Thermoelectric Properties Measurements with Boron Nitride Test Fixture and other Tests

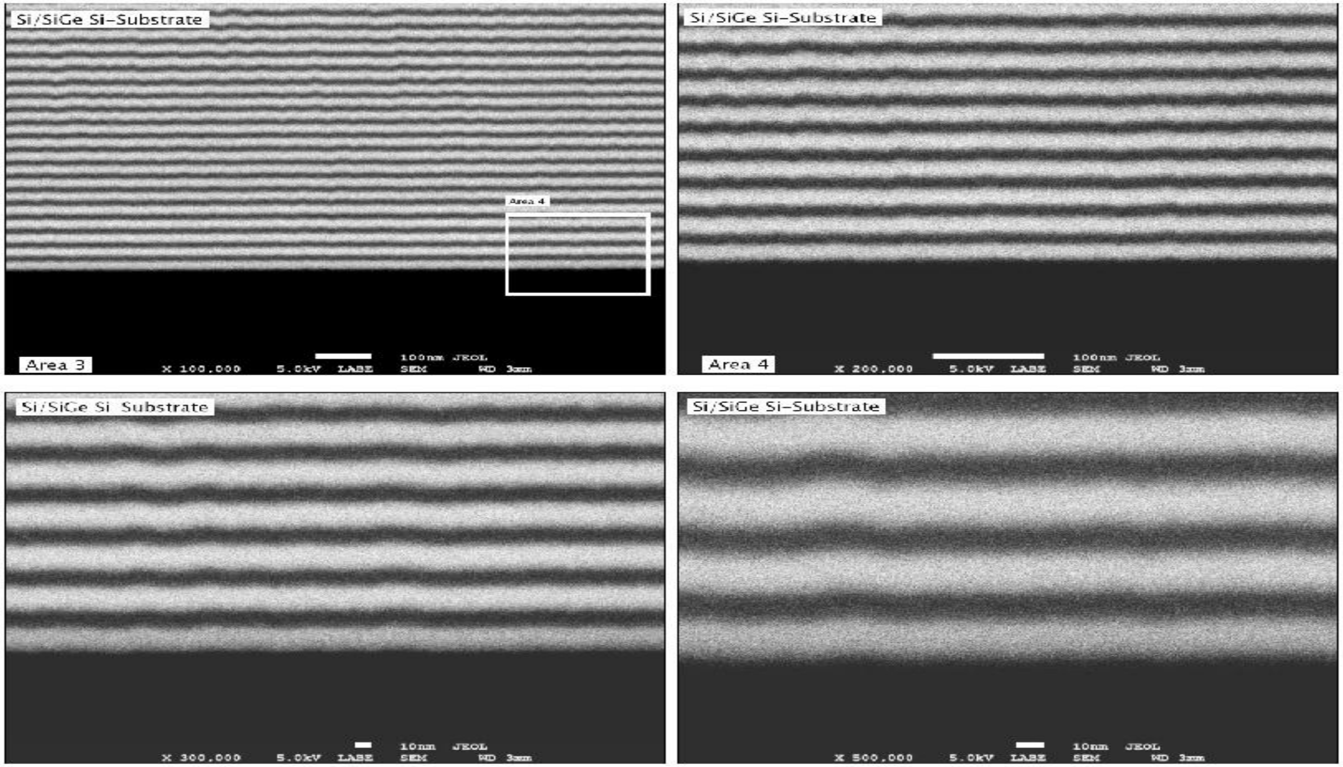
2009 Thermoelectrics Applications Workshop

San Diego, CA
September 29 - October 1, 2009

Velimir Jovanovic
Hi-Z Technology, Inc.
7606 Miramar Road, Suite 7400, San Diego, CA 92126
Telephone: 858-695-6660   Fax: 858-695-8870
www.hi-z.com   info@hi-z.com

Si/SiGe QW Films on Cross-section

Films were sectioned and then viewed by SEM (scanning electron microscopy)



Slight waving of layers is caused at the interfaces to the large difference between the atom size of Si and Ge

