2009 DOE Hydrogen Program High Temperature Thermoelectric Materials

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Hi-Z Technology
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Project ID #
acep_04_elsner

Overview

Timeline

- Project start date: 28, June 2006
- Project end date : 7 August 2009
- Percent complete: 77%

Barriers

- Develop low contact resistance for production scale into Quantum Well materials
- Develop better technique for appraising microstructure and measuring the figure of Merit (ZT)
- Obtain outside confirming thermoelectric measurements

Budget

- Total project funding
  - DOE share: 850,000
  - Contractor share: 298,000
    BAE Systems
- Funding received in FY08 : 375,000
- Funding for FY09: 375,000

Partners

- SUNY Albany nanostructure group
- General Atomics nano film production facility
- UCSD for thermal conductivity measurements
- BAE Systems

Objectives

1. Obtain Thermoelectric properties measurements outside Hi-Z on Quantum Well materials that exhibit high figures of merit (ZT)
2. Develop new techniques for obtaining ZT directly
3. Develop techniques for obtaining low contact resistance joints
4. Optimize the sputter deposition techniques for producing consistent material and how they can be scaled up.
5. Develop low thermal conductivity substrate materials.

APPROACH

Criteria/Components for Developing QW Films

1. QW films
   - Compositions defined: N and P Si/SiGe, P type B_4C/B_9C and N and P type Si/SiC
   - Deposition parameters established with sputtering
   - Third party verification of QW films performed and continuing
2. Substrate
   - Need low thermal Κ materials at low cost and can be readily coated with QW films
3. Joining techniques needed for fabricating couples that will operate at various T_H up to 1000°C
4. Life testing of materials and couples
   - Isothermal
   - Gradient
5. Fabricate and evaluate modules and production scale up.
6. Continue cost analysis as fabrication techniques evolve

Relevance

- Projected increase from the current 5% to 15- 40% efficiency

- Waste heat can be recovered from any vehicle, industrial and geothermal heat sources

- Hi-Z pursuing nanosized Quantum Well materials Their potential for high ZTs (figures of merit) which means higher efficiencies.

- Many samples prepared with high Seebeck coefficients (α1,000 Micro V/°C) and low electrical resistivities (ρ1milli Ω –cm)

- Several measurements by outsiders confirm Hi-Z's encouraging results for α,ρ, and Κ

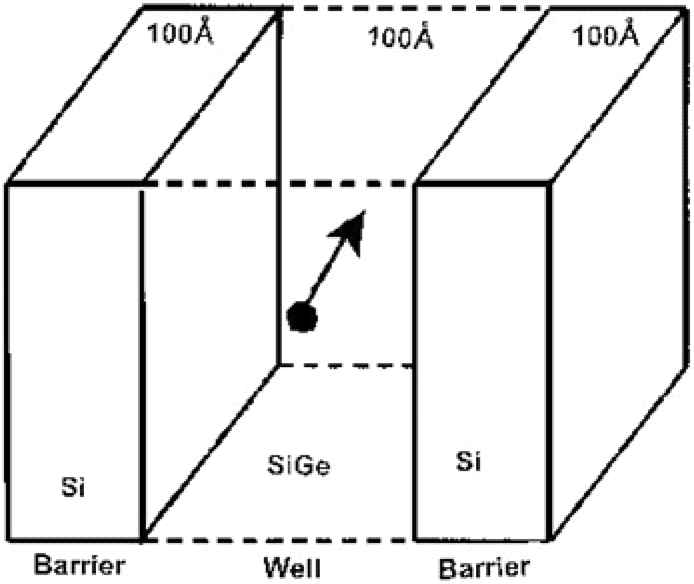
- New measuring technique developed for measuring ZT directly.

- Hi-Z is pursuing fabrication/testing of N&P couples and modules

- Over eight—1 Billion sized markets exist for converting waste heat into electricity if more efficient thermoelectrics can be developed.

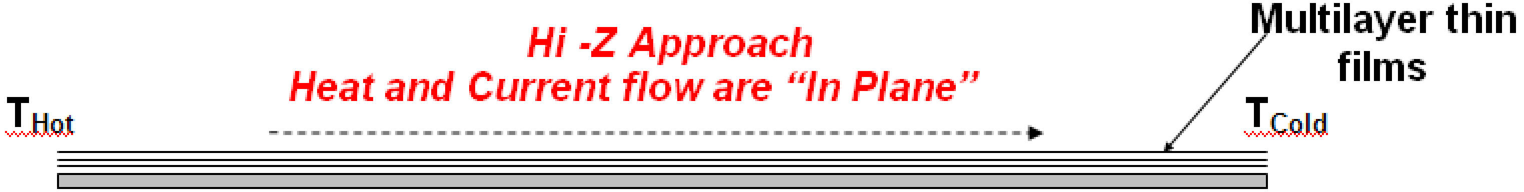
Two-Dimensional Enhanced Thin Film Thermoelectrics using Quantum Well Structures

- Active layer sandwiched between materials with band offset to form a barrier for the charge carriers
- Increased Seebeck coefficient (α) due to an increase in the density of states
- Significant reduction on resistivity (ρ) due to quantum confinement of carriers
- Significant reduction on thermal conductivity (κ) due to strained lattice and other factors
- Quantum Well (QW) effects become significant at a layer thickness of <200Å



Enhanced Thin Film - Orientation Difference

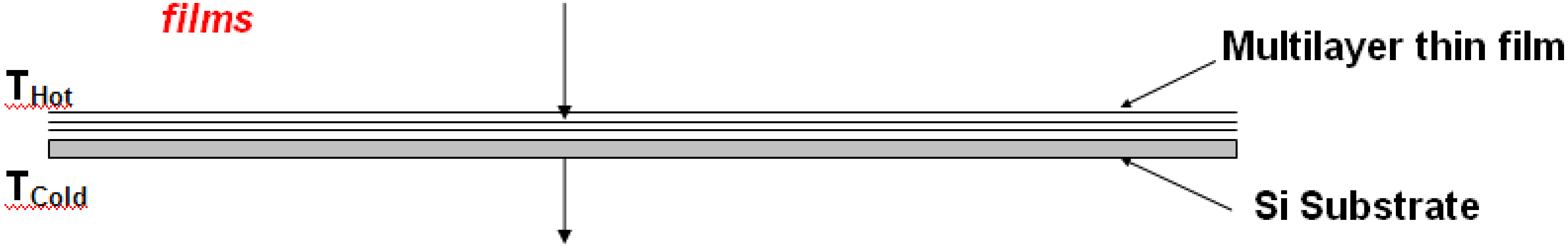
Hi -Z Approach
Heat and Current flow are “In Plane”



When Substrate and film are parallel to current flow:

1. **Large ΔT’s can be obtained**
2. **The *Quantum Well* effect for increasing ZT will be realized**

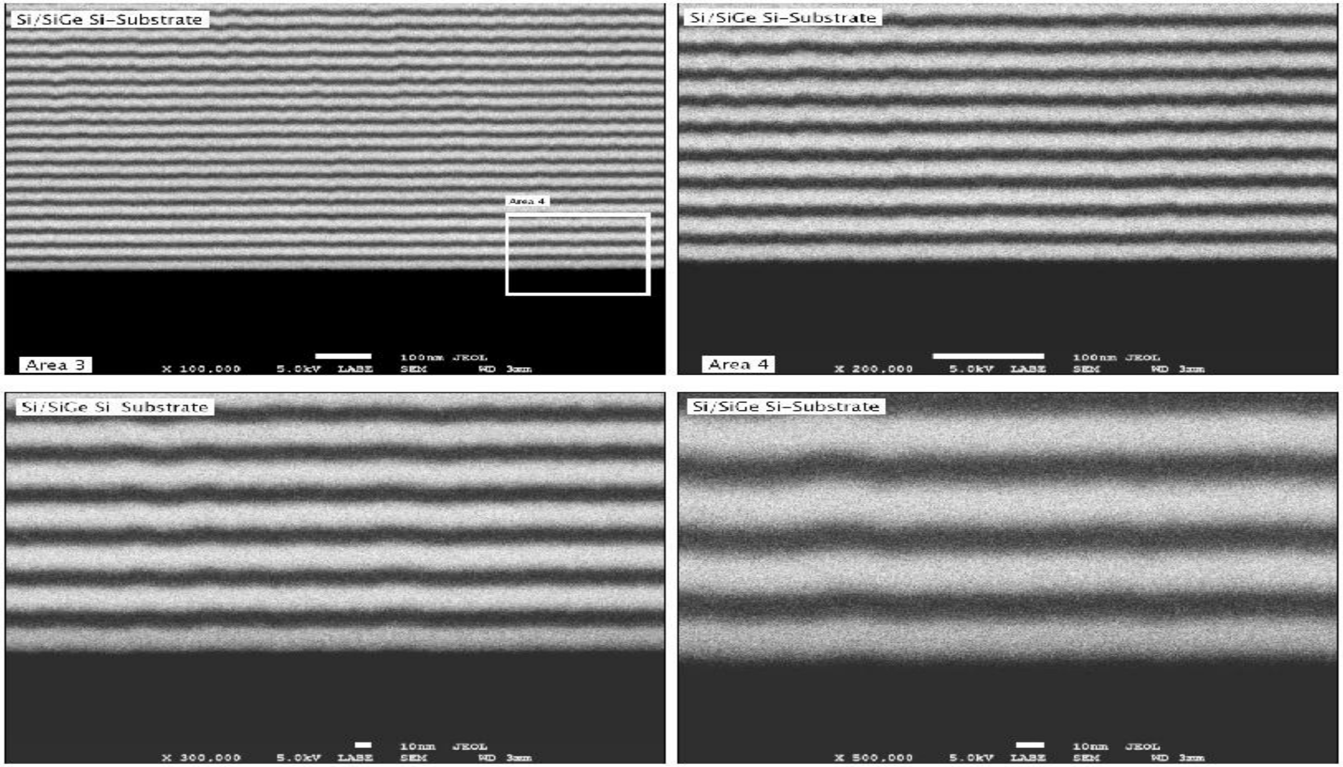
Alternate Approach is less favorable when Heat and Current Flow are “Cross Plane” to films



1. **Large ΔT’s are difficult to obtain across the thin films. Large heat fluxes required**
2. **Not useful for power generator**
3. **No Quantum Well effect is realized**
4. **However thermal conductivity will be reduced.**

Si/SiGe Films on Cross-section

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



X 100,000

X 200,000

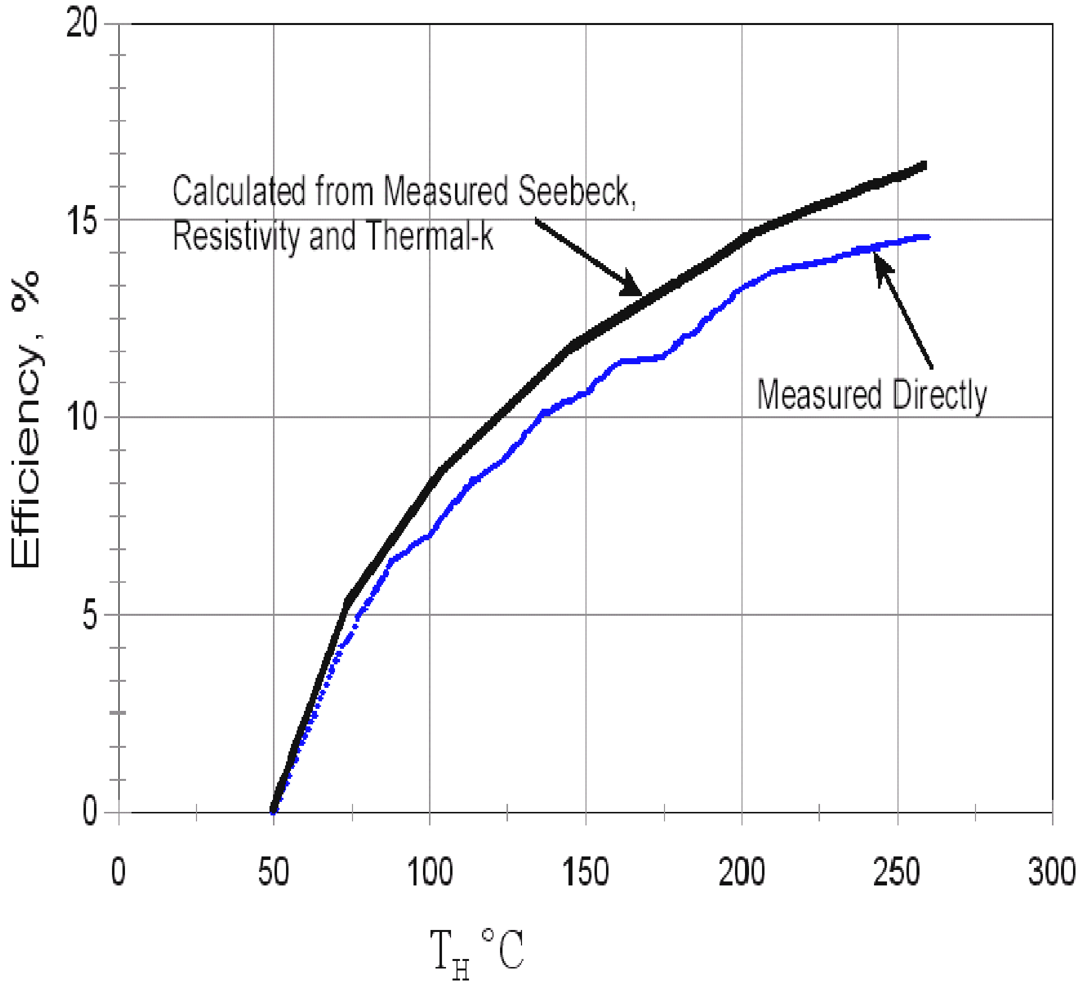
X 300,000

X 500,000

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

Quantum Well Couple Efficiency

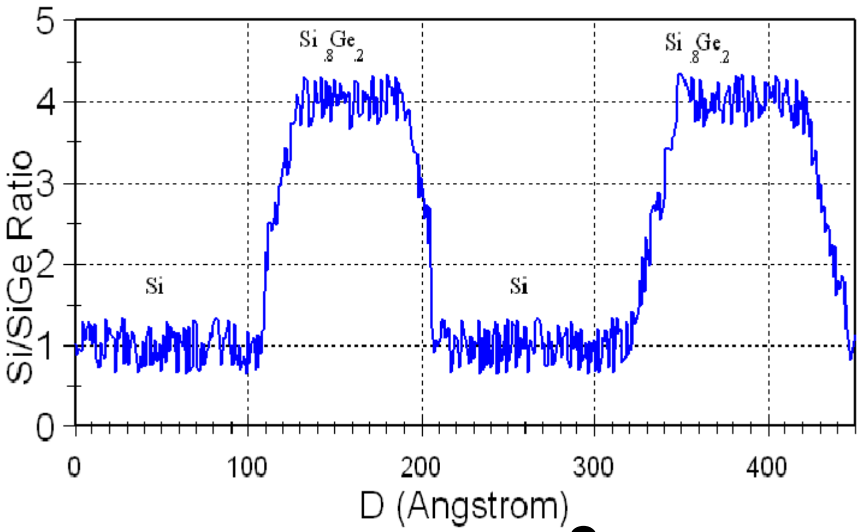
Highest Measured Thermoelectric Efficiency



