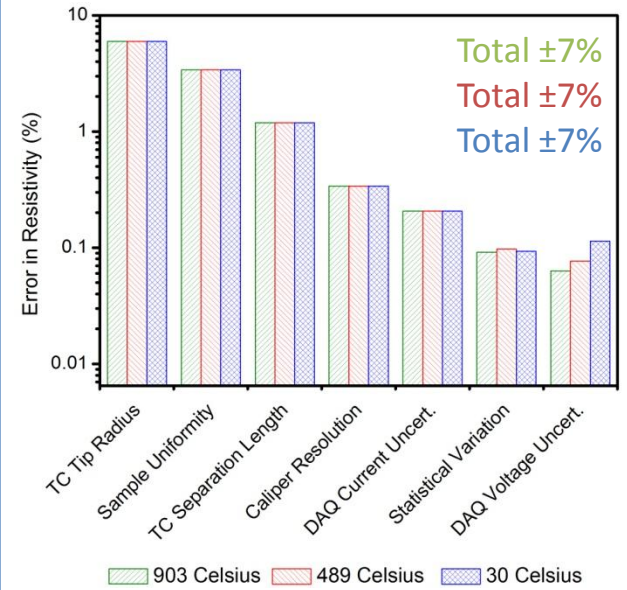
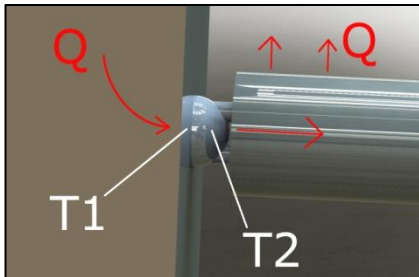
Sources of Error

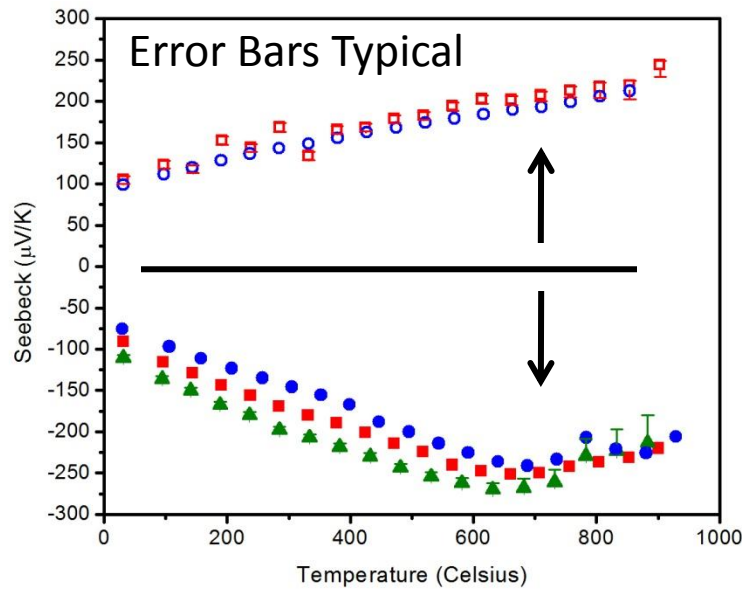
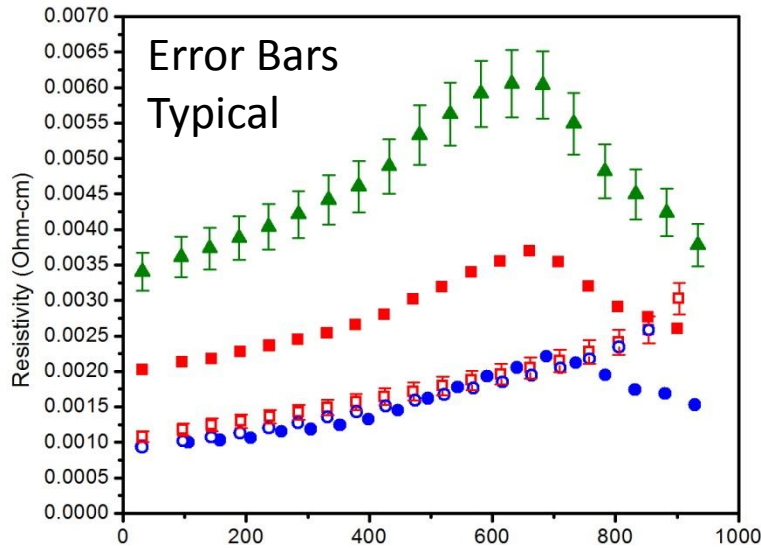


Resistivity

Seebeck

Source	Magnitude
Thermocouple radius	0.25 mm
Sample uniformity	± 0.1 mm
Thermocouple separation	± 0.1 mm
Caliper resolution	0.01 mm
Statistical variation	Calculated
DAQ voltage uncertainty	50ppm+1.2 μ V
DAQ current uncertainty	0.2%+0.3mA
Cold-finger effect	Calculated
Wire Seebeck variation	± 3 %
Statistical variation	Calculated
Absolute temperature	± 2 K
DAQ voltage uncertainty	50ppm+1.2 μ V
DAQ temp. uncertainty	50ppm+1.2 μ V