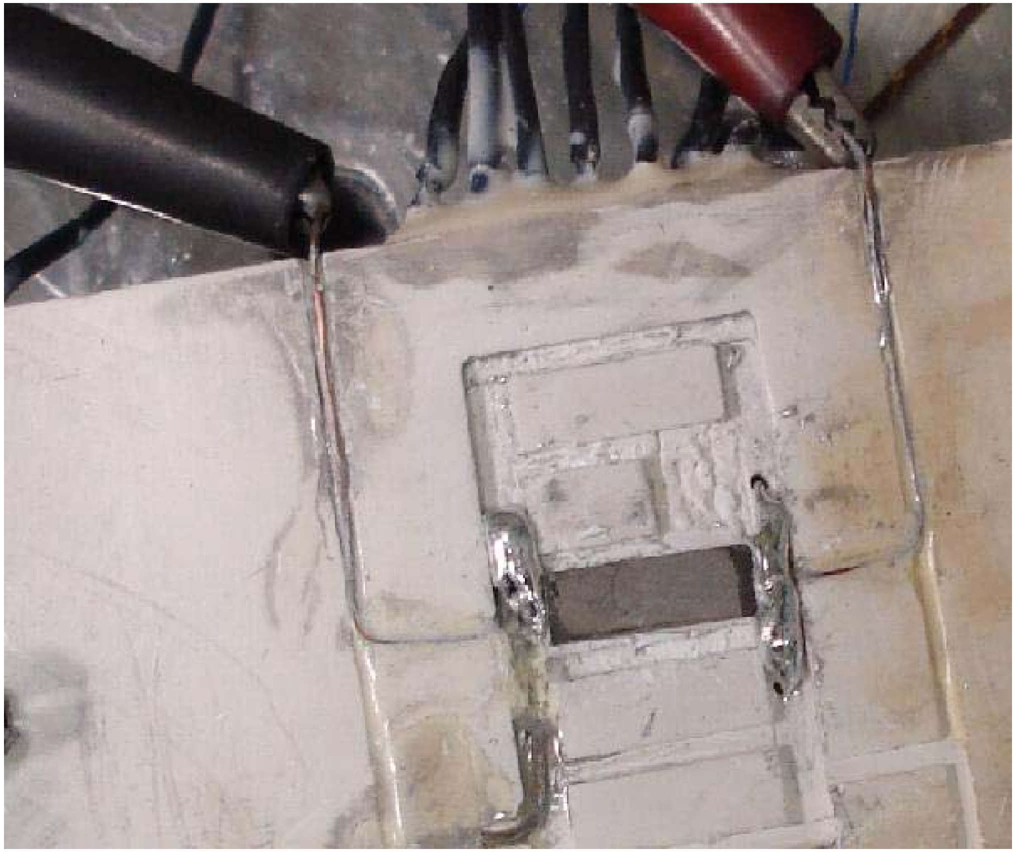
Thermal Properties Measurements with Boron Nitride Test Fixture

BN Fixture

Goal: Obtain ZT and efficiency directly

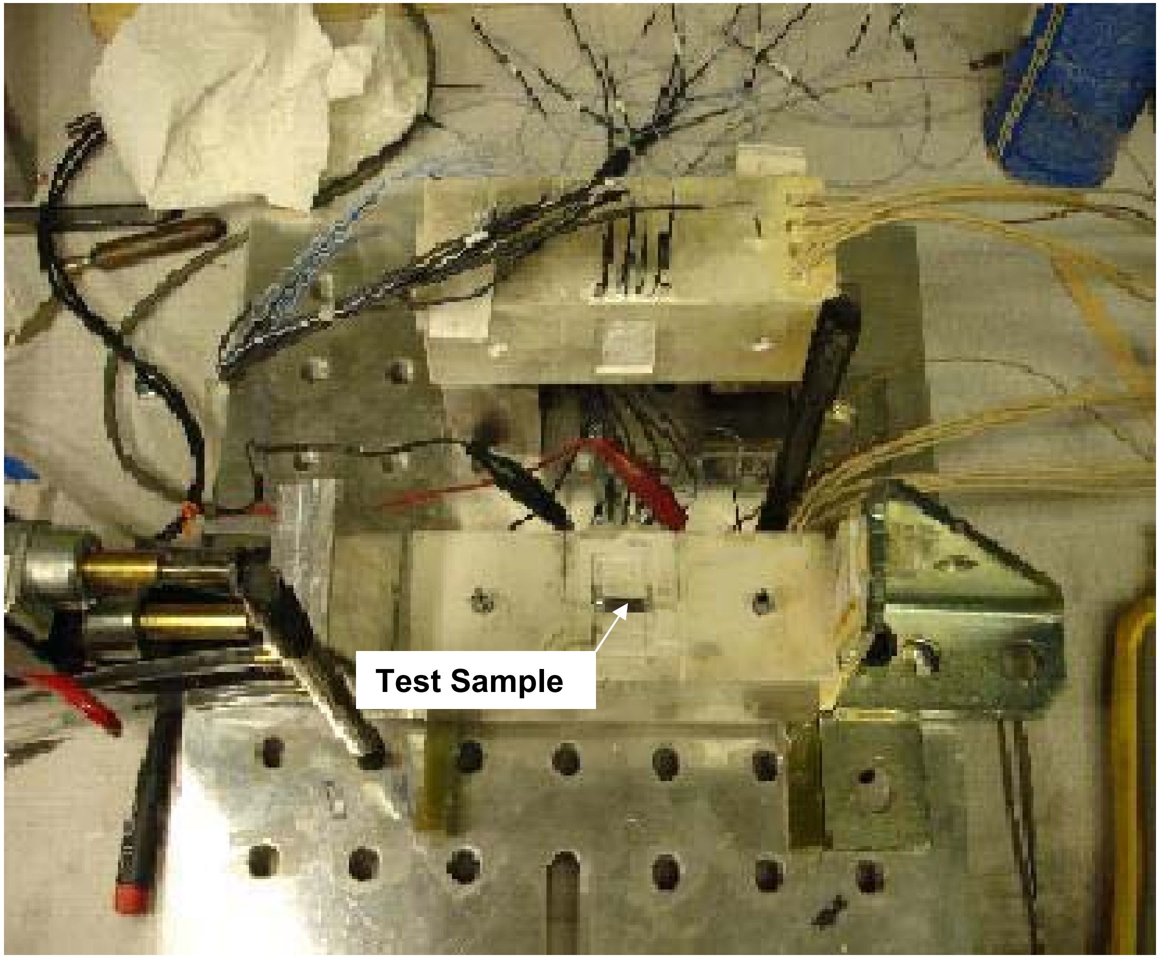
- Sample housed in large blocks of BN
- ΔT imposed on sample is the same as in BN
- ZT and efficiency based on measured values:
  - T_{hot} , T_{cold}
  - V_{load}, V_{oc}
  - R_{load} , R_{sample}