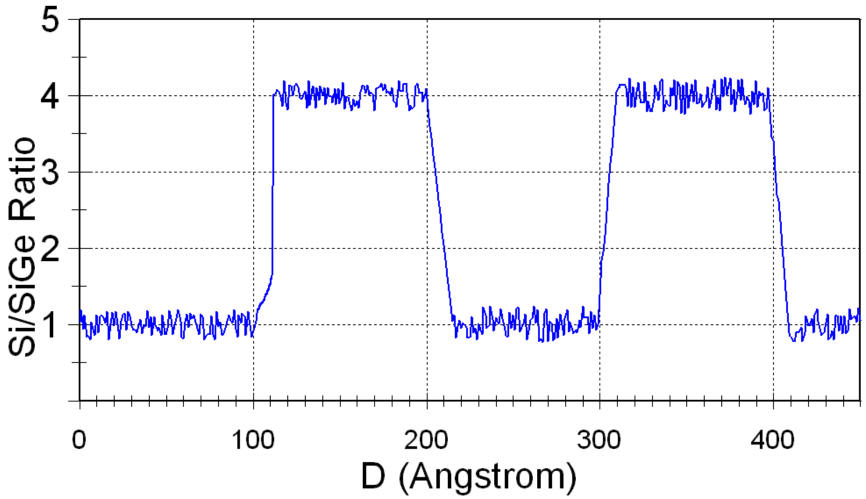
- Measured Quantum Well Couple Efficiency Versus temperature at a T_C = 70°C
- Over 100 Data Points Were Obtained – N-leg Si/SiGe, P-leg B_4C/B_9C
- Both Films 11 μm Thick and Deposited on a 5 μm Thick Si Substrate
- Average ZT for N &P couple is ~ 3

Auger Electron Spectroscopy (AES) Results

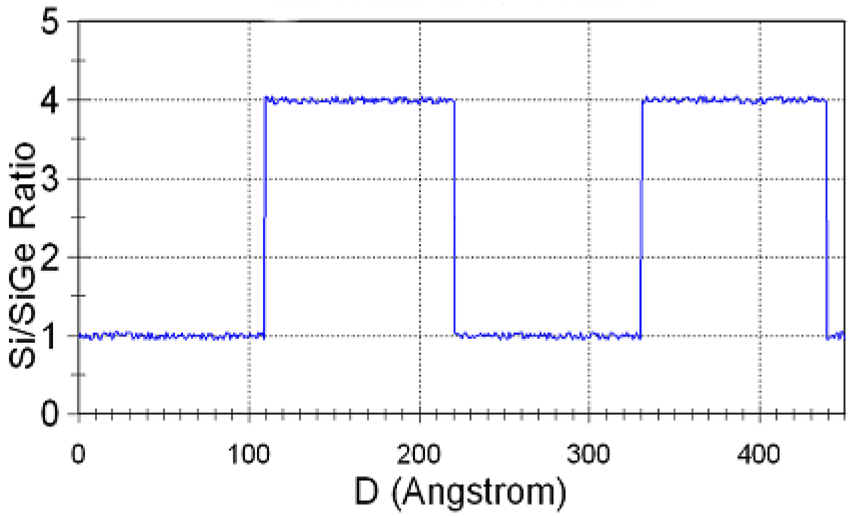
1 Amorphous Film



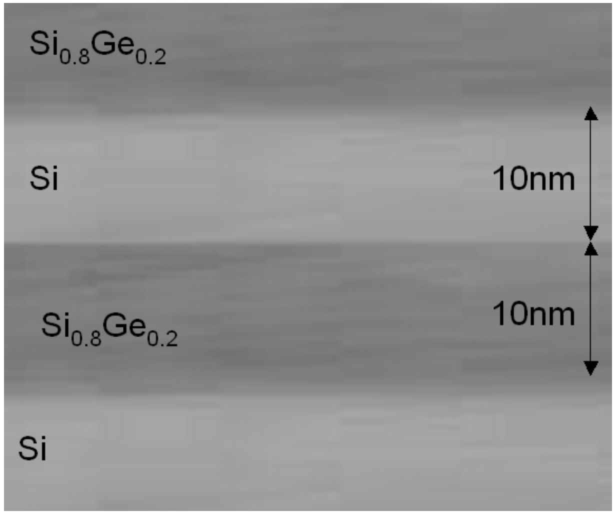
2 Near Neighbor Film



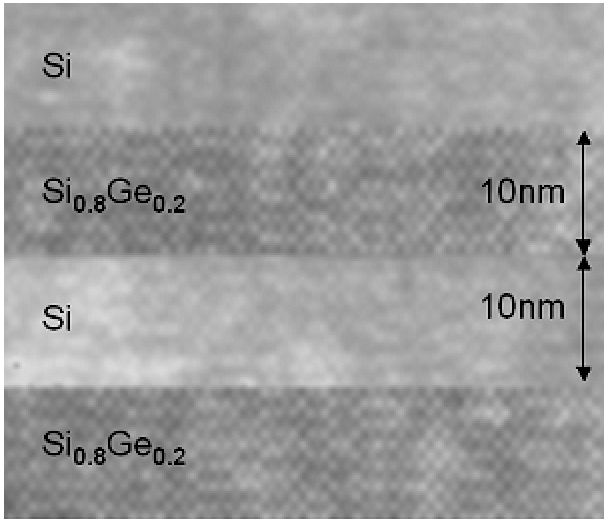
3 Superlattice(single crystal) Film



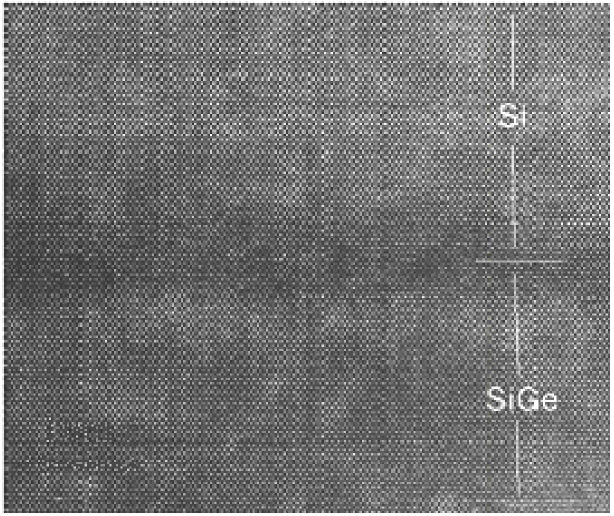
Transmission Electron Microscopy (TEM) Results



1 amorphous film



2 near neighbor film

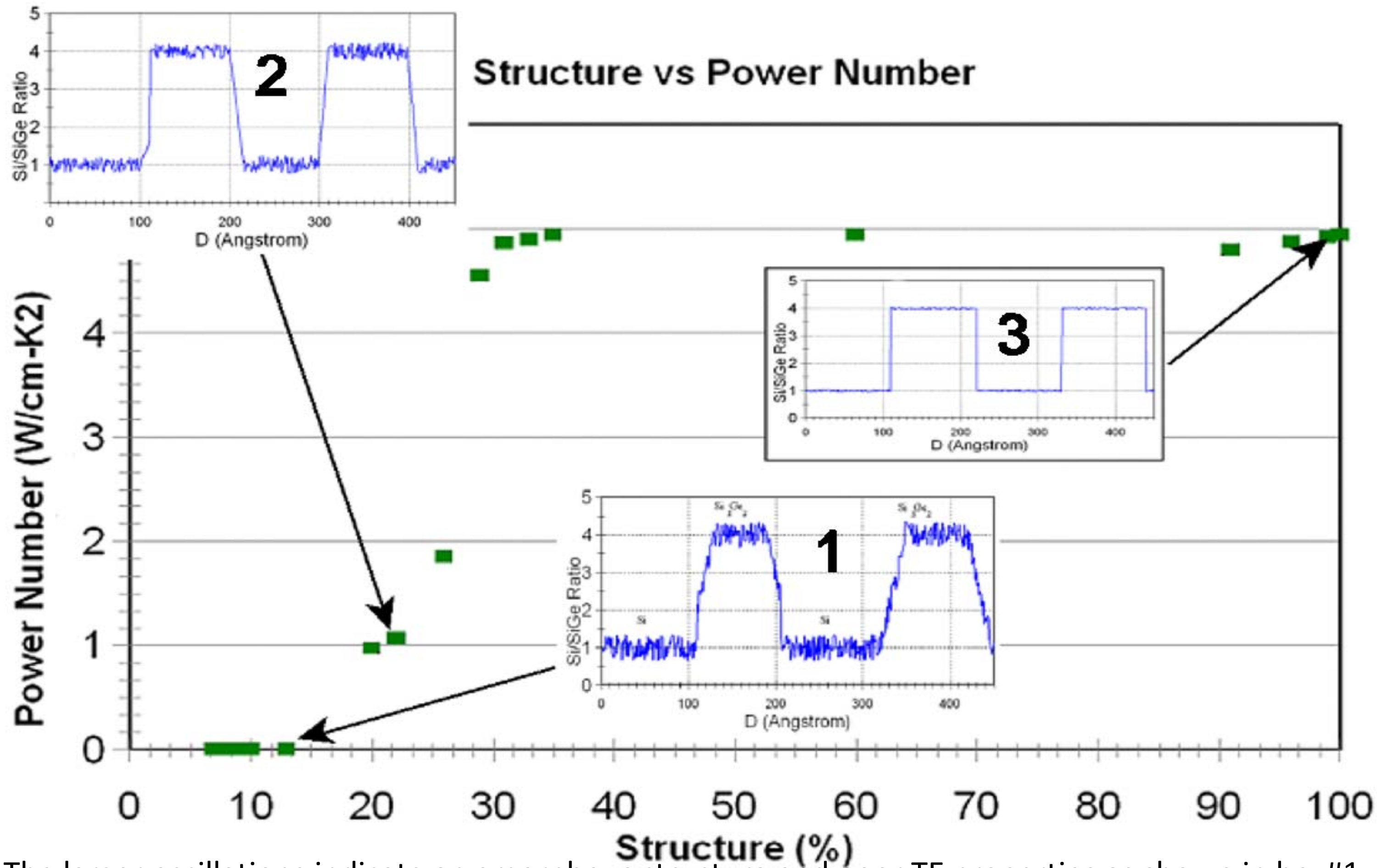


3 superlattice (single crystal) film

- Each layer is ~10nm thick

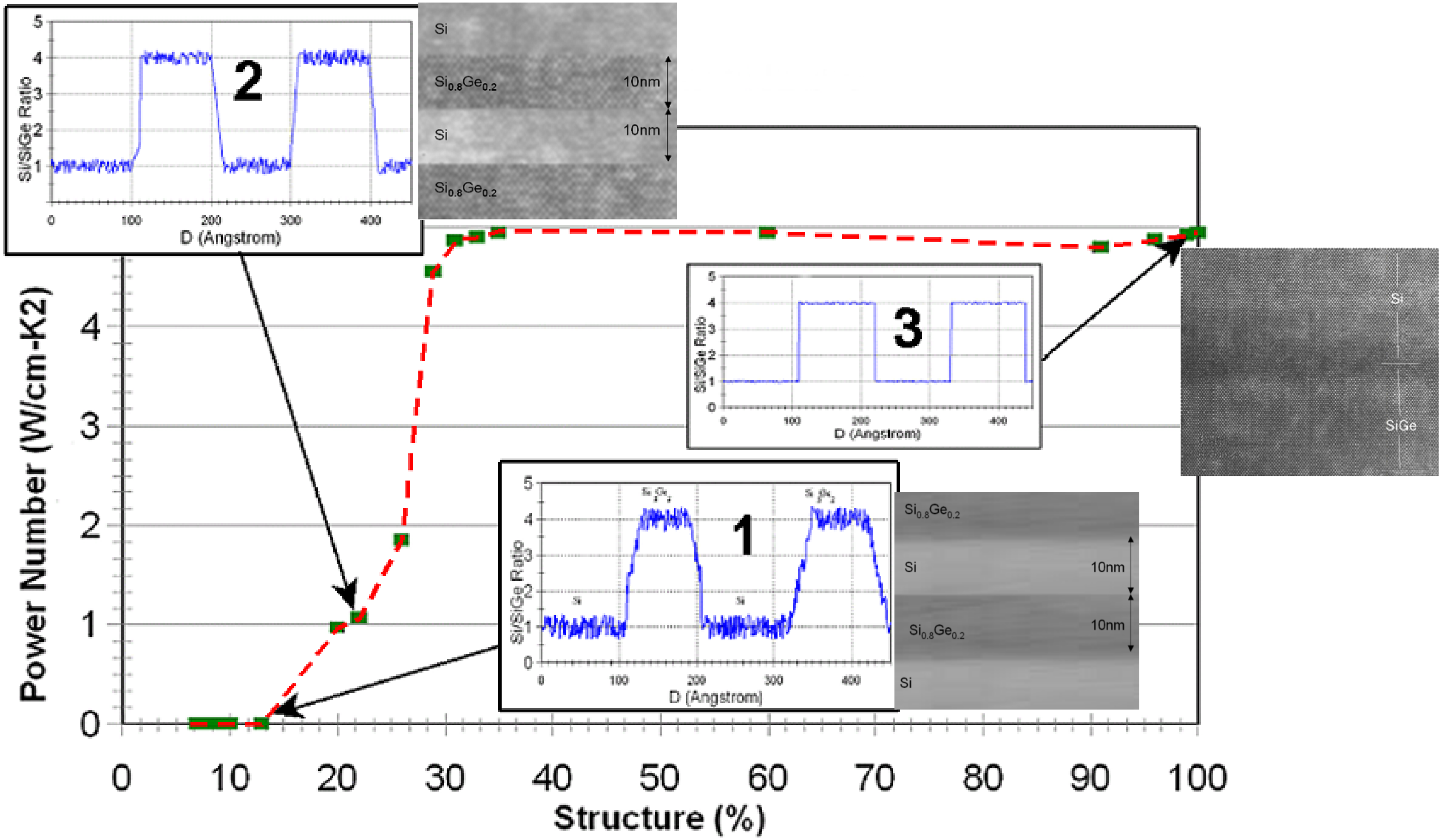
•The boundaries between each layer are as sharp as the as fabricated films indicating no diffusion is occurring and films do not break up

Relation between TE properties and structure using AES



The larger oscillations indicate an amorphous structure and poor TE properties as shown in box#1. As oscillations variance decrease as shown in box#2 TE properties begin to improve. When best TE properties are obtained the profile in box#3 is obtained.