2% Doped

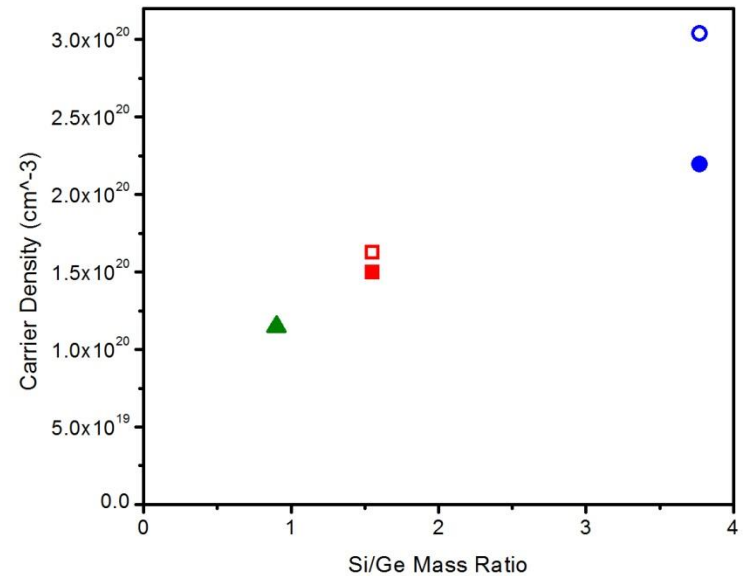
○ P-type, B

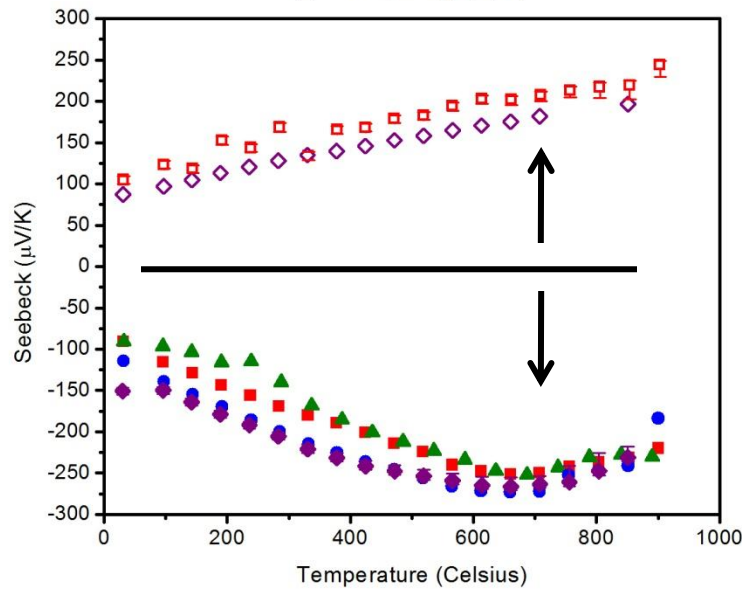
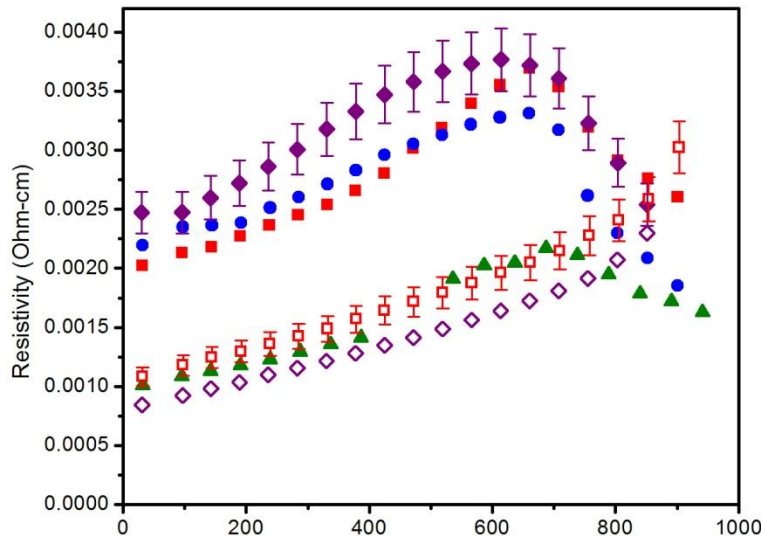
● N-type, P

Si/Ge at% Ratio

70/30 80/20 90/10

Tungsten Silicide Volume Fraction	Si/Ge at% Ratio		
	70/30	80/20	90/10
0%	X	X	X
1%	X	X	X
2%	▲	■	●
5%	X	X	X