  except for thermal κ
- Measure α and ρ
- Heat flowing through QW is readily calculated using a conservative thermal κ
- Obtain efficiency by:
  - Power output divided by heat flowing through test sample
  - Calculation from measured T_{hot}, T_{cold}, α, ρ and conservative bulk thermal κ



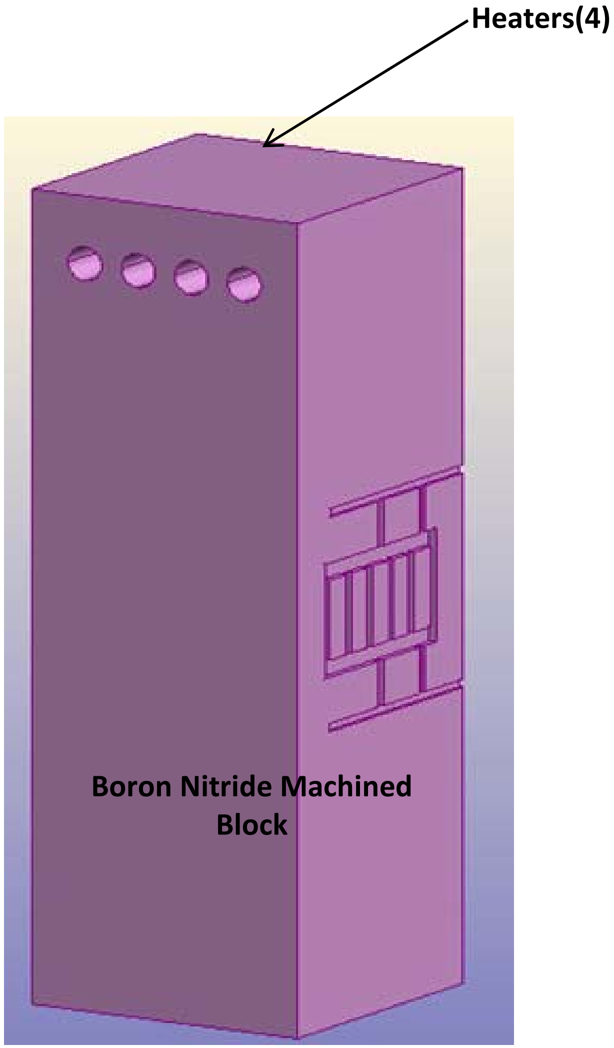
Sample Position in BN Test Fixture.
Up to 5 samples can be evaluated at once.

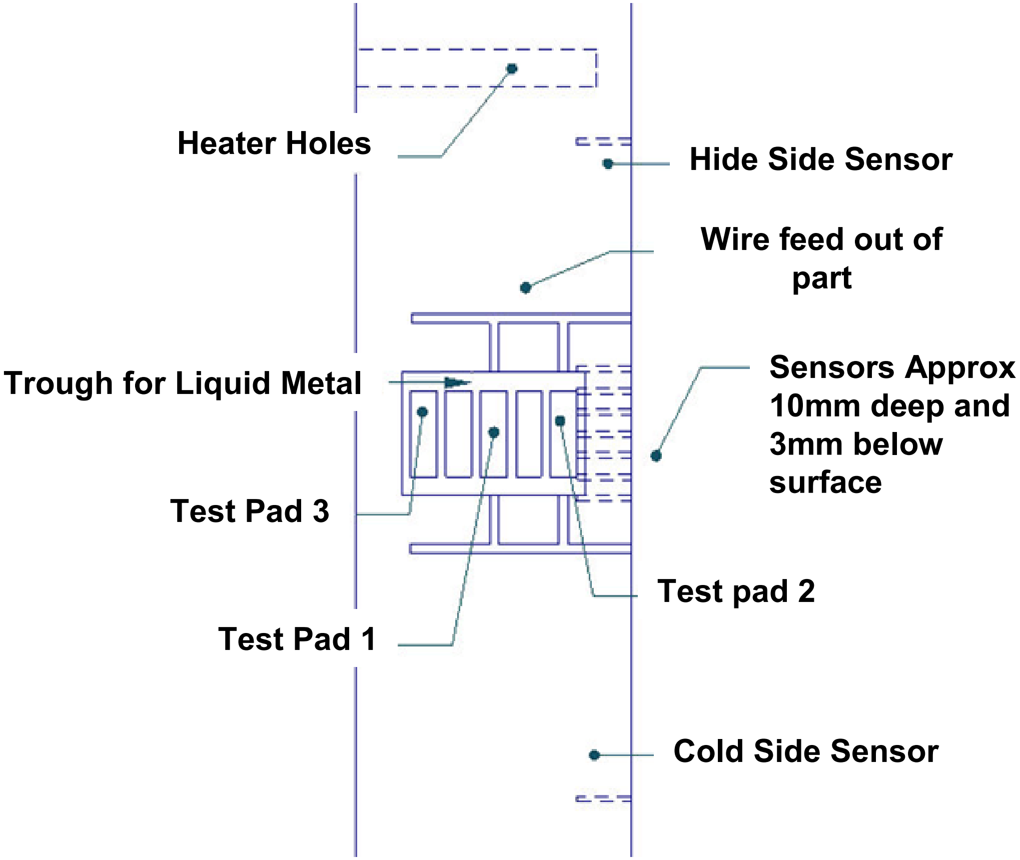
Thermal Properties Measurements with Boron Nitride Test Fixture