Relation between TE properties and structure using AES & TEM

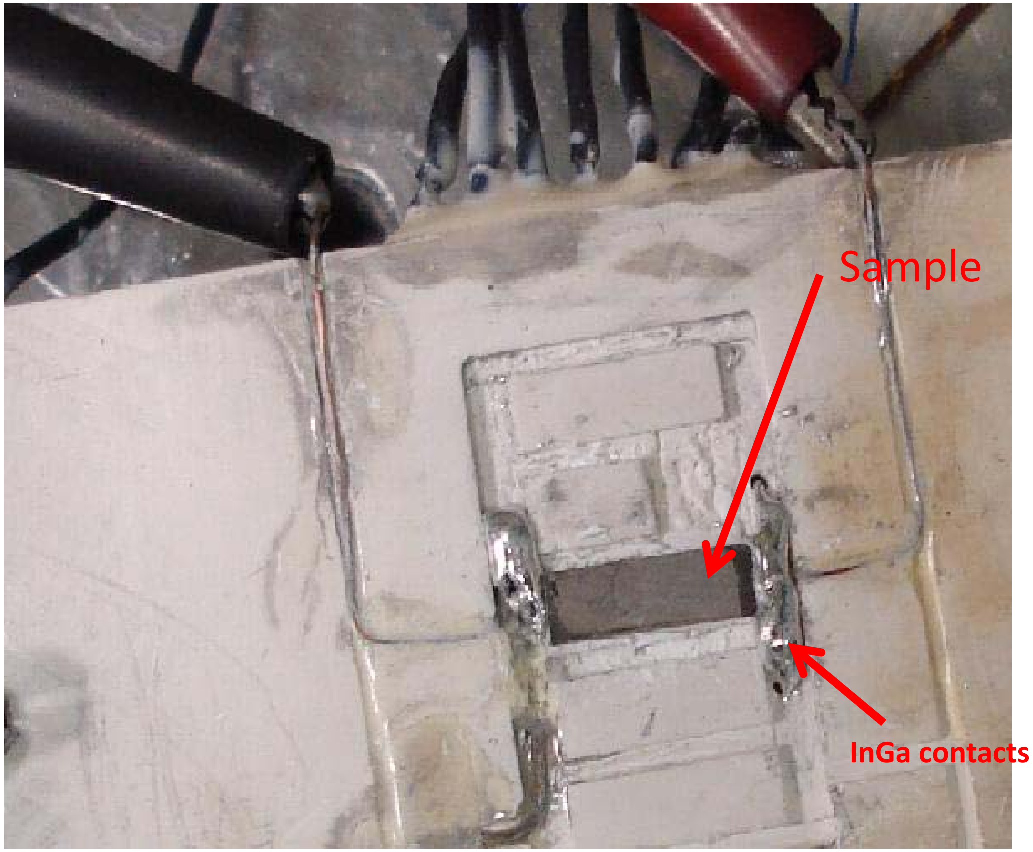


The larger oscillations indicate an amorphous structure and poor TE properties as shown in box#1. As oscillations variance decrease as shown in box#2 TE properties begin to improve. When best TE properties are obtained the profile in box#3 is obtained. For superlattice (box#3) structures is ~100%, for near neighbor (box#2) structures is ~ 10-90%, and for all amorphous (box#1) structure ~0%

Thermelectric Property Measurements with Boron Nitride Test Fixture

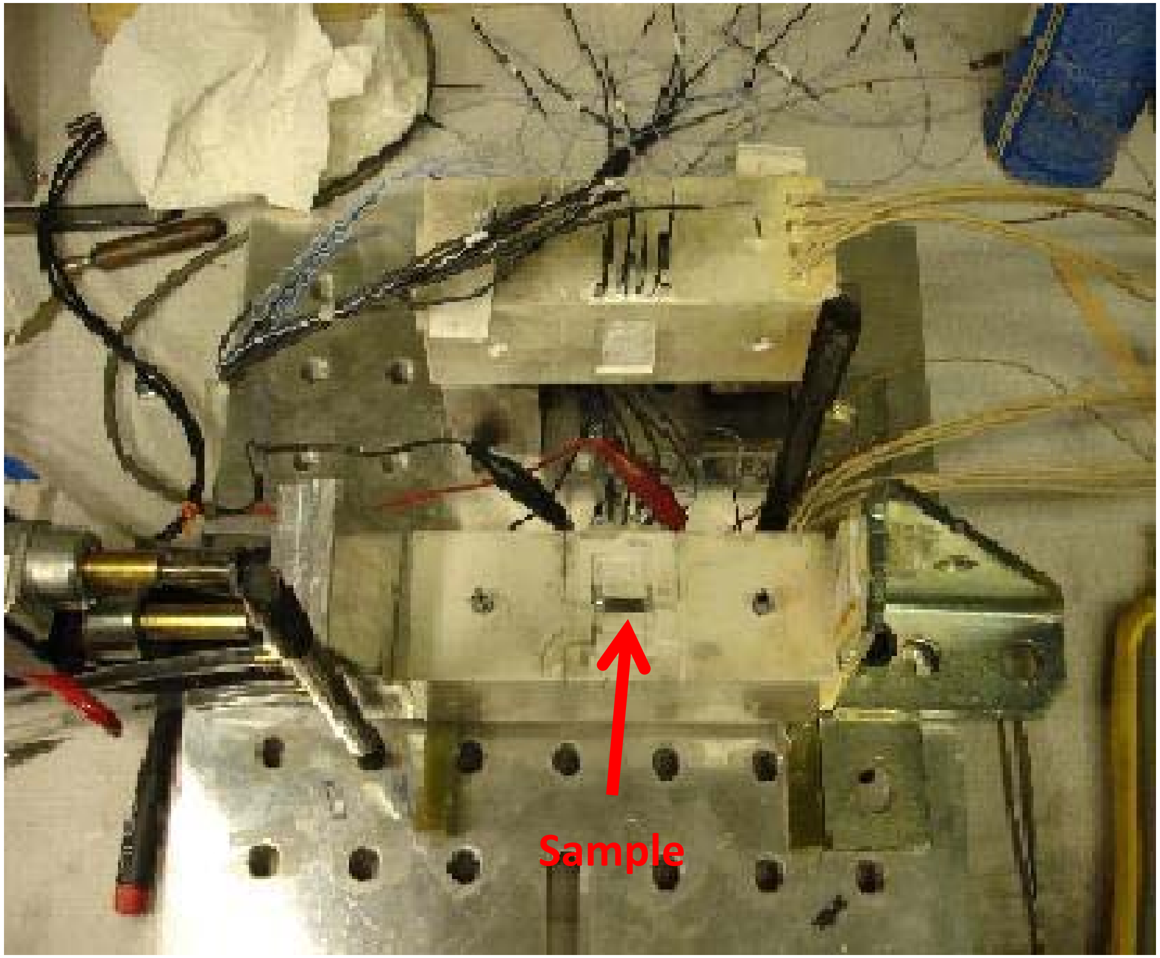
Goal: Obtain ZT and efficiency directly

- Si/SiGe Films deposited on Si Substrate
- Sample housed in large two large blocks of BN
- ΔT imposed on sample is the same as measured in BN
- Heat flowing through QW films is readily calculated using a conservative thermal conductivity
- Both Seebeck coefficient and electrical resistivity measured (p)
- From these measurements an approximate efficiency and ZT obtained



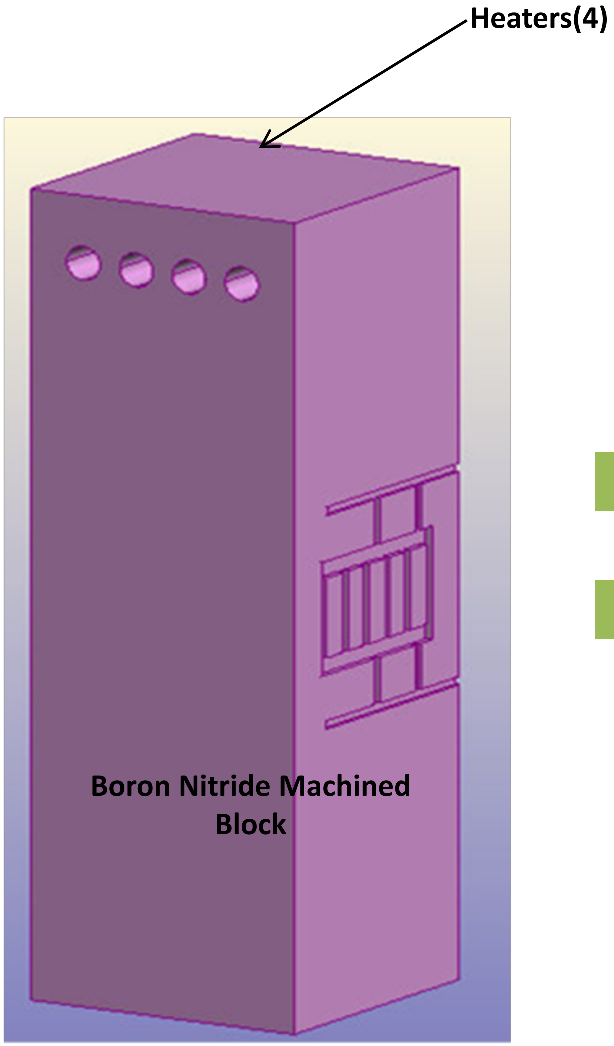
Sample Position in BN Test Fixture. Up to 5 samples can be evaluated at once. Liquid InGa is used to contact the sample.

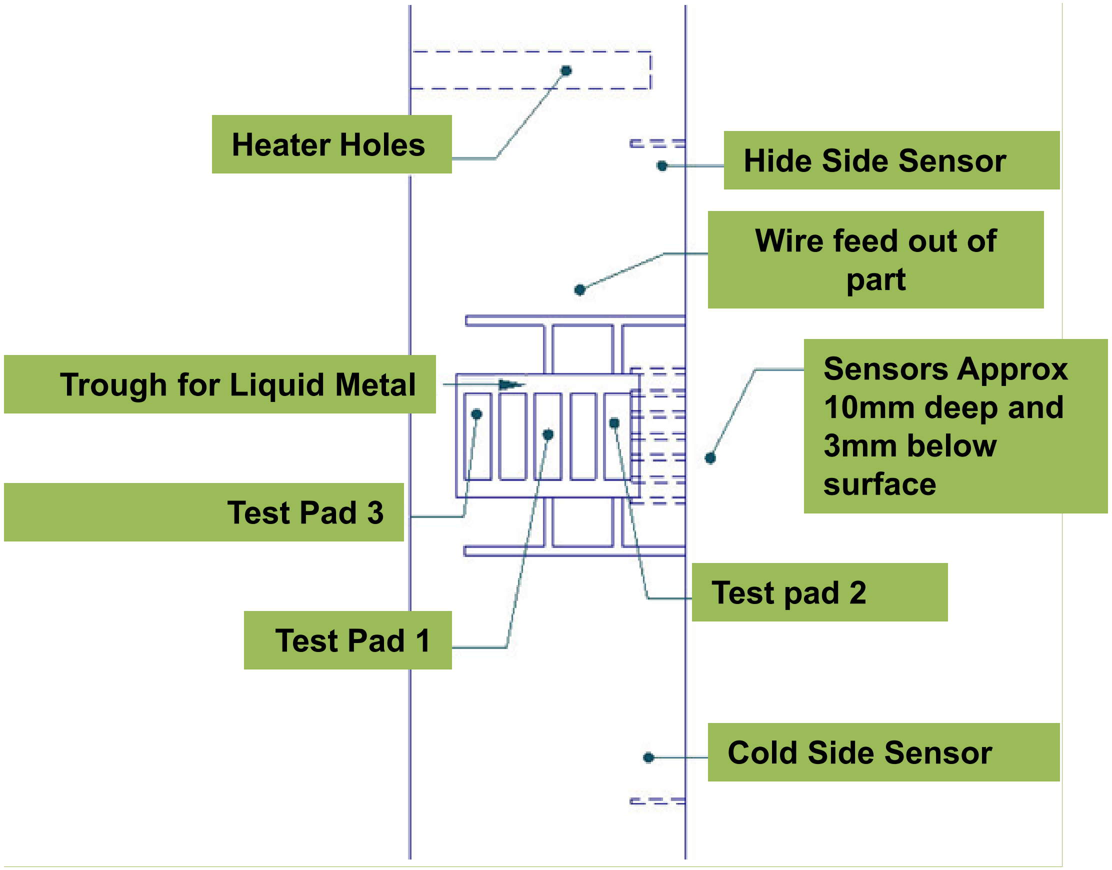
Thermal Properties Measurements
Boron Nitride Test Fixture



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 QW Film Data Obtained With Boron Nitride Test Fixture