2% Doped

○ P-type, B

● N-type, P

Si/Ge at% Ratio

70/30

80/20

90/10

Tungsten Silicide
Volume Fraction

0%

X

◆

X

1%

X

●

X

2%

X

■

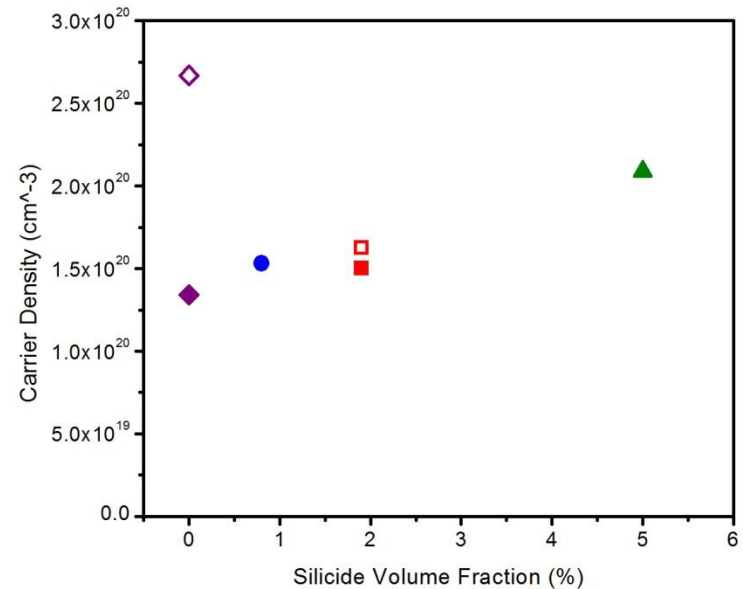
X

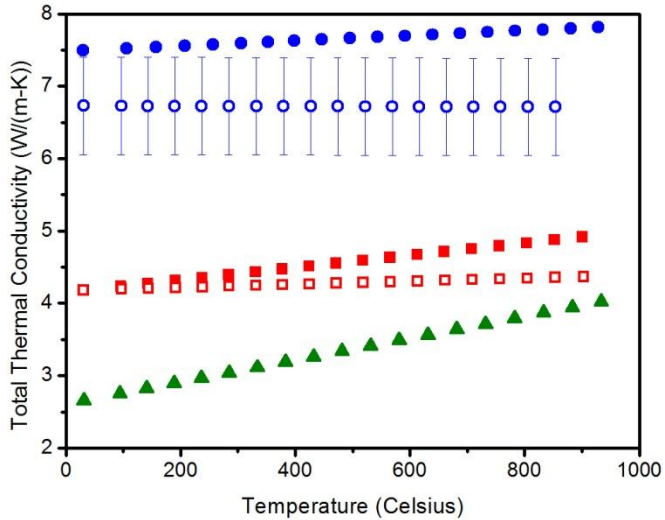
5%

X

▲

X



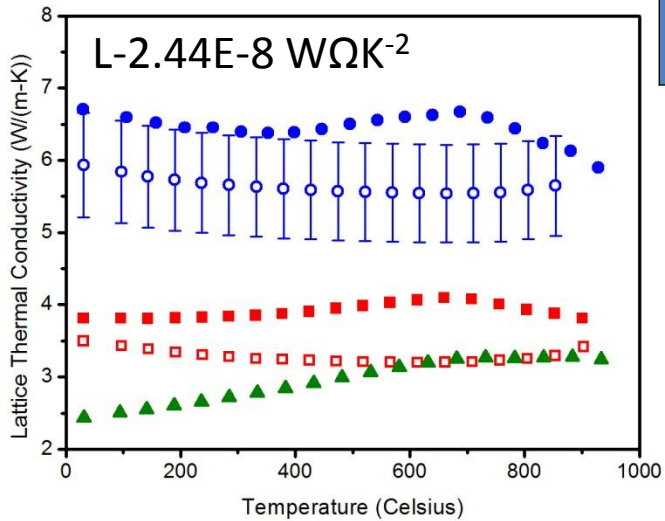


Increasing Ge

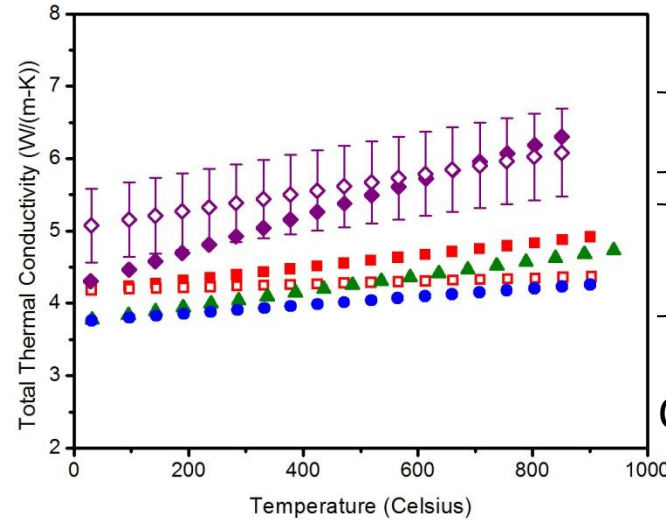


Si/Ge at% Ratio		
70/30	80/20	90/10

V.F.	0%	x	x	x
	1%	x	x	x
	2%	▲	■	●
	5%	x	x	x