Both Halves of the BN Test Fixture are Shown with Test Sample in Place

Thermal Properties Measurements with Boron Nitride Test Fixture





One Half of Boron Nitride Block showing three test pad locations

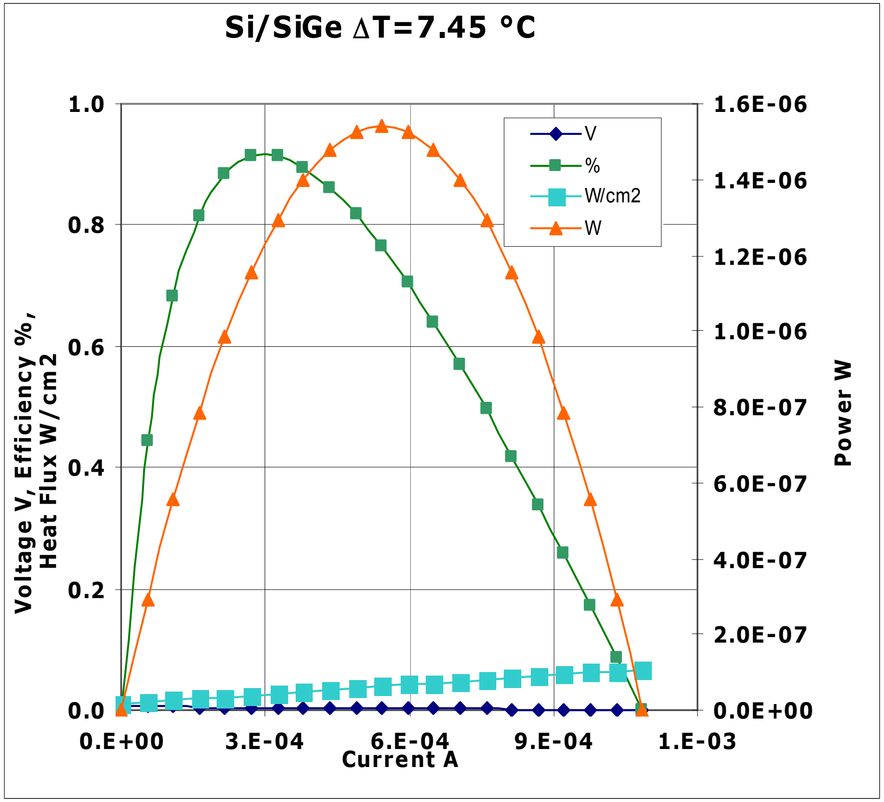
Summary of Test Results With Boron Nitride Test Fixture

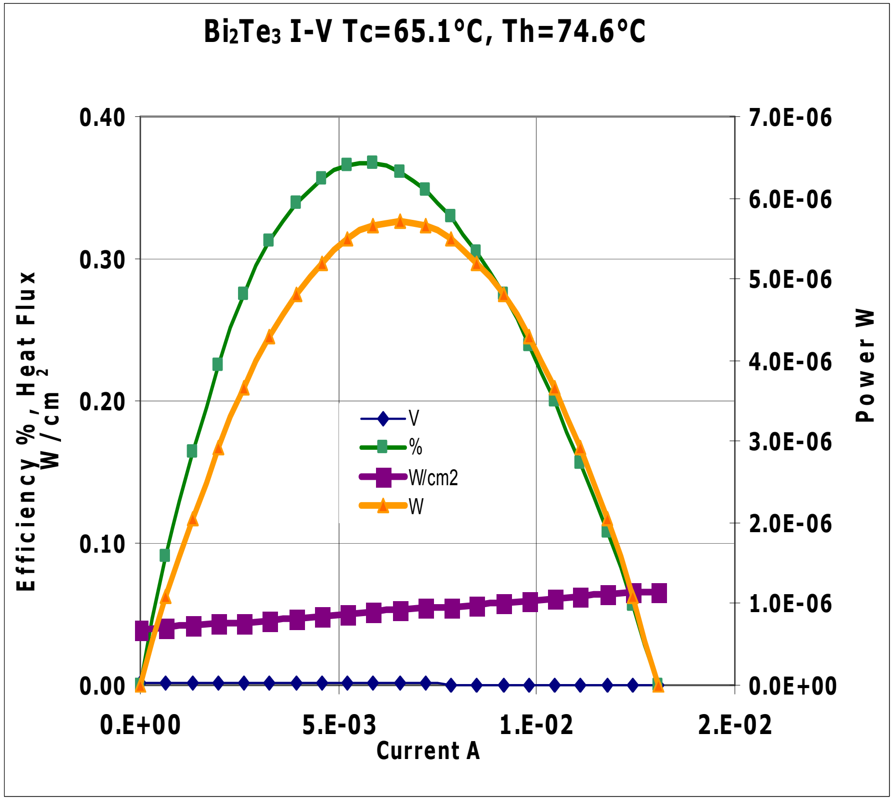
Status:

- Four TE Samples Tested, one was Bi_2Te_3, others were QW
- ZT > 5 Obtained for QW Samples
- Efficiency of QW Samples ~ 3X Higher than for Bulk Bi_2Te_3 Sample
- Achieved 50% of Carnot Efficiency in QW Samples
- The conversion efficiency (based on output power and heat flow) is:

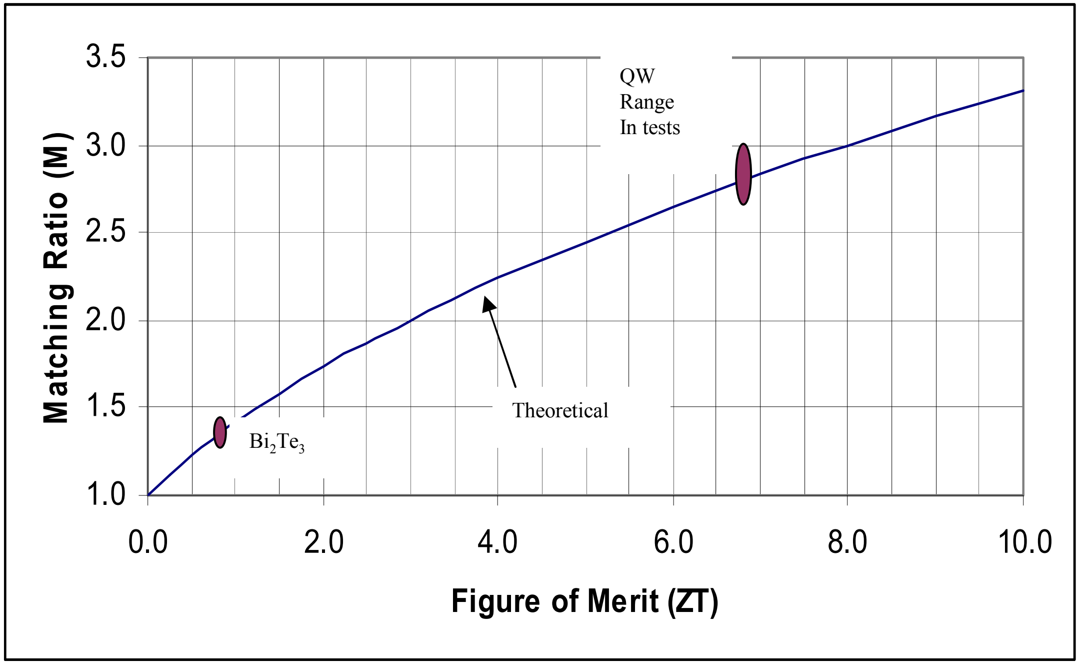
$$\eta = \frac{\frac{V^2}{R} \;\swarrow \text{POWER OUTPUT}}{\underset{\substack{\nearrow \\ \text{SEEBECK HEAT}}}{\alpha T I} - \underset{\substack{\nwarrow \\ \text{JOULE HEAT}}}{\frac{1}{2} I^2 R} + \underset{\substack{\nwarrow \\ \text{FOURIER HEAT}}}{\kappa \frac{A}{l} \Delta T}}$$

Performance Curves for Si/SiGe QW Based on Boron Nitride Test Data and for Bulk Bi_2Te_3





Variation of Resistance Matching Ratio (M) with Figure of Merit (ZT)

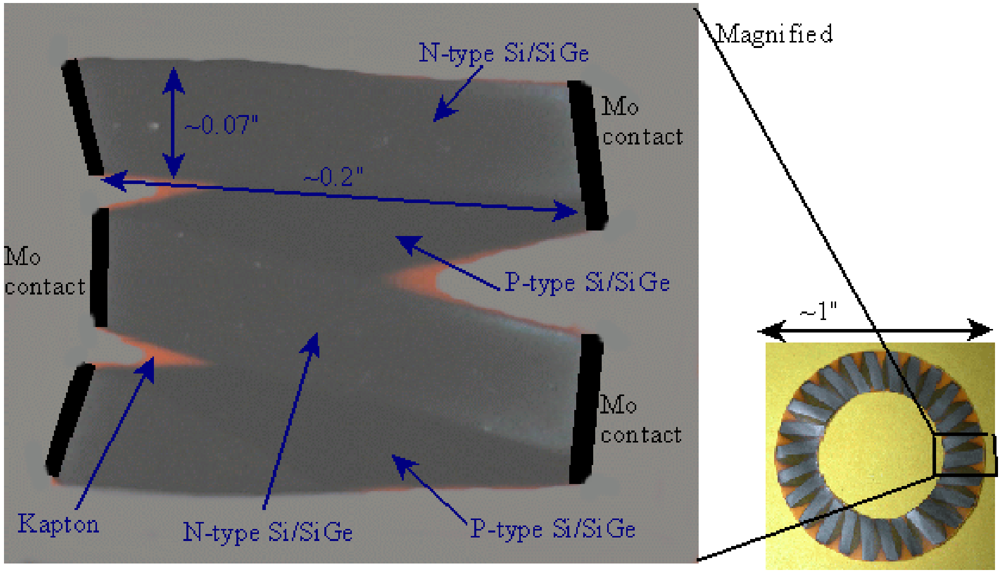


Note that the ZT values of the Bi_2Te_3 alloy and Si/SiGe QW samples are close to the theoretical values.