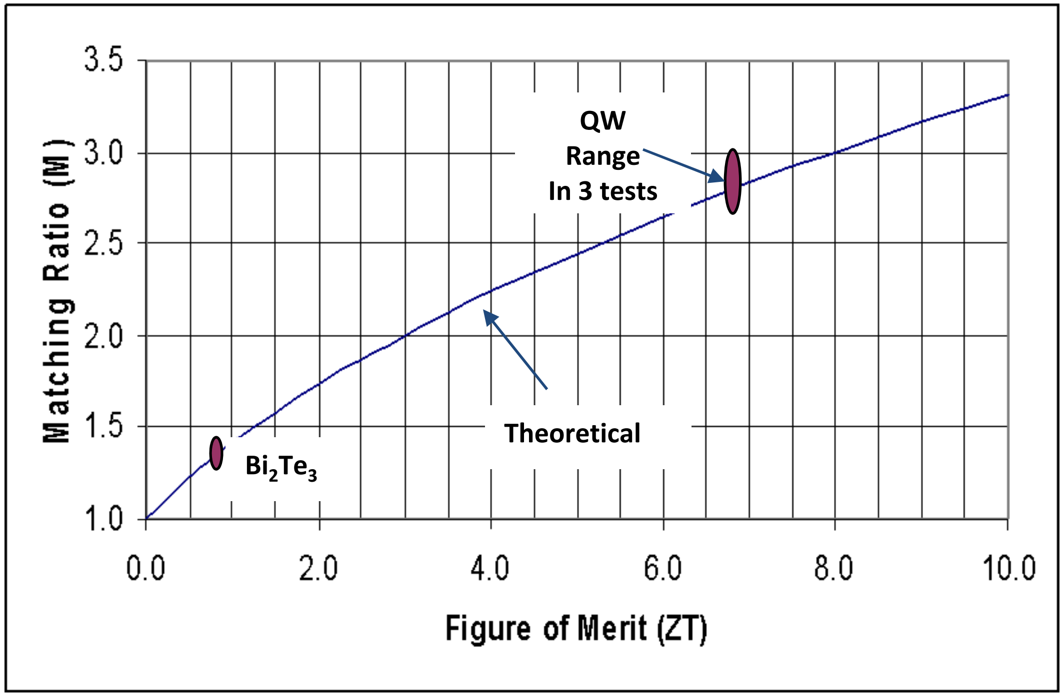
		Temperatures			Measurements			Lit. Data	Efficiency Based on ZT from Measured Data and Literature Bulk κ						Normalized Efficiency to Bi_2Te_3 & ΔT
	Sample #	T_H (°C)	T_C (°C)	ΔT (°C)	α (μV/°C)	ρ (mΩ-cm)	P Pwr (μW)	κ (W/cm-°C)	Z (1/K)	ZT_{ave}	M	Carnot Efficiency (%)	Materials Efficiency(a) η_{mat} (%)	Total Efficiency (%)	
	Bi_2Te_3	74.6	65.08	9.52	-176.7	1.02	7.35	0.012	0.0025	~0.8	1.36	2.74	15.6	0.43	1.00
Si/SiGe	HZ-069	77.6	70.49	7.108	794.6	0.28	0.58	0.110	0.0208	~7	2.87	2.03	48.6	0.98	3.11
	HZ-071	92.94	85.49	7.45	758.8	0.25	1.8	0.110	0.0210	~7	2.93	2.04	49.4	1.01	3.17
	HZ-040108	83.07	72.1	10.97	642.7	0.22	1.9	0.110	0.0168	~6	2.63	3.08	45.2	1.39	2.90

		Efficiency based on measured power and heat balance					
	Sample #	Seebeck Heat (μW)	Joule Heat (μW)	Fourier Heat (μW)	Total Heat (μW)	Efficiency at maximum power (%)	Normalized Efficiency to Bi_2Te_3 & ΔT
	Bi_2Te_3	520.9	-3.67	1159	1676	0.44	1.00
Si/SiGe	HZ-069	65.5	-0.29	21	86	0.68	2.06
	HZ-071	175.8	-0.90	45	220	0.82	2.39
	HZ-040108	121.1	-0.94	40	160	1.17	2.32
	Maximum efficiency calculation for QW from efficiency-current plot					Value at maximum efficiency	
Si/SiGe	HZ-069	39.29	-0.10	21	60	0.97	2.96
	HZ-071	123.1	-0.44	45	168	1.07	3.13
	HZ-040108	84.75	-0.46	40	125	1.51	2.98

Good correlation between both approaches

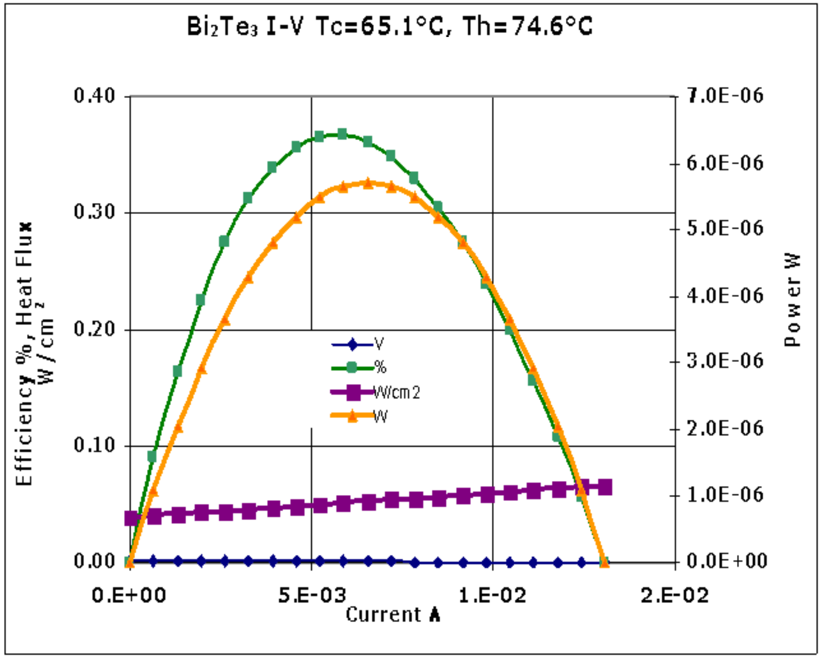
Sample # N type bulk Bi_2Te_3
Sample # HZ-069: Hi-Z UCSD sample, P type QW Si/SiGe (50 periods) on Si substrate
Sample # HZ-071: Hi-Z JPL sample, P type QW Si/SiGe (50 periods) on Si substrate
Sample # HZ-040108: Hi-Z sample, P type QW Si/SiGe (50 periods) on Si substrate

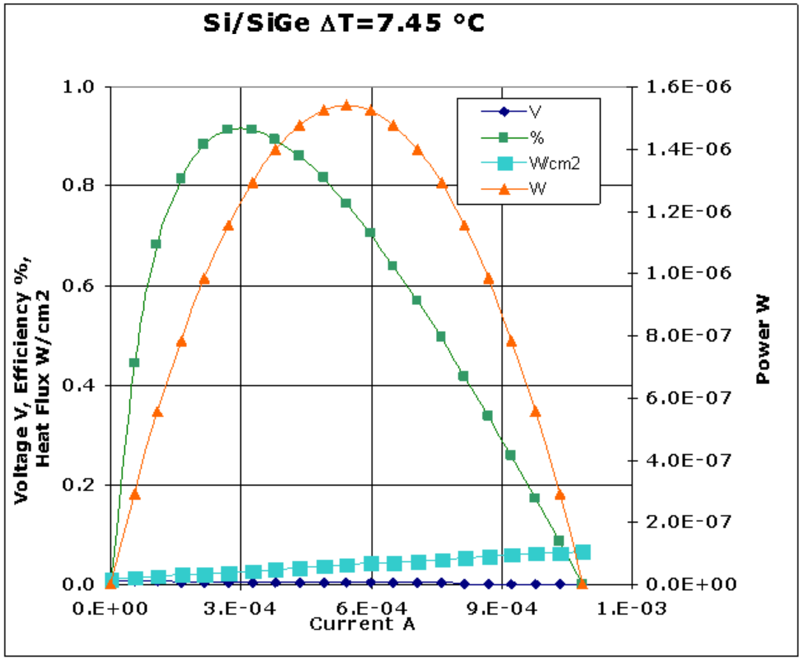
Theoretical Variation of Resistance Matching Ratio (M) with Figure of Merit (ZT)



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

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





Typical Thermoelectric Performance Curves for Bi_2Te_3 Based Alloys.

- **Note that the max power and max efficiency values are relatively close with Bi_2Te_3 where as higher ZT materials show a wider separation as shown in with the Si/SiGe performance curves**
- **With Si/SiGe however it has a higher ZT and the max efficiency and max power points as further separated.**

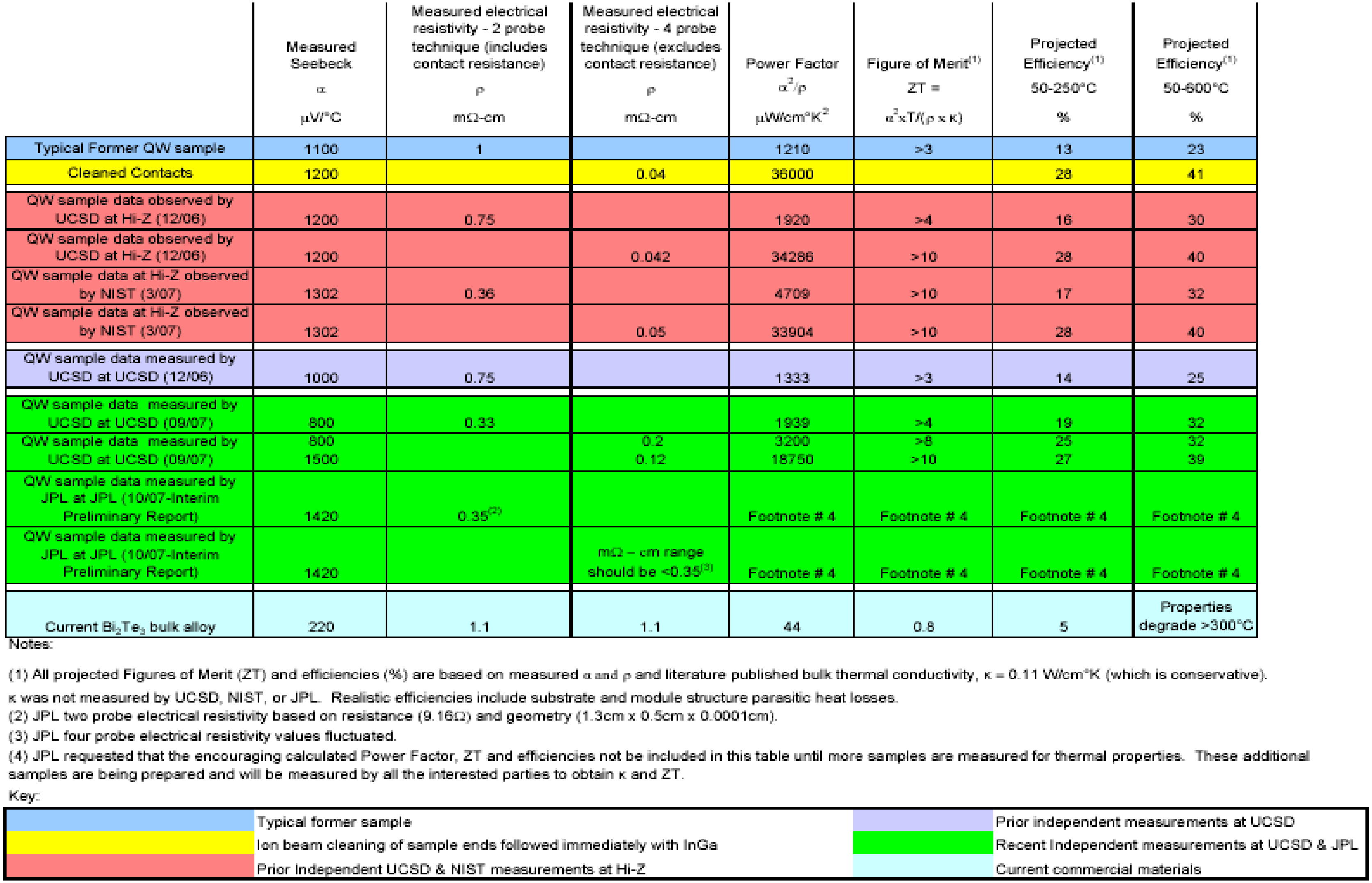
Thermoelectric Property Measurements by Various Organizations

- University of California San Diego (UCSD)
- National Institute of Standards and Tests (NIST)
- Jet Propulsion Laboratory (JPL)
- Hi-Z
- Consultant

- Above organizations have evaluated Hi-Z’s QW films.

- All organizations show large gains in thermoelectric properties primarily in Seebeck coefficient.

Thermoelectric Property Measurements by Various Organizations and Calculated Figures of Merit ZT and Efficiency for Si/SiGe QW Materials



	Measured Seebeck α μV/°C	Measured electrical resistivity - 2 probe technique (includes contact resistance) ρ mΩ-cm	Measured electrical resistivity - 4 probe technique (excludes contact resistance) ρ mΩ-cm	Power Factor α^2/ρ μW/cm°K^2	Figure of Merit(1) ZT = α^2xT/(ρ x κ)	Projected Efficiency(1) 50-250°C %	Projected Efficiency(1) 50-600°C %
Typical Former QW sample	1100	1		1210	>3	13	23
Cleaned Contacts	1200		0.04	36000		28	41
QW sample data observed by UCSD at Hi-Z (12/06)	1200	0.75		1920	>4	16	30
QW sample data observed by UCSD at Hi-Z (12/06)	1200		0.042	34286	>10	28	40
QW sample data at Hi-Z observed by NIST (3/07)	1302	0.36		4709	>10	17	32
QW sample data at Hi-Z observed by NIST (3/07)	1302		0.05	33904	>10	28	40
QW sample data measured by UCSD at UCSD (12/06)	1000	0.75		1333	>3	14	25
QW sample data measured by UCSD at UCSD (09/07)	800	0.33		1939	>4	19	32
QW sample data measured by UCSD at UCSD (09/07)	800 1500		0.2 0.12	3200 18750	>8 >10	25 27	32 39
QW sample data measured by JPL at JPL (10/07-Interim Preliminary Report)	1420	0.35(2)		Footnote # 4	Footnote # 4	Footnote # 4	Footnote # 4
QW sample data measured by JPL at JPL (10/07-Interim Preliminary Report)	1420		mΩ – cm range should be <0.35(3)	Footnote # 4	Footnote # 4	Footnote # 4	Footnote # 4
Current Bi_2Te_3 bulk alloy	220	1.1	1.1	44	0.8	5	Properties degrade >300°C

Notes:

(1) All projected Figures of Merit (ZT) and efficiencies (%) are based on measured α and ρ and literature published bulk thermal conductivity, κ = 0.11 W/cm°K (which is conservative). κ was not measured by UCSD, NIST, or JPL. Realistic efficiencies include substrate and module structure parasitic heat losses.

(2) JPL two probe electrical resistivity based on resistance (9.16Ω) and geometry (1.3cm x 0.5cm x 0.0001cm).