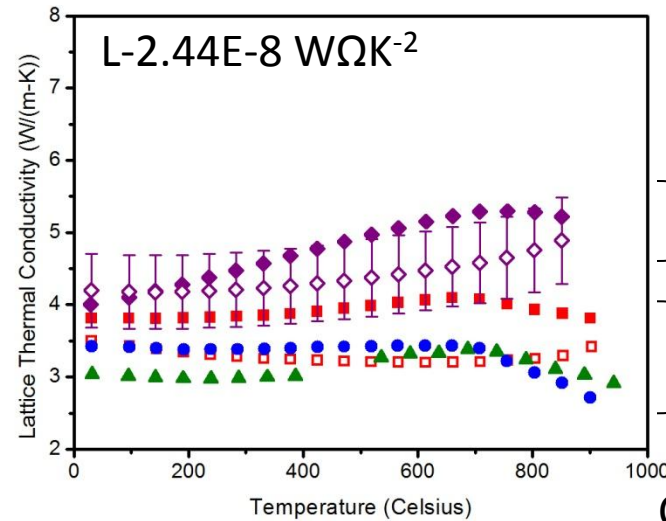
Increasing Ge



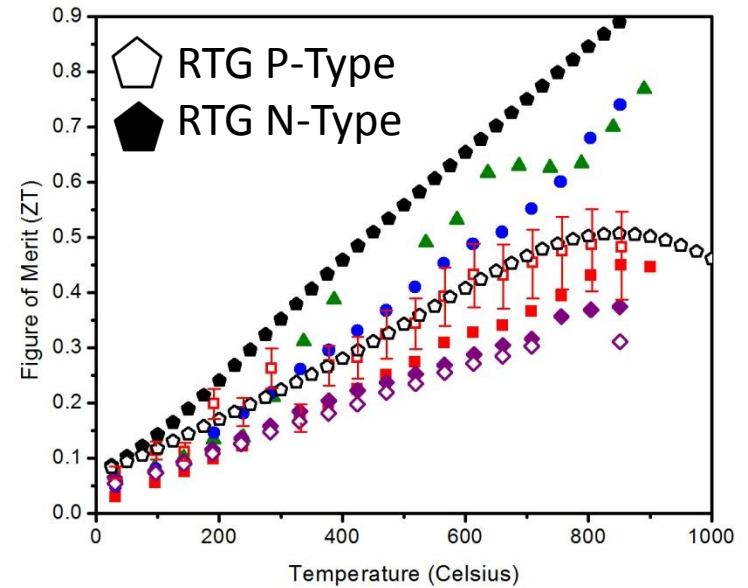
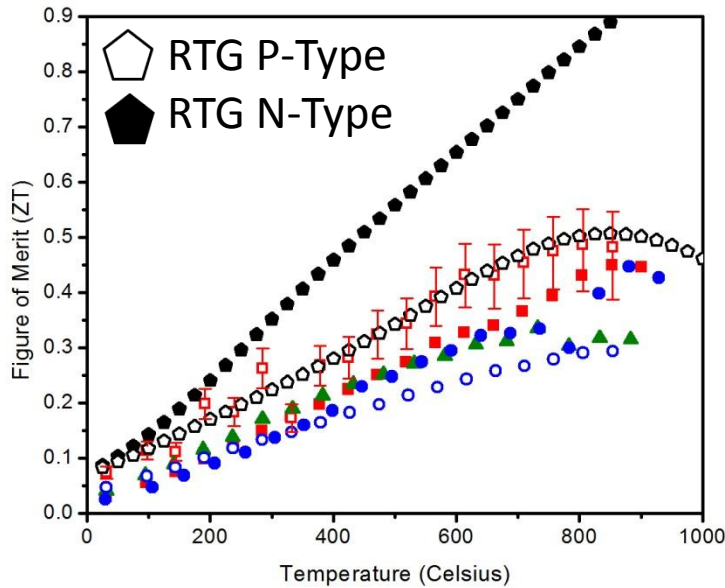
Si/Ge
Silicide Composites

Si/Ge at% Ratio		
70/30	80/20	90/10

V.F.	0%	x	◆	x
	1%	x	●	x
	2%	x	■	x
	5%	x	▲	x



Si/Ge
Silicide Composites

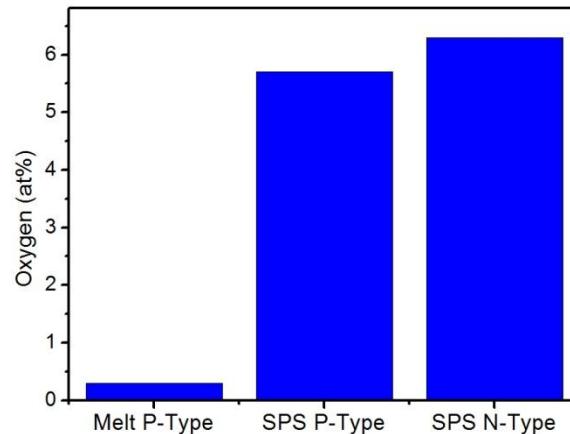


2% Doped

○ P-type, B

● N-type, P

		Si/Ge at% Ratio		
		70/30	80/20	90/10
Tungsten Silicide Volume Fraction	0%	X	●	X
	1%	X	X	X
	2%	▲	■	●
	5%	X	X	X