$$M = \sqrt{1 + \frac{1}{2}\,\overline{Z}\,(T_C + T_H\}}$$

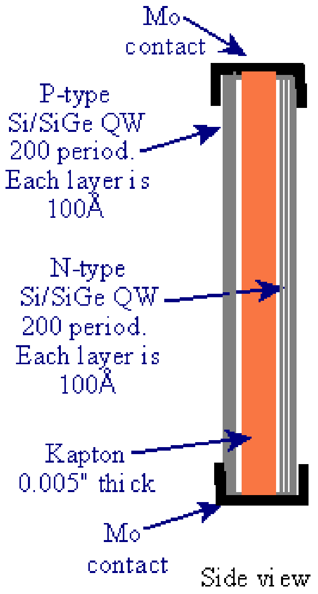
Other Experimental Results at Hi-Z:

QW on Kapton Module Performance Verified in a 2-Couple Test With Molybdenum Contacts Having Small Contact Resistance; Comparison with Bulk Module



Two couple device with N&P Si/SiGe QW on Kapton substrate

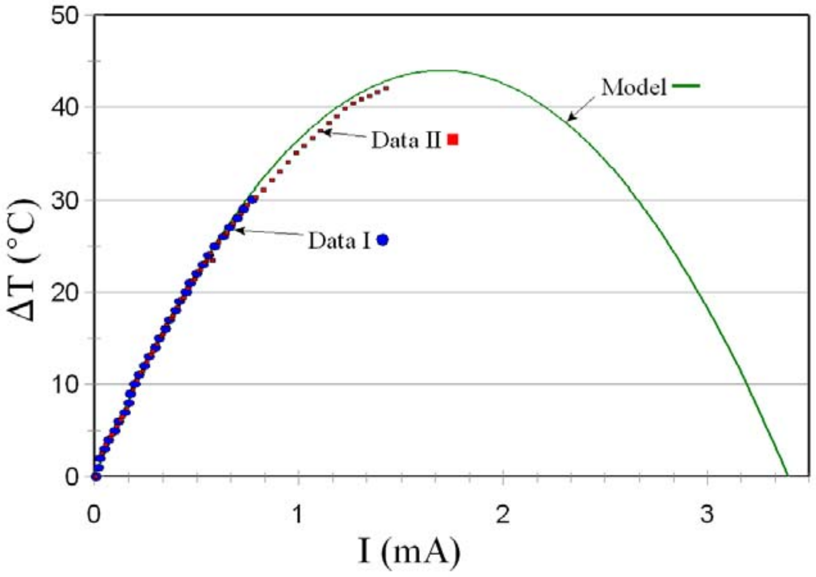
Complete 26 couple device



	Experimental		Calculated 26 Couple Module at ΔT = 40°C	
T_{Cold} = 26°C T_{Hot} = 66°C	**2 QW Couples Measured at ΔT= 40°C**	**2 QW Couples Measurements Extrapolated to 26 Couple Module at ΔT = 40°C**	**QW With ZT ~3.0**	**Bulk $(Bi,Sb)_2Se,Te)_3$ With ZT ~0.75**
Voltage (V_{OC})	225 mV	2.93 V	3V	0.5V
Power	0.371 mW	4.82 mW	5 mW	1.5 mW

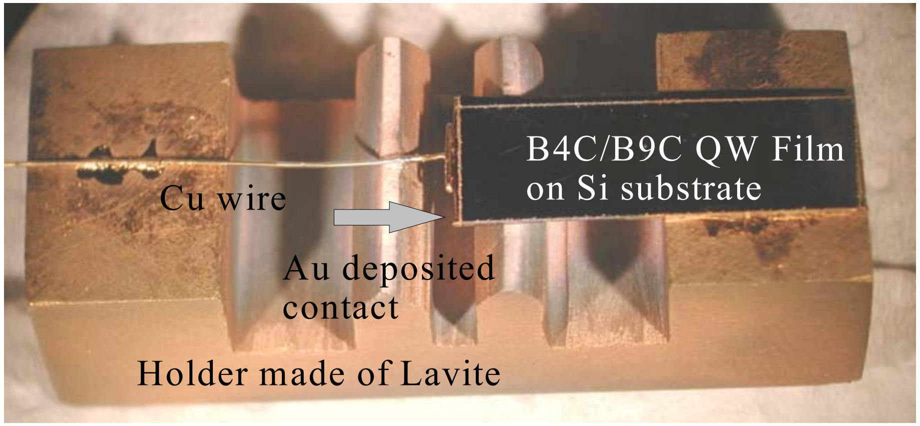
Other Experimental Results at Hi-Z:
Quantum Well Film ZT From Cooling Test Data