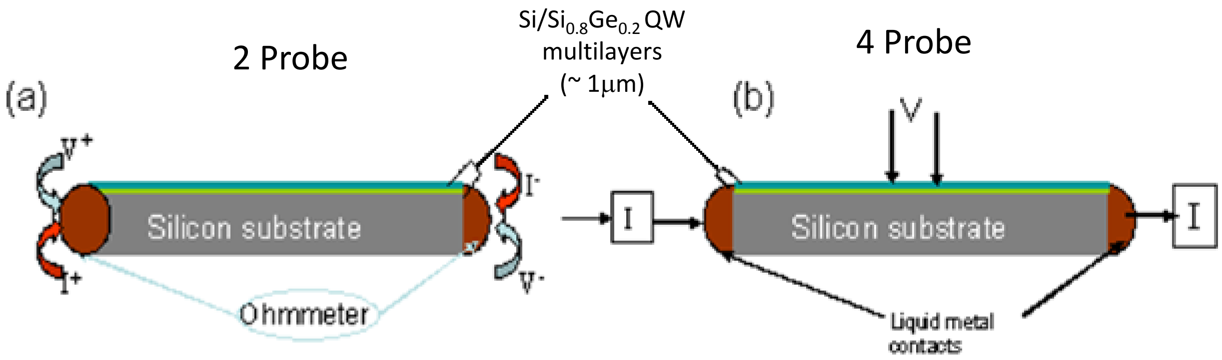
(3) JPL four probe electrical resistivity values fluctuated.

(4) JPL requested that the encouraging calculated Power Factor, ZT and efficiencies not be included in this table until more samples are measured for thermal properties. These additional samples are being prepared and will be measured by all the interested parties to obtain κ and ZT.

Key:

🟦	Typical former sample	🟪	Prior independent measurements at UCSD
🟨	Ion beam cleaning of sample ends followed immediately with InGa	🟩	Recent Independent measurements at UCSD & JPL
🟥	Prior Independent UCSD & NIST measurements at Hi-Z	▨	Current commercial materials

Schematic of the Measurement Setups for Obtaining the Resistivity (R) of the Si/SiGe Multilayer on Si Substrates



2 Probe

$Si/Si_{0.8}Ge_{0.2}$ QW multilayers (~ 1µm)

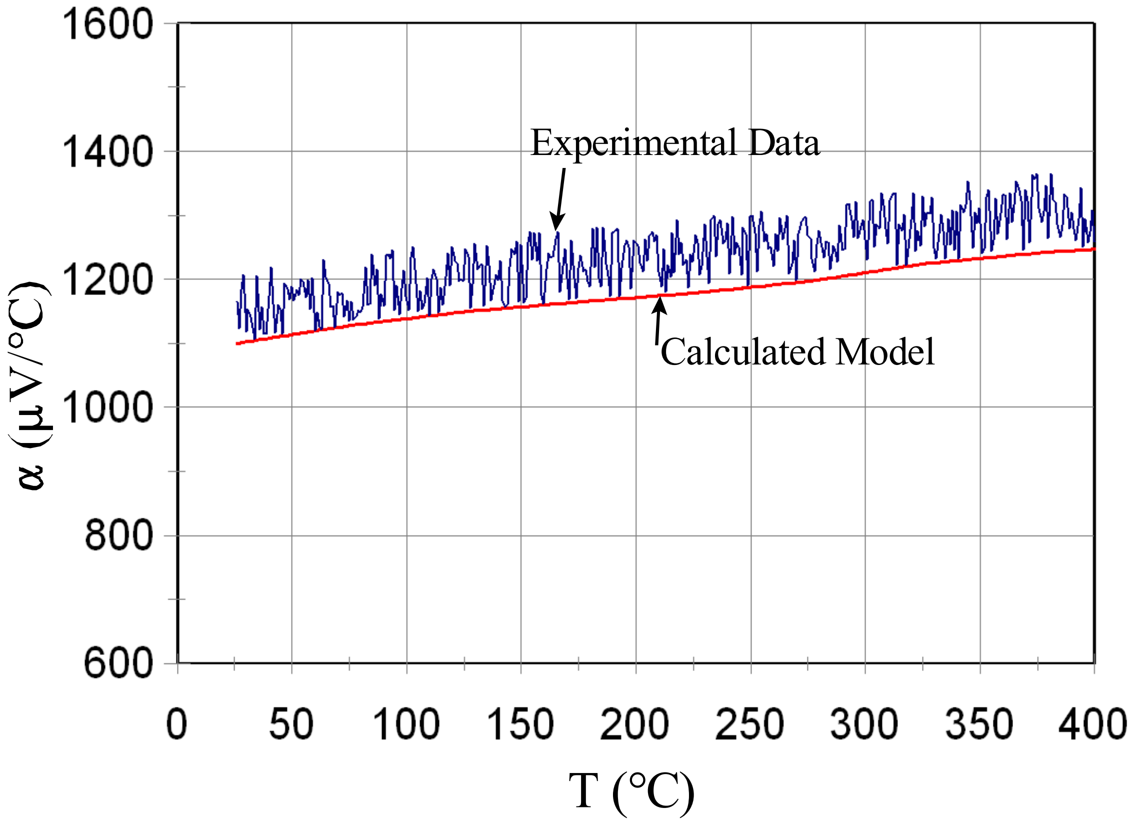
4 Probe

(a) two-terminal Ohmmeter (Tegam, Inc.) probes and,

(b) four probe arrangements, where the current is sent through the liquid metal contacts at the ends while the voltage is measured along the sample with two more probes. Note: typical specimen is grown to 8-10 µm of Si/SiGe multilayer; however, test specimen had 1 µm Si/SiGe

The resistivity parallel to the layers ($\rho||$) is then calculated from measured resistance (R) through the sample geometry. The lateral dimensions of the sample are 1.2 cm x 0.5 cm, and the thickness of the Si/SiGe multilayer are ~1 µm (the substrate is ~500 µm thick).

Calculated *vs.* Experimental Seebeck Coefficient *vs.* Temperature for QW Films



The calculated model closely matches the experimental data. This excellent match between the analytical and experimental data underscores the model's viability for understanding the ***α*** *behavior.*

Measurement of superlattice thermal conductivity (κ) on Hi-Z enhanced films at the University of California San Diego

by Dr. Prab Bandura, 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/mK
0.4μm	~4.6
1.0μm	4.3
5.6μm	3.5

Samples courtesy Hi-Z Inc.

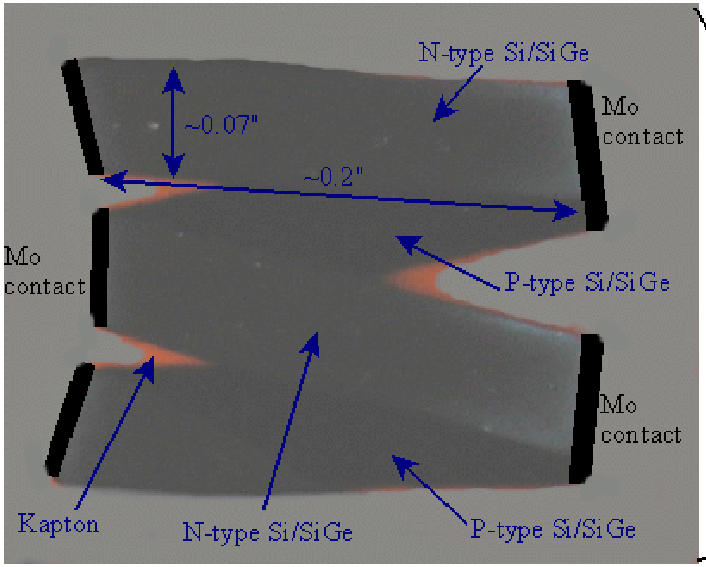
•Bulk Si Κ =150 W/mK, and bulk SiGe Κ =70W/mK

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

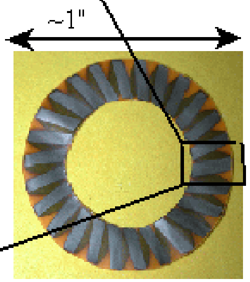
- To be presented at the MRS Spring meeting, San Francisco, April, 2009

Other Experimental Results at Hi-Z:

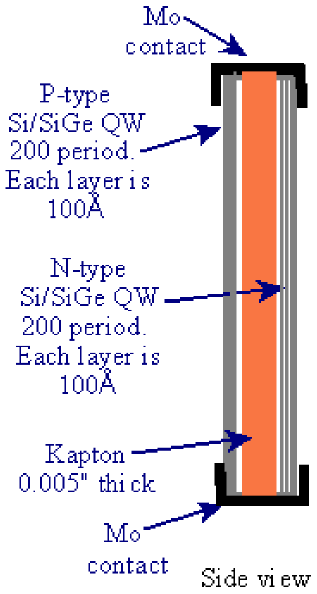
QW Module Performance Verified in a 2-Couple Test With Molybdenum Contacts Having Small Contact Resistance; Comparison with Bulk Module



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



Complete 26 couple device



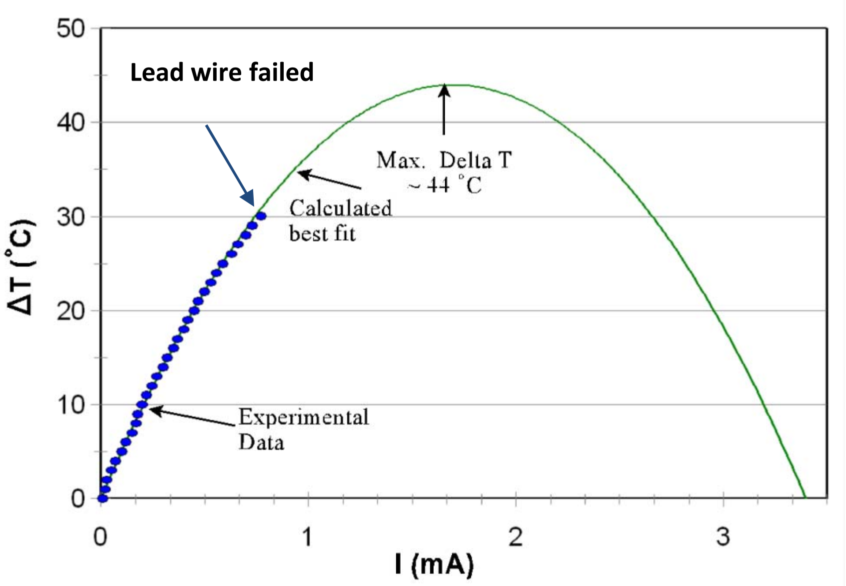
Side view

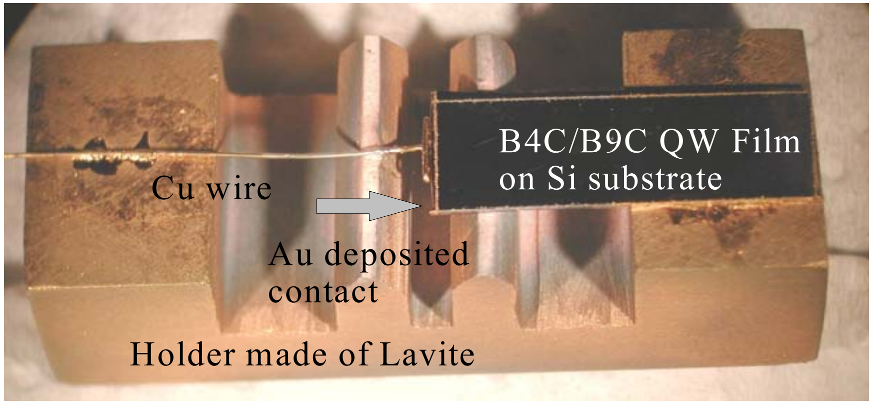
T_{Cold} = 26°C T_{Hot} = 66°C	Experimental		Calculated 26 Couple Module at ΔT = 40°C	
	2 QW Couples Measured at ΔT= 40°C	2 QW Couples Measurements Extrapolated to 26 Couple Module at ΔT = 40°C	QW With ZT ~3.0	Bulk $(Bi,Sb)_2Se,Te)_3$ With ZT ~0.75
Voltage (V_{OC})	225 mV	**2.93 V**	**3V**	0.5V
Power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