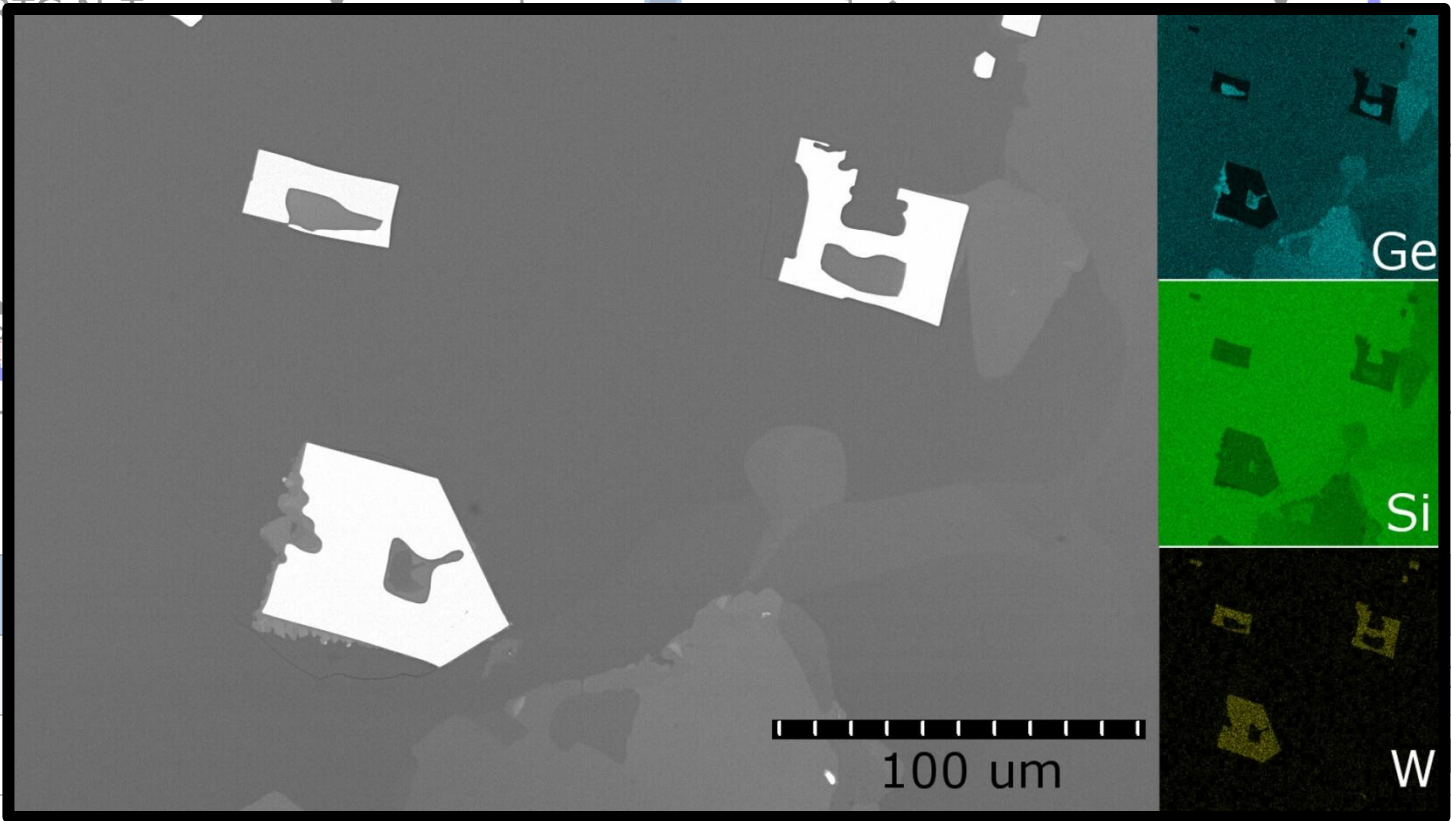
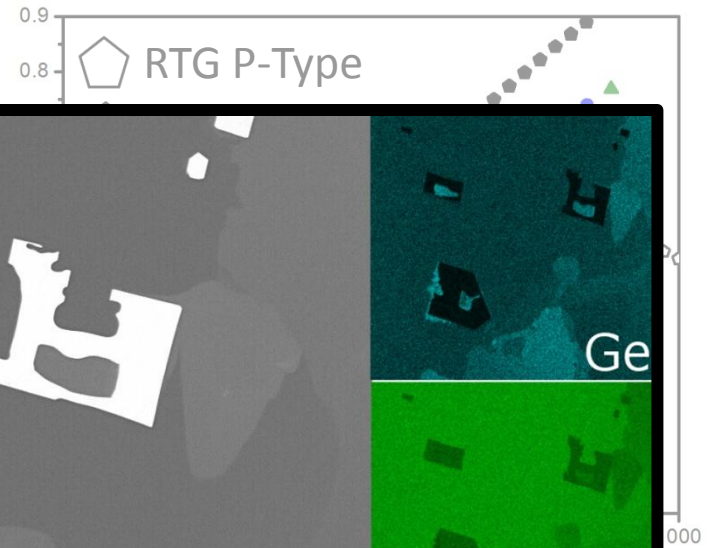
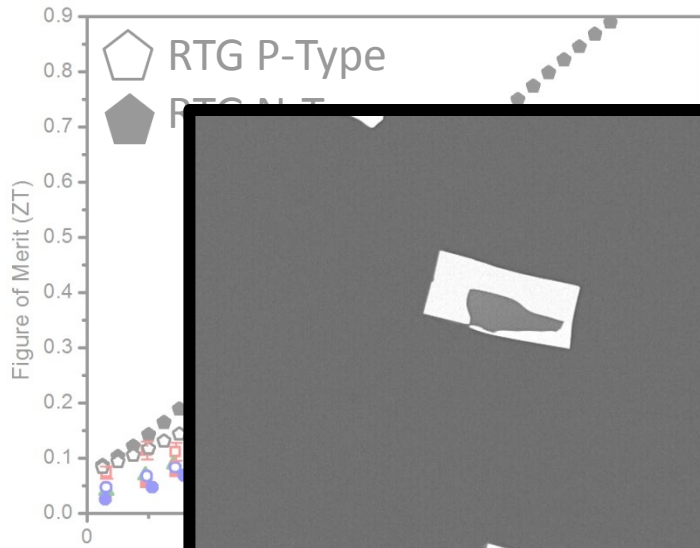