Recent Test with P-Type Si/SiGe QW Element on Kapton Substrate



Max. ΔT ≈ 44ºC
ZT ≈ 3 @ T ≈ 25ºC

Previous Test with P-Type B_4C/B_9C QW Element on Silicon Substrate



Max. ΔT = 45ºC
ZT ≈ 3 @ T ≈ 25ºC

Measurement of Superlattice Thermal Conductivity (κ) of Hi-Z Enhanced Films at the University of California San Diego

by Dr. Prabhakar Bandaru, UCSD

- **Measurements on $Si_{0.8}Ge_{0.2}/Si$ superlattice films for heat flow parallel to thin films**
- **Using the 3ω technique over a range of frequency**
  - (1) Low frequency → large thermal diffusion length → for film and substrate κ
  - (2) Higher frequency → smaller thermal diffusion length → for film κ, alone

Film Thickness	$\kappa^{\text{in-phase}}$ (W/m-K)
0.4 μm	~ 4.6
1.0 μm	4.3
5.6 μm	3.5

Samples courtesy Hi-Z Technology

Experimental thin film data in agreement with analysis indicating large reduction in thermal conductivity compared to bulk materials

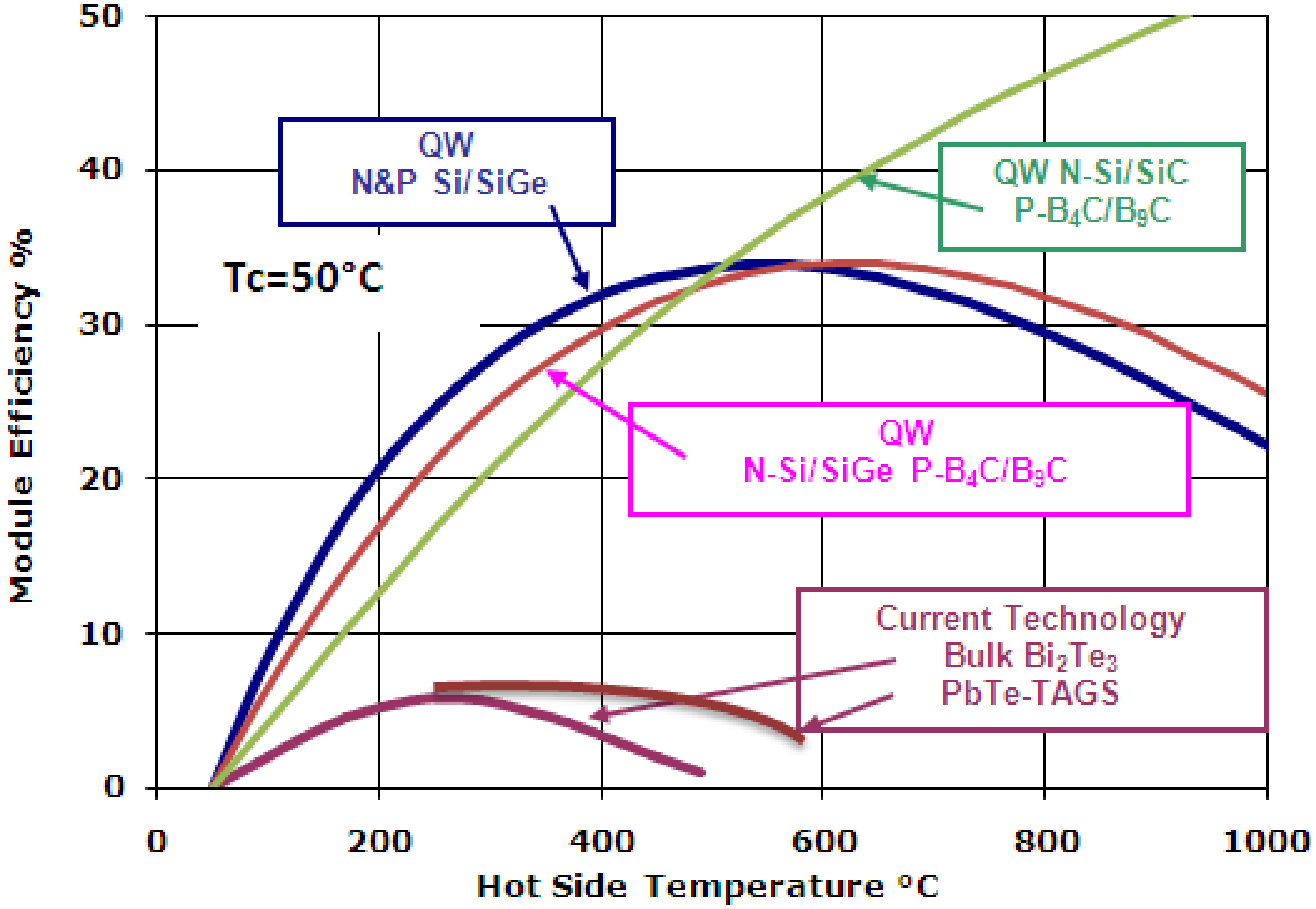
Presented at the MRS Spring meeting, San Francisco, April, 2009