Current Test with P-Type
Si/SiGe QW Element

Previous Test with P-Type
B_4C/B_9C QW Element

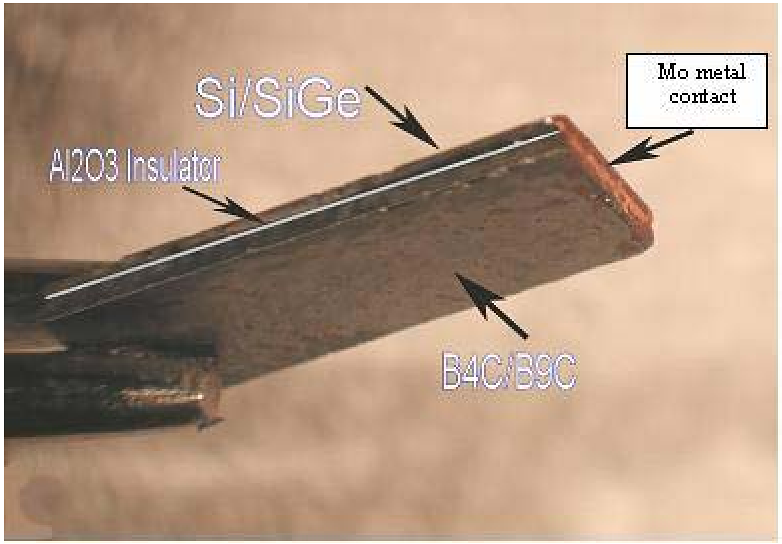




Max. ΔT ≈ 44ºC
ZT ≈ 3.5 @ T ≈ 25ºC

Max. ΔT = 45ºC
ZT>3 @ T ≈ 25ºC

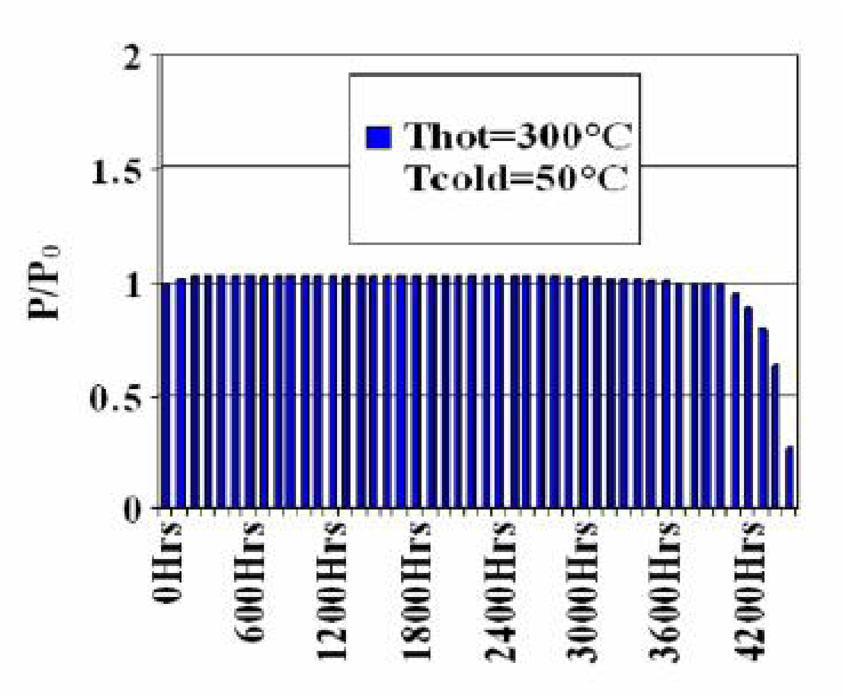
Molybdenum Contacted QW Couple



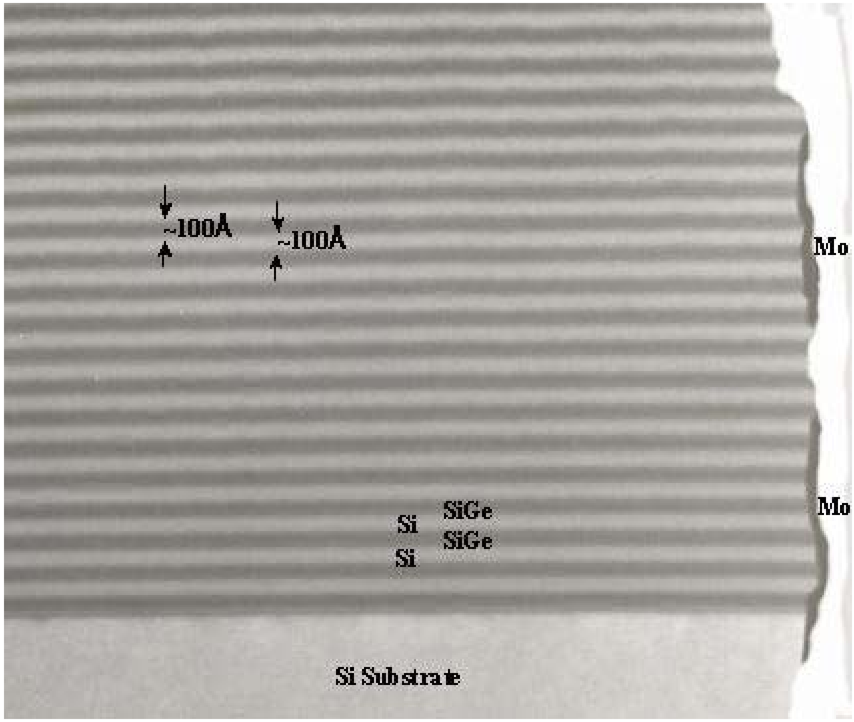
Thermoelectric properties of QW couple with Mo contact compared to calculated values

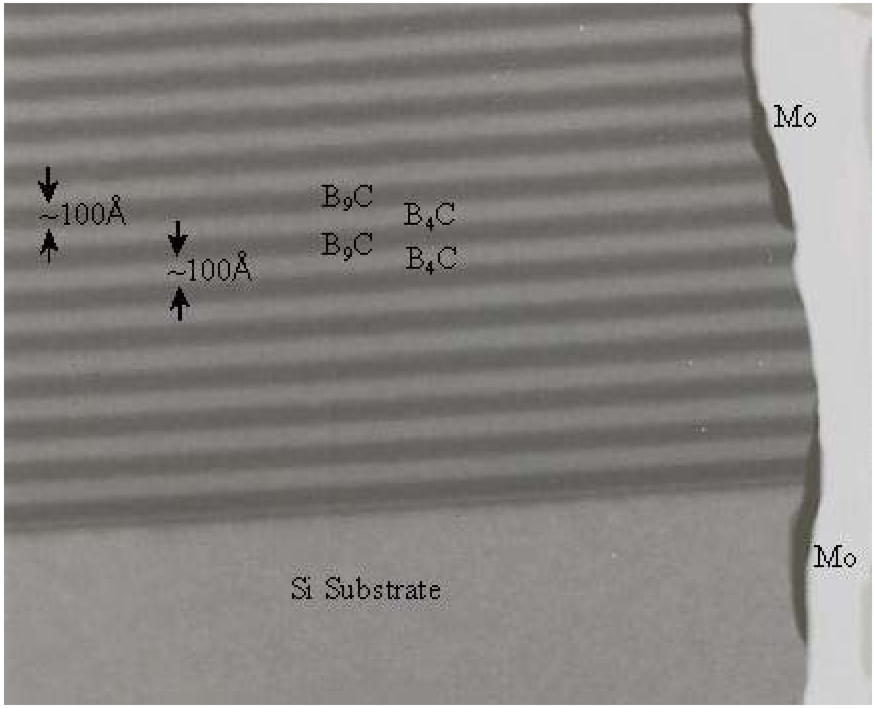
Room temperature properties	As Fabricated	Calculated
Couple Resistance	1.23 κΩ	1.25κΩ
Couple Voltage output @ ΔT ~ 5°C	9.56 mV	9.60 mV

Life Test Data



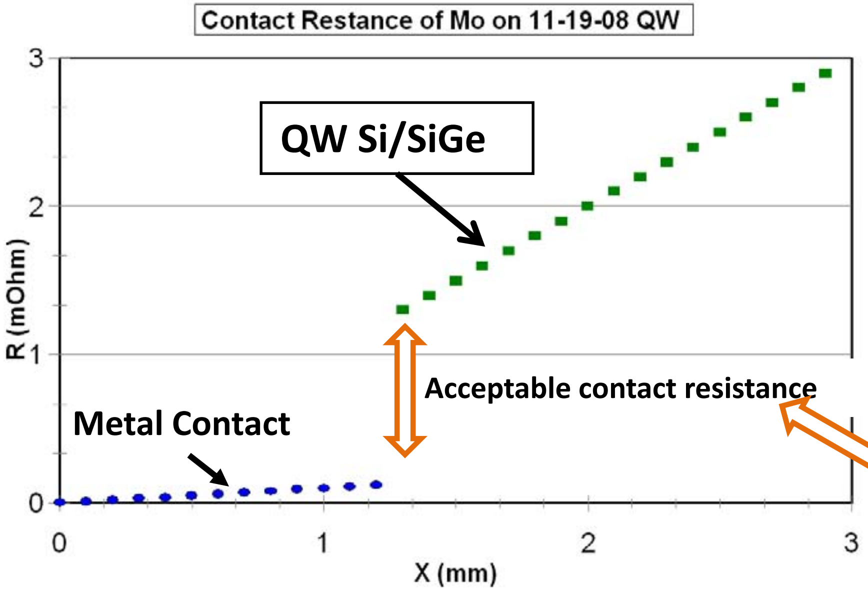
150 kX SEM of Si/SiGe Leg of the ~4000 Hours Aged Couple





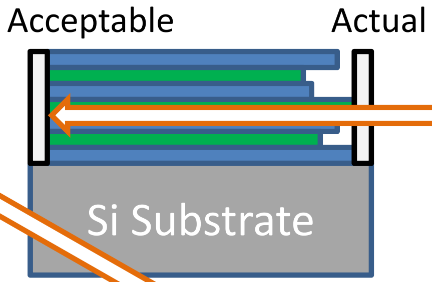
N and P couple failed due to thermal expansion differences between Mo and QW Materials

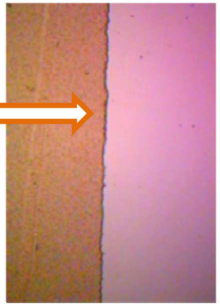
Electrical contact resistance reduced with photolithography, etch and annealing



Process Steps

1. Enhanced thin films fabricated by Hi-Z
2. Photolithography & etch by SUNY
3. Annealing by Hi-Z



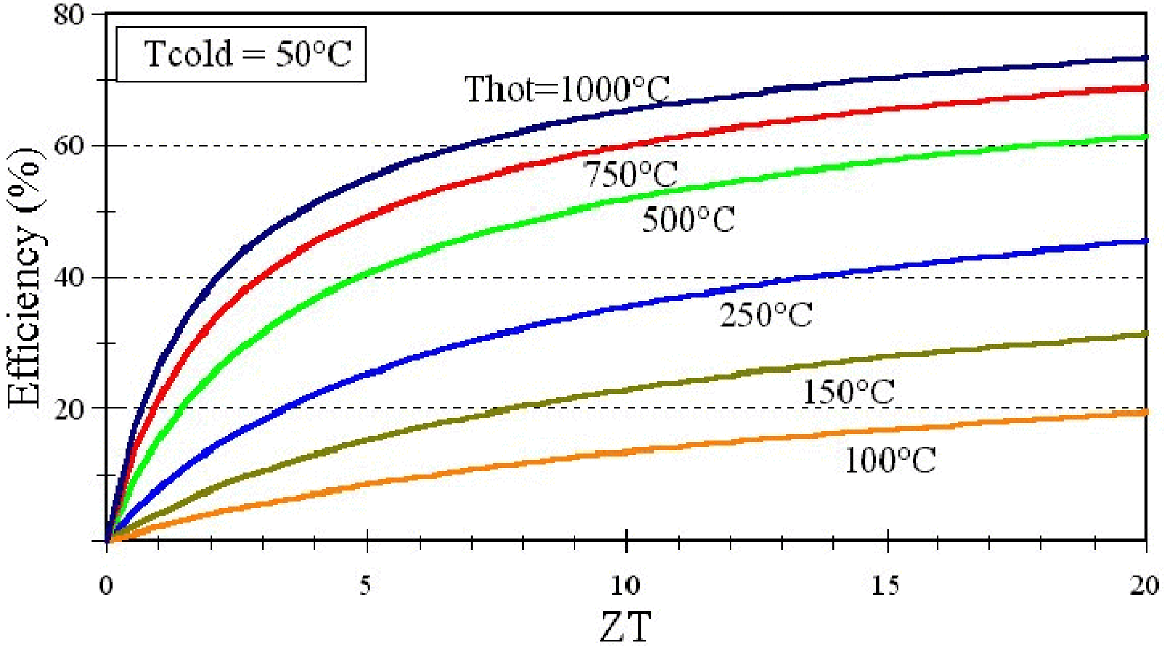


Sample ID	Mat.	Cont.Res, Ohm		24hr @ 400°C	24hr @ 600	10Sec @ 900°C	IonMill Etch
11/19/2008-1	Mo	4.3		4.3	1.1	0.001	NA
11/19/2008-2	None	5.1	with In-Ga	NA	NA	NA	0.0001
11/26/2008	Pt	2.8		2.8	0.8	0.21	NA
12/1/2008	Ti	0.9		0.9	0.1	0.042	NA

Thermoelectric Efficiency

$$Efficiency = \frac{T_H - T_C}{T_H} \; x \; \frac{M - 1}{M + \frac{T_C}{T_H}} \qquad M = \sqrt{1 + \frac{1}{2}\overline{Z}\,(T_C + T_H)}$$