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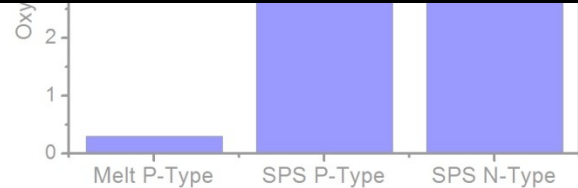
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		Si/Ge at% Ratio		
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Tungsten Silicide Volume Fraction	0%	X	◆ ●	X
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	2%	X	■	X
	5%	X	▲	X

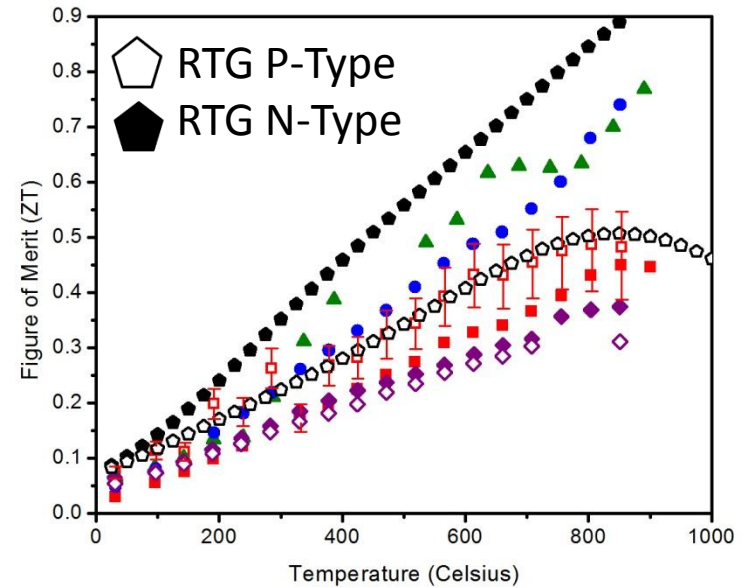
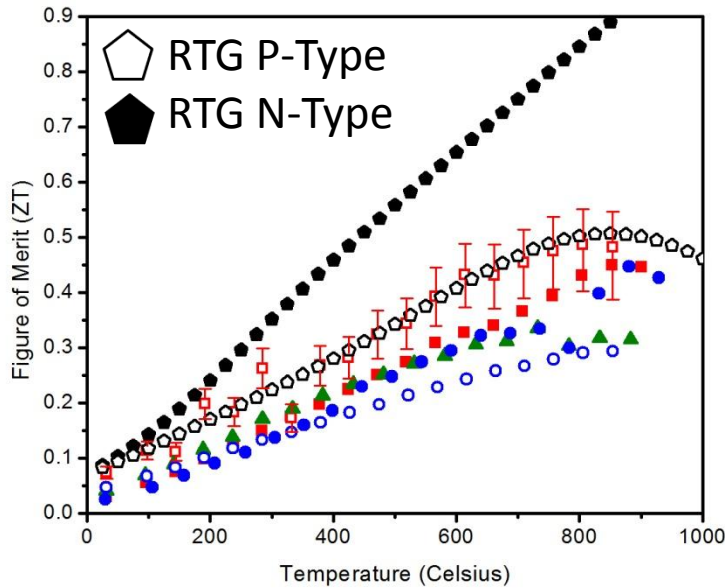


2% Doped
 ○ P-type, B
 ● N-type, P

Tungsten Silicide Volume Fraction	0%	1%	2%	5%
0%				
1%	X	X	X	
2%		▲	■	●
5%	X	X	X	



Tungsten Silicide Volume Fraction	1%	2%	5%	Ratio
1%	X	●		90/10
2%	X	■		X
5%	X	▲		X