Conclusions

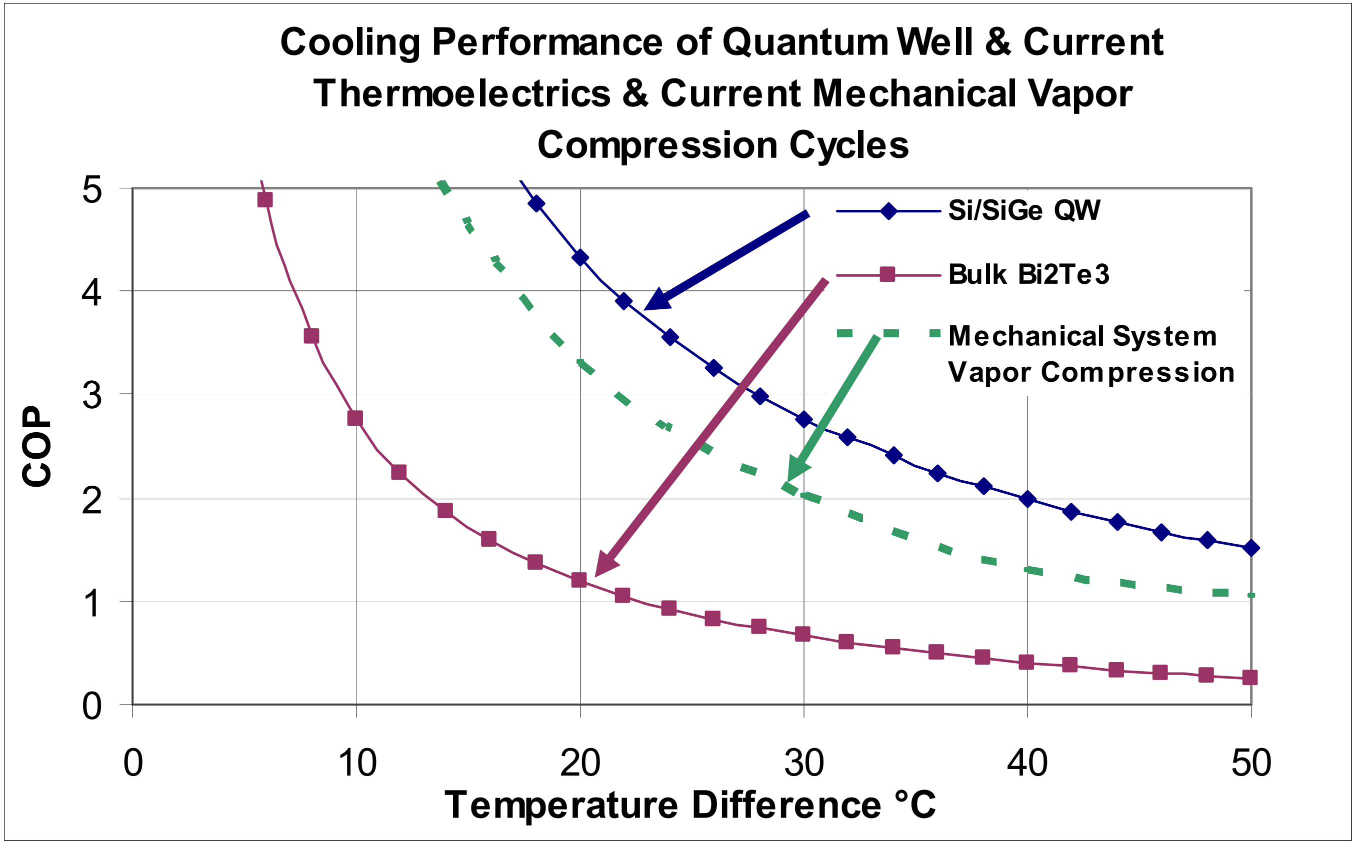
- Advanced Quantum Well Thermoelectrics Are Currently Under Development and Testing at Hi-Z
- Boron Nitride Test Technique Developed
  - Test Fixture Designed and Fabricated
  - Tests Conducted and Data Analyzed
    - Three QW TE Samples Tested
    - One Reference Bulk TE Sample Tested
  - Single Element Cooling Tests
  - Two-Couple Power Test
- Consistent High ZTs > 3 Obtained from Boron Nitride Tests and Previous Tests in Power Generation and Cooling Modes
- QW Thermoelectric Properties Leading to High ZTs, Conversion Efficiencies and COPs Were Independently Verified by UCSD and NIST
- Potential Commercial Applications of QW Thermoelectrics
  - Waste Heat Recovery from Trucks, Automobiles and Industrial Plants
  - Commercial Air Conditioning and Refrigeration

Boron Nitride Test Results Presented at ASME InterPack'09 Conference in San Francisco, July 19-23, 2009 (Paper No. IPACK2009-89328)

Predicted Conversion Efficiencies for Quantum Well (QW) Power Generation Thermoelectric Module



Si/SiGe Quantum Well Thermoelectrics for Cooling Applications



Quantum Well thermoelectrics have large coefficient of performance that exceeds current mechanical vapor compression cycle.