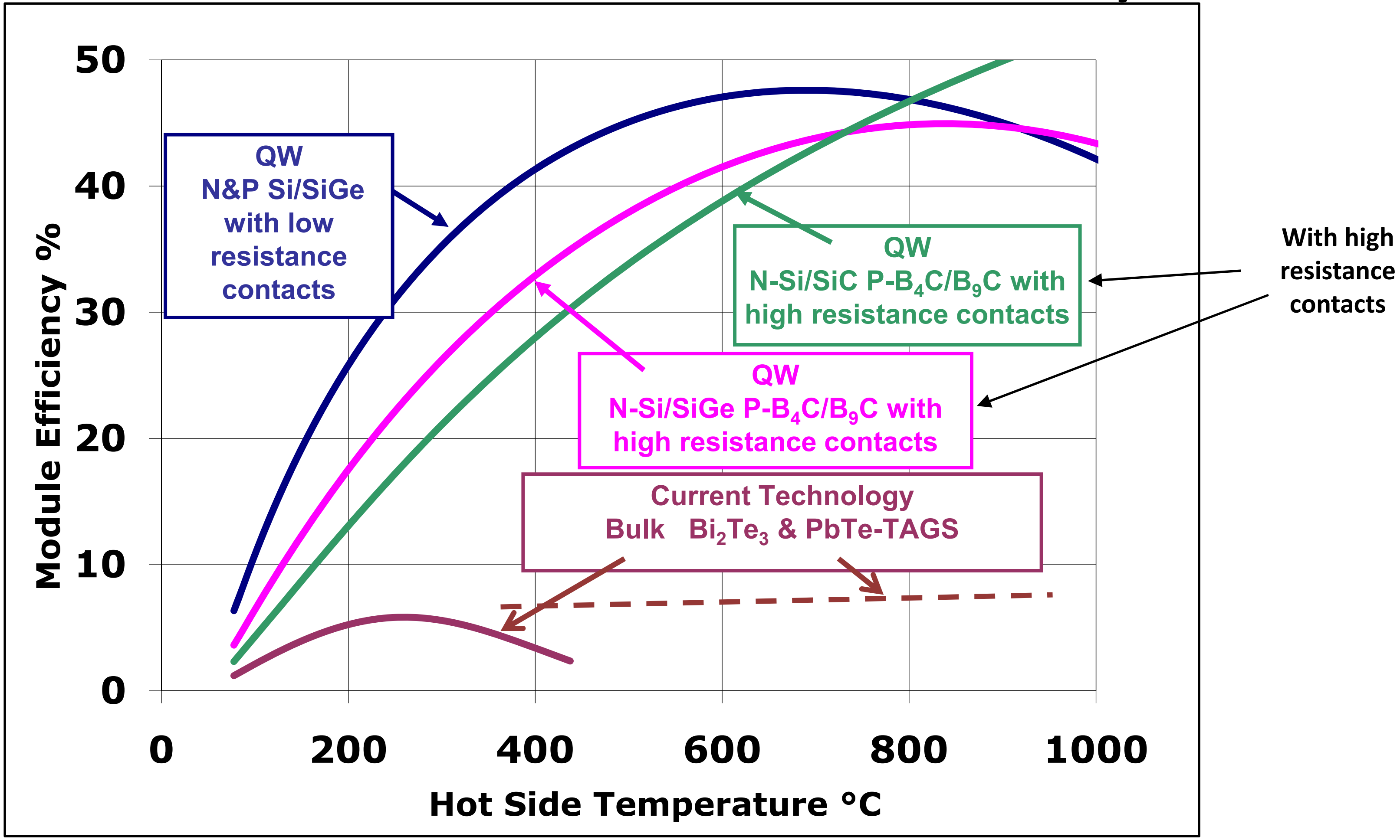
Theoretical Efficiency Vs ZT



$$Z = \frac{\alpha^2}{\rho\,\kappa}$$

$$ZT = \frac{\alpha^2 T}{\rho\,\kappa}$$

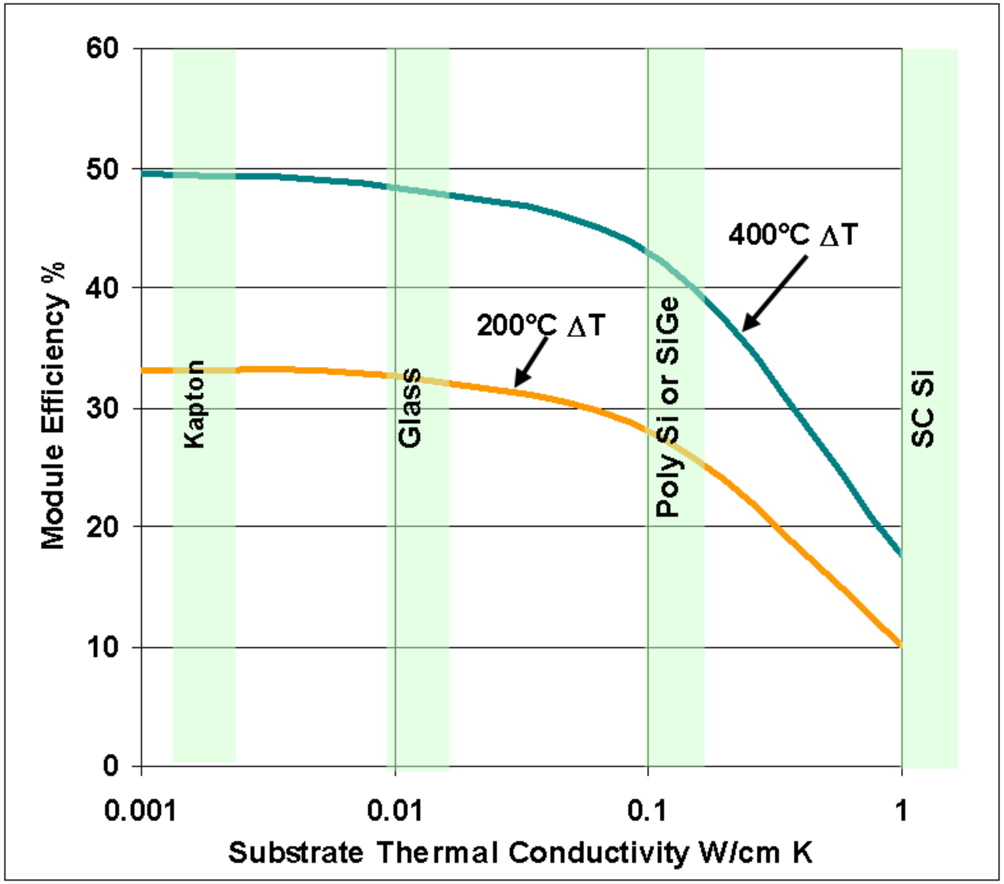
Predicted QW TE Efficiency

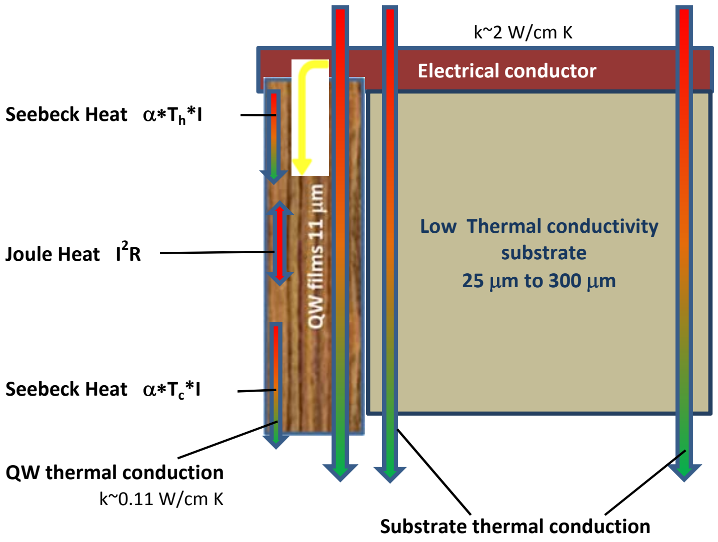


Performance should exceed Si/SiGe with lower resistance contacts.

Potential Si/SiGe QW TE Module Efficiency with Various Substrates

- Efficiency is strongly dependent on substrate thermal conductivity
- Best QW properties obtained on Single Crystal (SC) Si
- Predicted QW efficiencies for 0.051 mm (0.002 in.) substrate using recent NIST (3/07) and UCSD (12/06) measured QW properties





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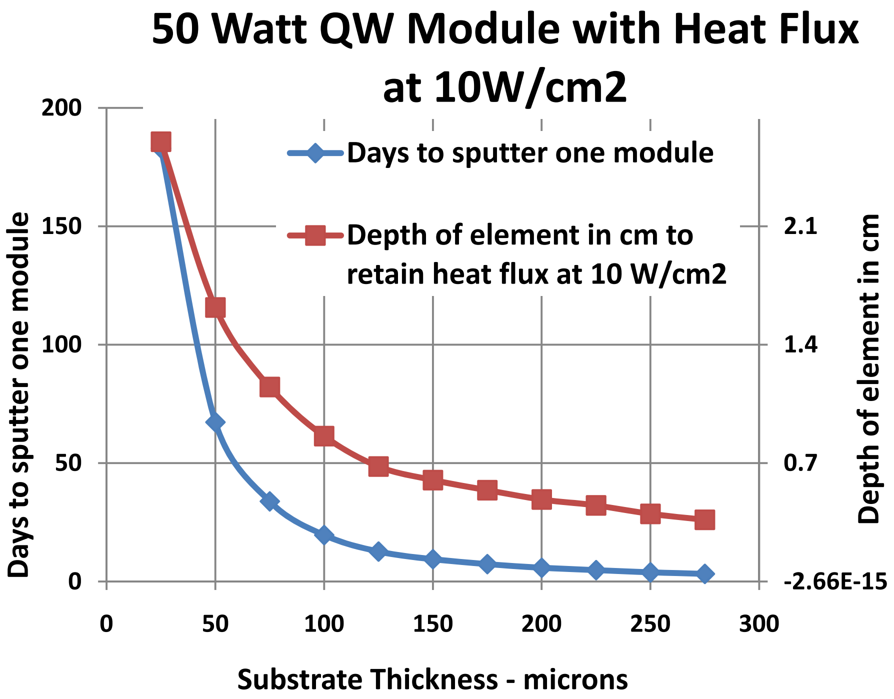

50 Watt QW Module with Heat Flux at 10W/cm2

Reduced production time for enhanced thin films possible with heat flux concentration

Hi-Z's large sputtering machine operating 21 hours/day

Film thickness = 11 μm

Sputtering rate = 5 nm/min

Predicted Efficiency of Enhanced Thin Film Thermoelectrics

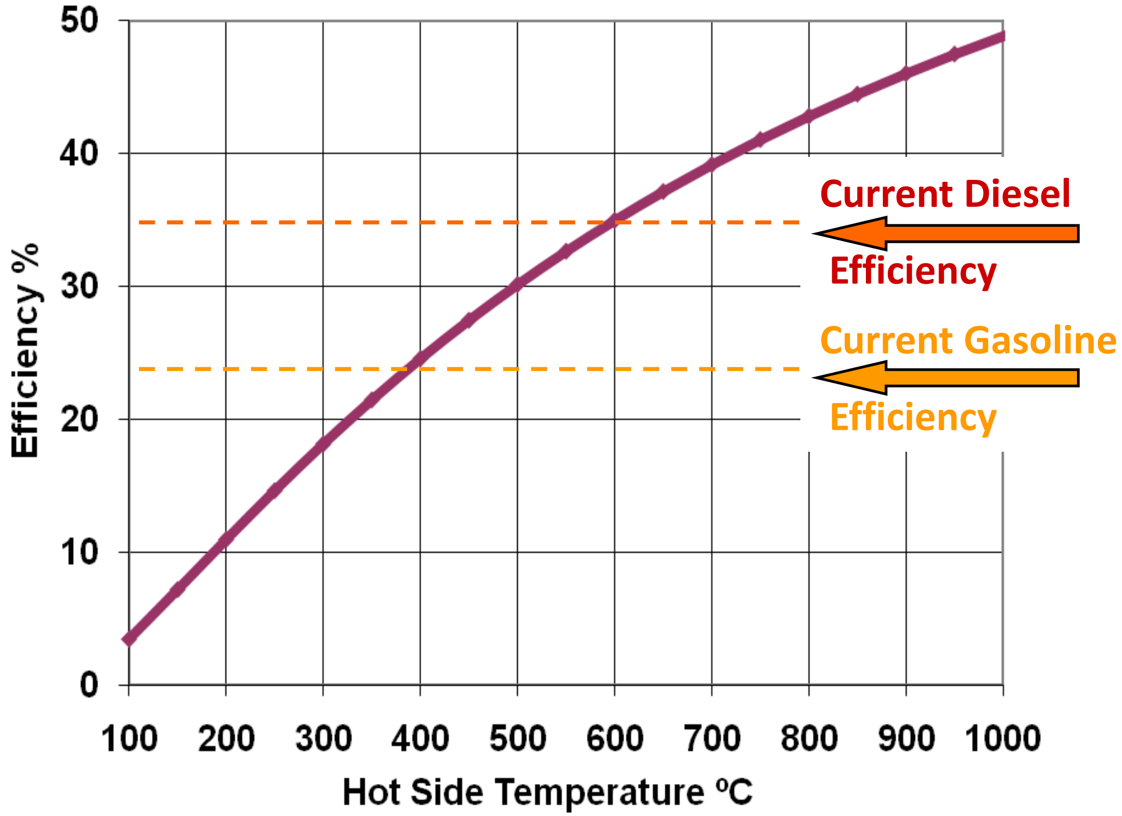
QW TE Efficiency > Current Engines at Lower Temperatures

QW TE Generator
- Cold side = 50ºC
- N-type Si/SiC
- P-type B_4C/B_9C
- Single QW TE Material per Leg & Not Segmented

Multi-fuel combustor
- Reduced emissions

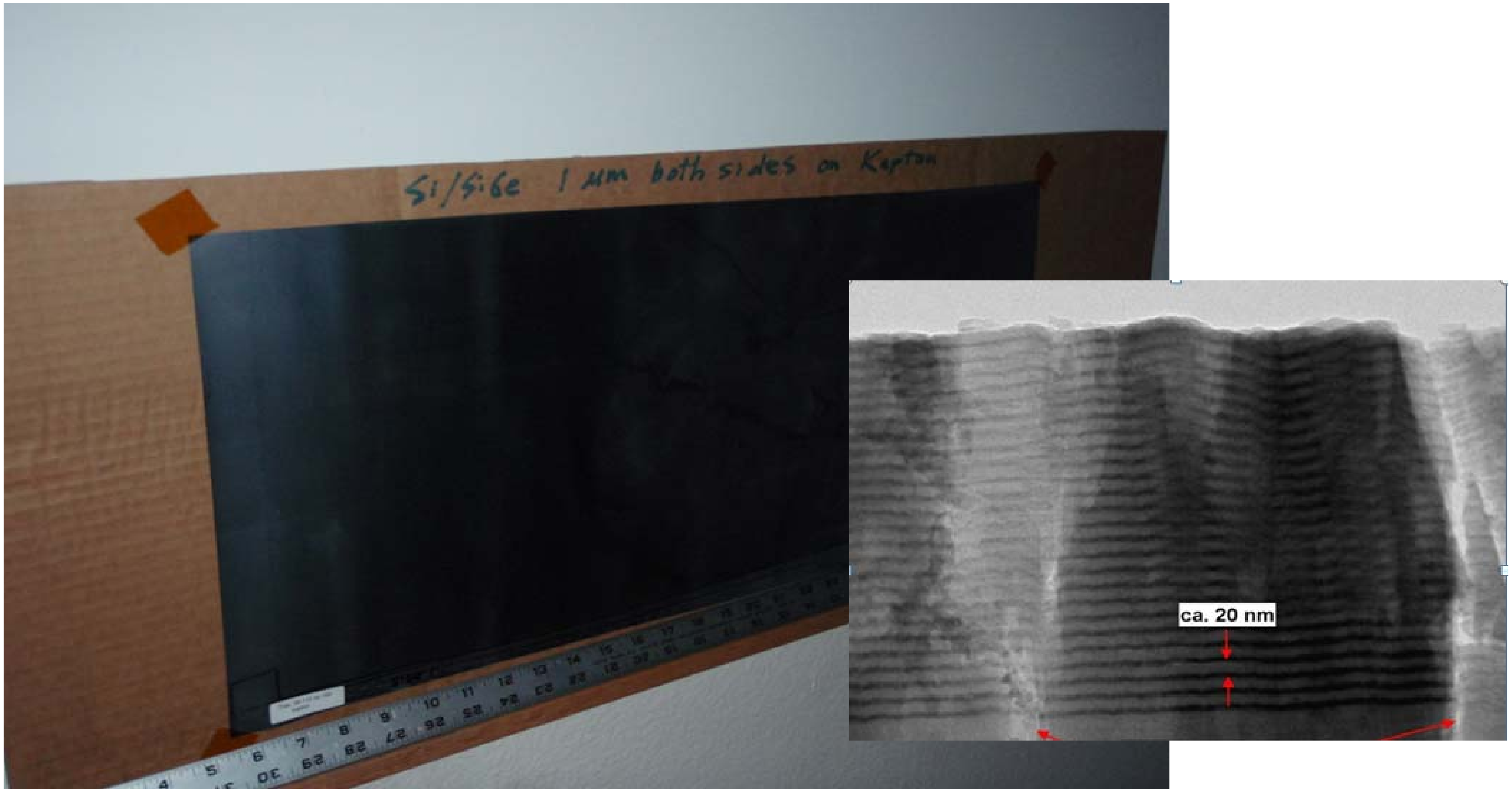
No Gasoline /Diesel Engine
- Adiabatic flame temperatures ~2000ºC or >>higher than multi-fuel combustor

(Drive cycle not included)