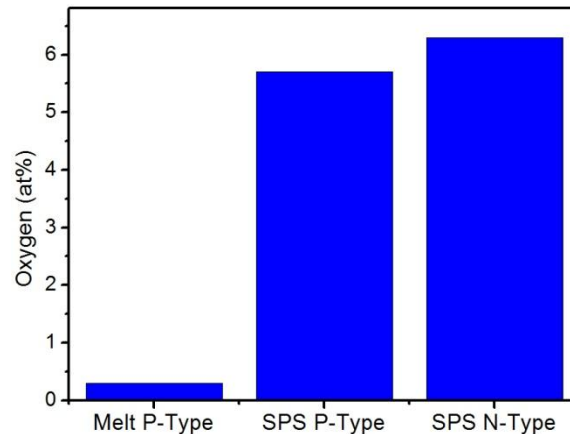


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	2%	▲	■	●
	5%	X	X	X

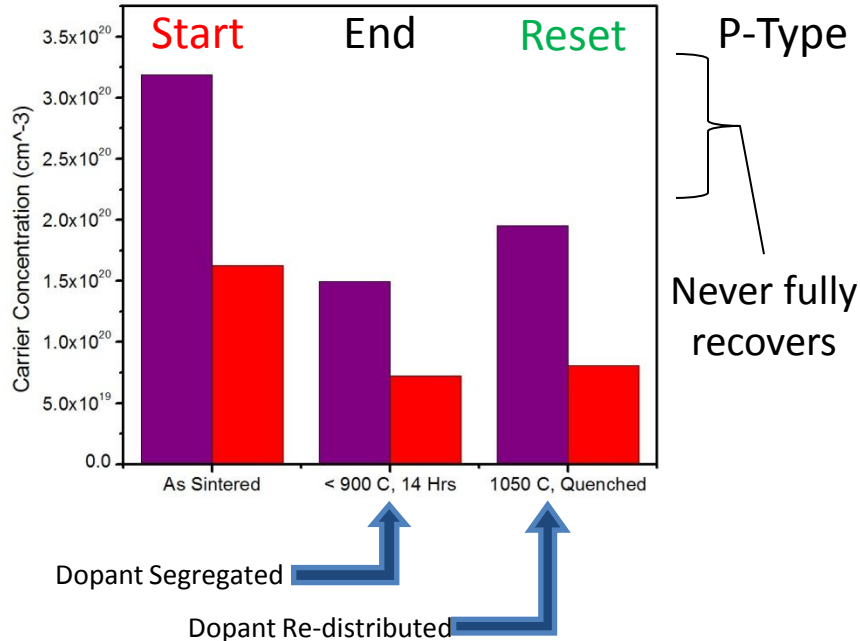
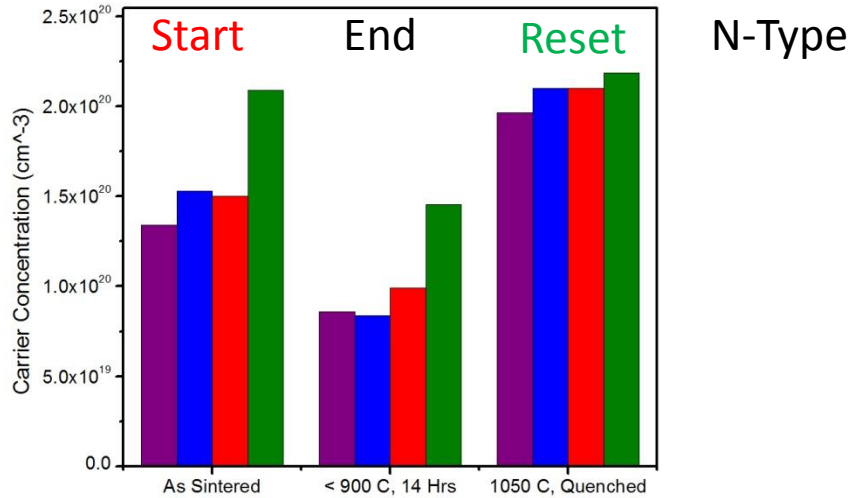


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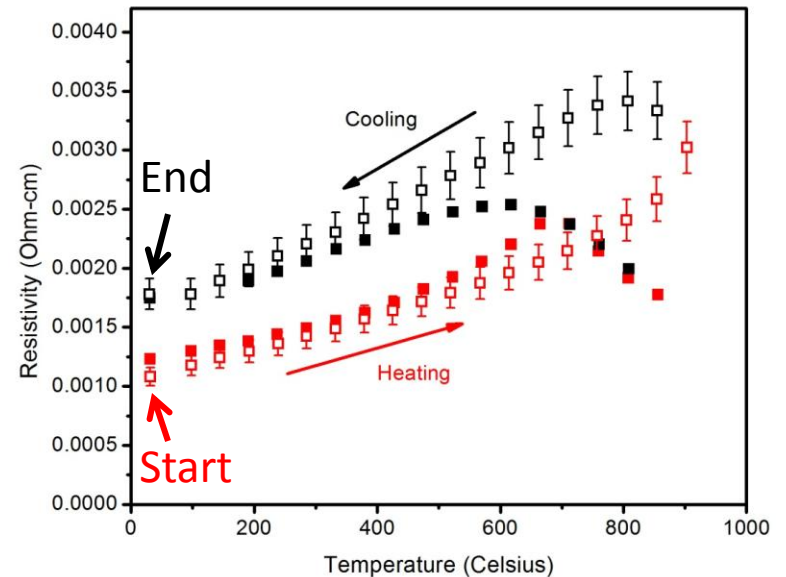
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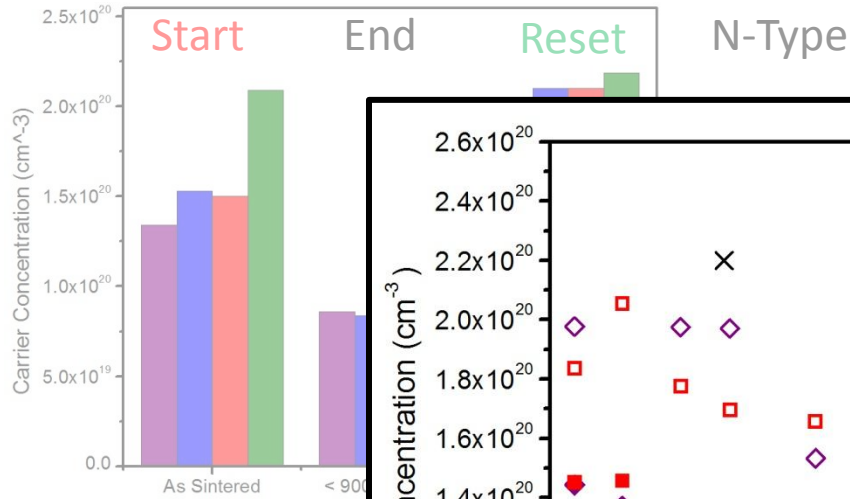


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- P-type, B
- N-type, P

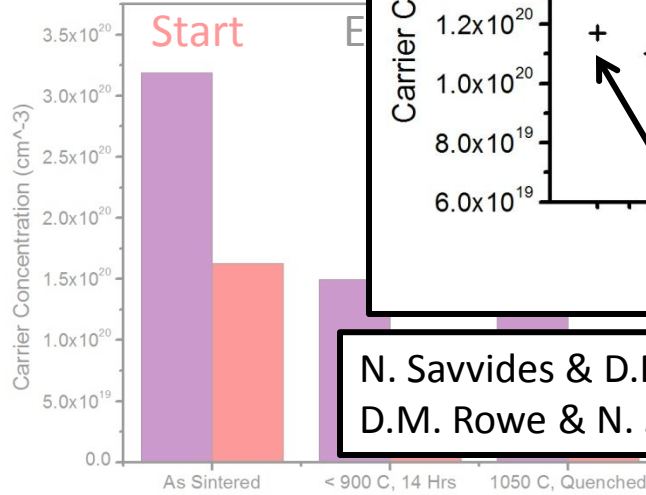
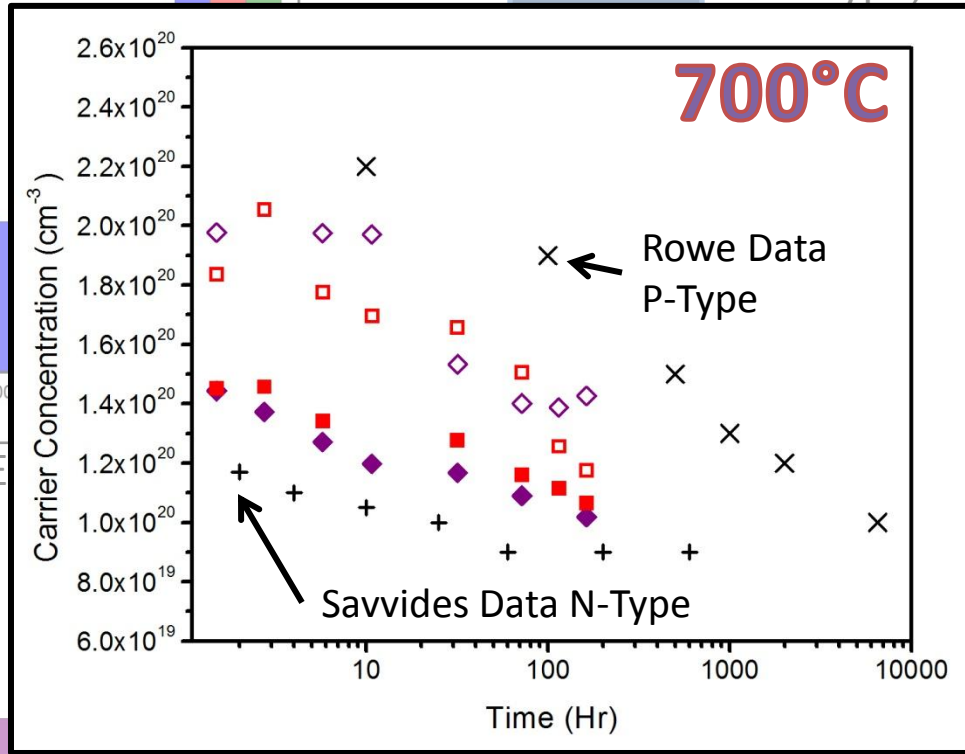
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Tungsten Silicide Volume Fraction	0%	X	◆	X
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	2%	X	■	X
	5%	X	▲	X





2% Doped
○ P-type, B

Si/Ge at% Ratio		
70/30	80/20	90/10
×	◆	×
×	●	×
×	■	×
×	▲	×

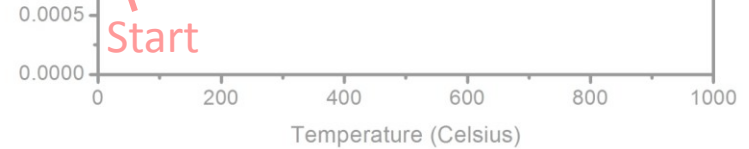


N. Savvides & D.M. Rowe, J. Phys. D: Appl. Phys. **14** (1981)
D.M. Rowe & N. Savvides, J. Phys. D: Appl. Phys. **12** (1979)

Dopant Segregated

Dopant Re-distributed

Start



Conclusion

- Silicide phase successfully reduces lattice thermal conductivity.
- Increased ZT for silicide composites as compared to baseline Si/Ge.
 - Need to control oxygen contamination to match baseline Si/Ge to RTG.
- Tungsten silicide phase offers tuning of carrier concentration.
- Silicide phase does not hinder thermal stability.

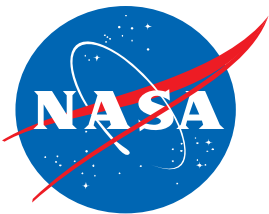
Acknowledgements

Tom Sabo, Ray Babuder, Ben Kowalski, Clayton Cross
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JPL

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