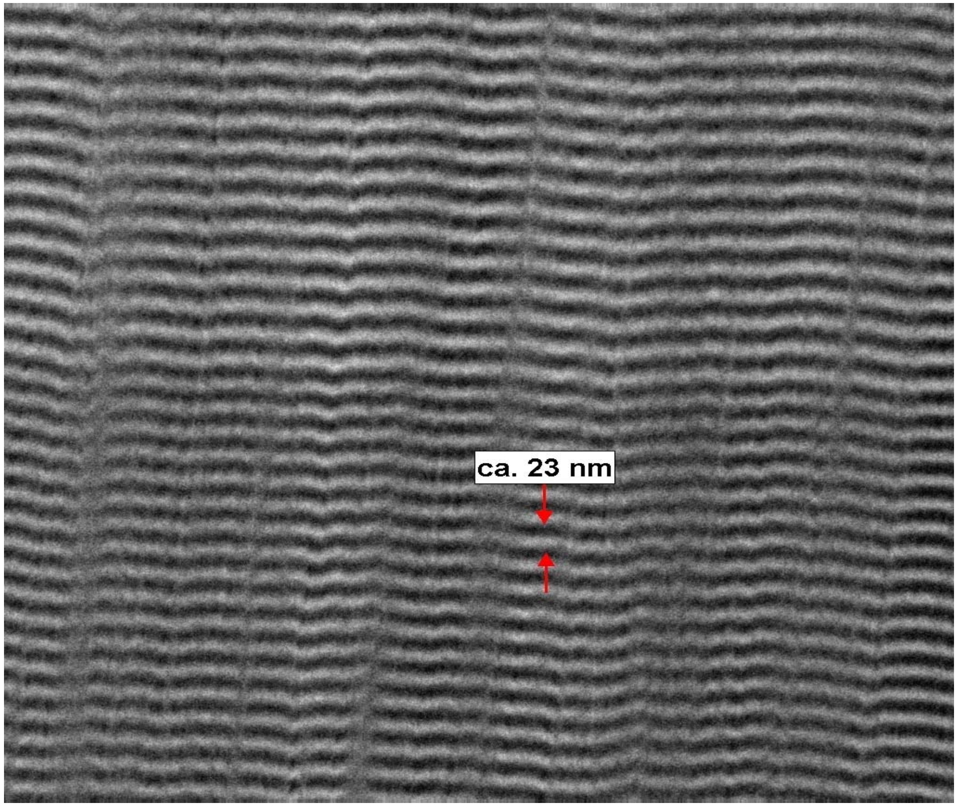
Large area (5 ft^2) Sputtering of SiGe Quantum Well Thermoelectrics on Kapton at the General Atomics Production Facility

Thin film deposition on both sides of Kapton produces uniform thickness



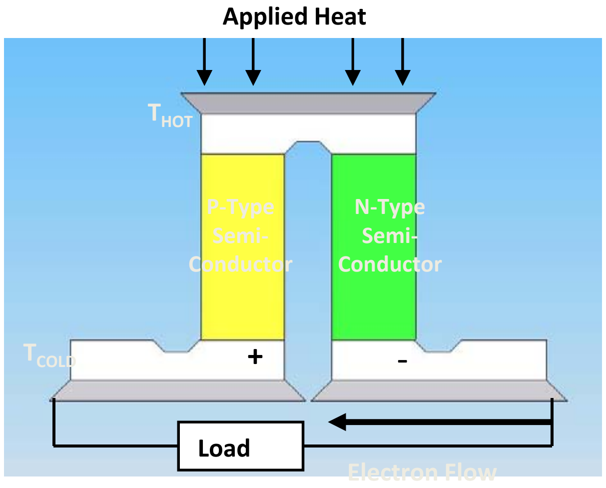
Slight waving of layers is caused at the interfaces due to the large difference between the atom size of Si and Ge

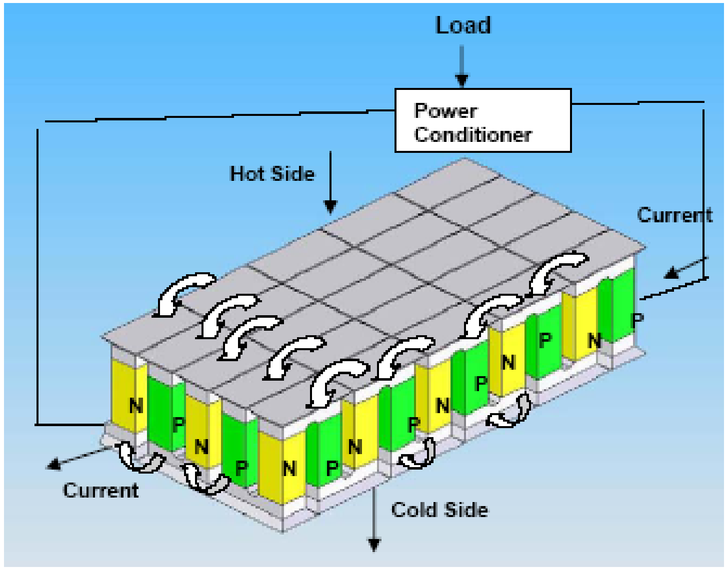
TEM Thin Films on Si Substrate
Sample was coated along with Kapton Film in large Scale Coating Facility at General Atomics



The 23 nanometers includes both a Si and a SiGe layer

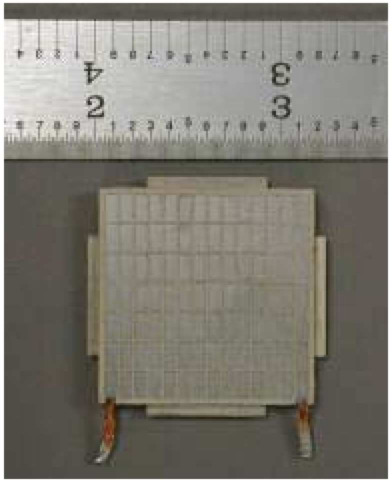
Module Fabrication with Bulk Materials & Enhanced Thin Films V (Quantum Wells)





- Thermoelectrics generate power with no moving parts
- Present bulk material technology: 5% efficient
- Quantum Well nanotechnology will be several times more efficient

One Current Product



HZ-2 Watt
Commercial
Module

Bulk Alloy Milli-Watt Modules

Assembly for Fabricating $(Bi,Sb)_2\ (Se, Te)_3$ Alloys into Monolithic Modules

Vacuum Hot Pressed Puck

Plates

KAPTON Insulation

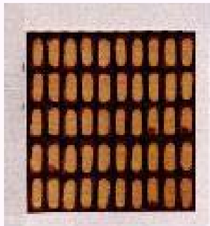
Plates with KAPTON Insulation (orange)

Bonded Stack

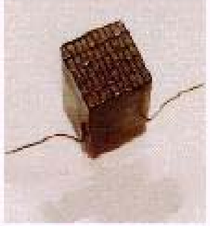
Slices

Slices with Kapton Insulation (orange)

Matrix



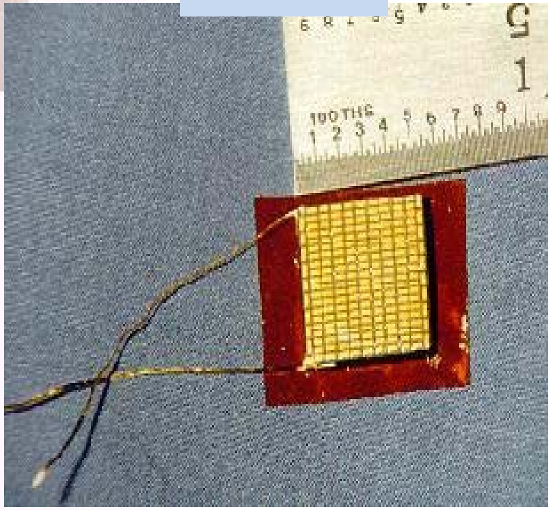
Connector Tabs Bonded to Matrix



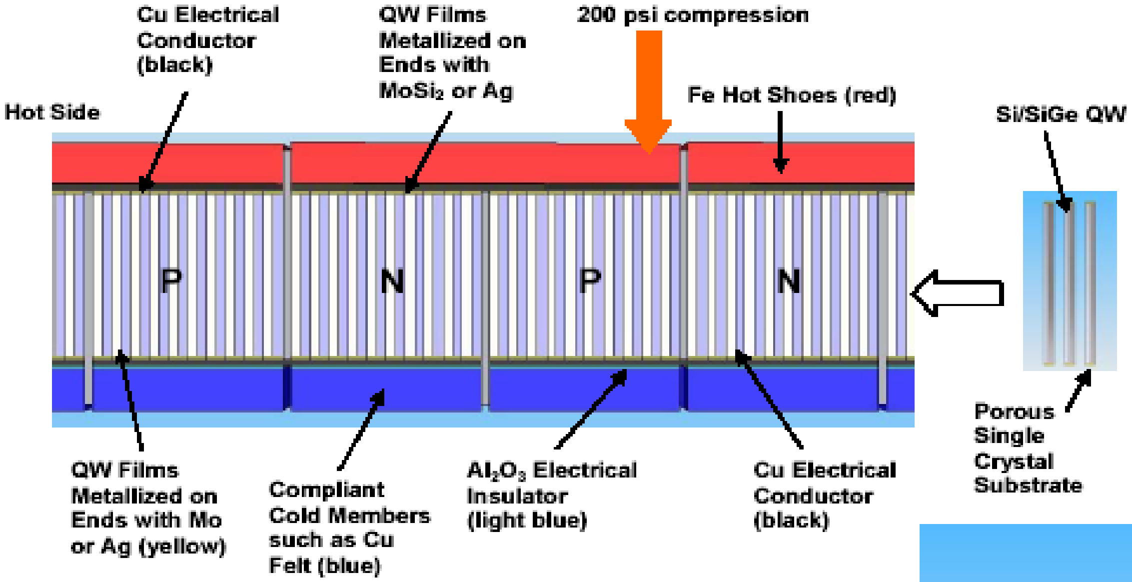
Hot - Side

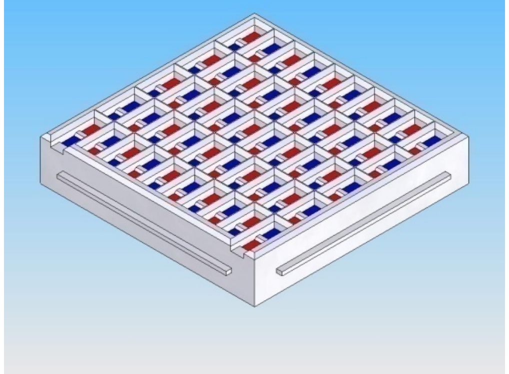
Cold - Side

800 milliWatt Module



Schematic Showing two N and P Couples in a Quantum Well Module





Schematic Showing two N and P couples in a Quantum Well module
Each leg consists of ~100 layers of 11 μm Si/SiGe on 1 *μm* Si buffer layer on 50 *μm* Si substrate. The assembly is based on prior PbTe work where this design provides excellent thermal contact with compliant members and will allow a large number of thermal cycles for power and cooling modules.

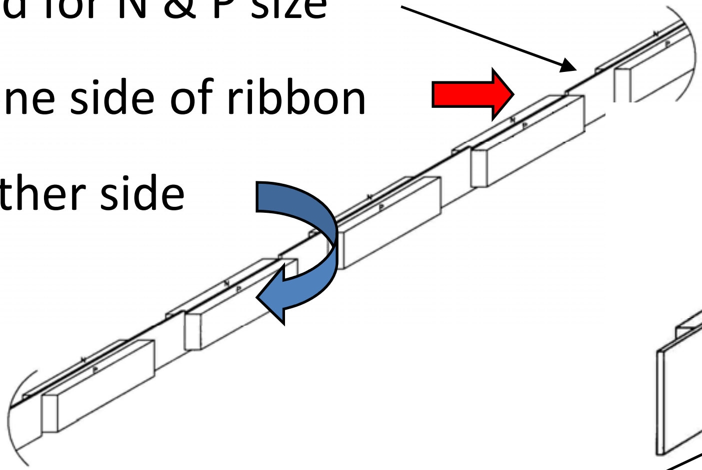
Process Change - Folded Quantum Well Module

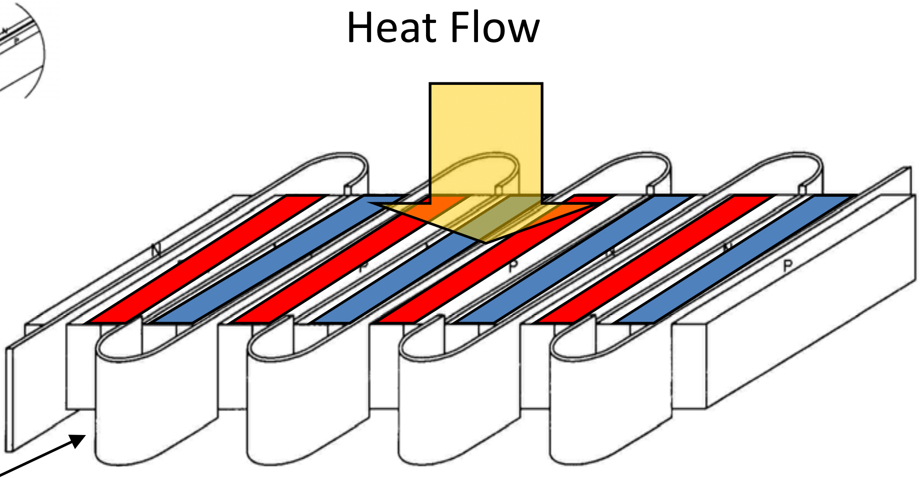
Sputtering process forms module & eliminates eggcrate
Improves efficiency and reduces costs

Masked for N & P size

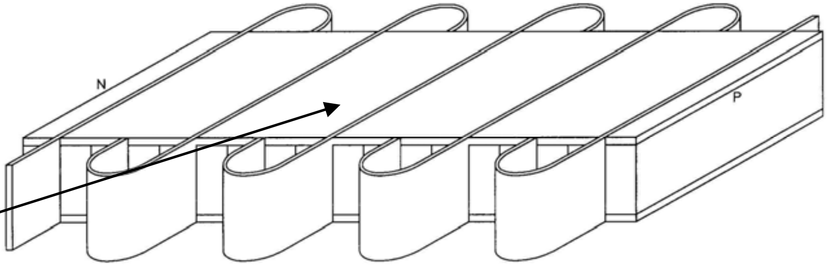
N on one side of ribbon

P on other side





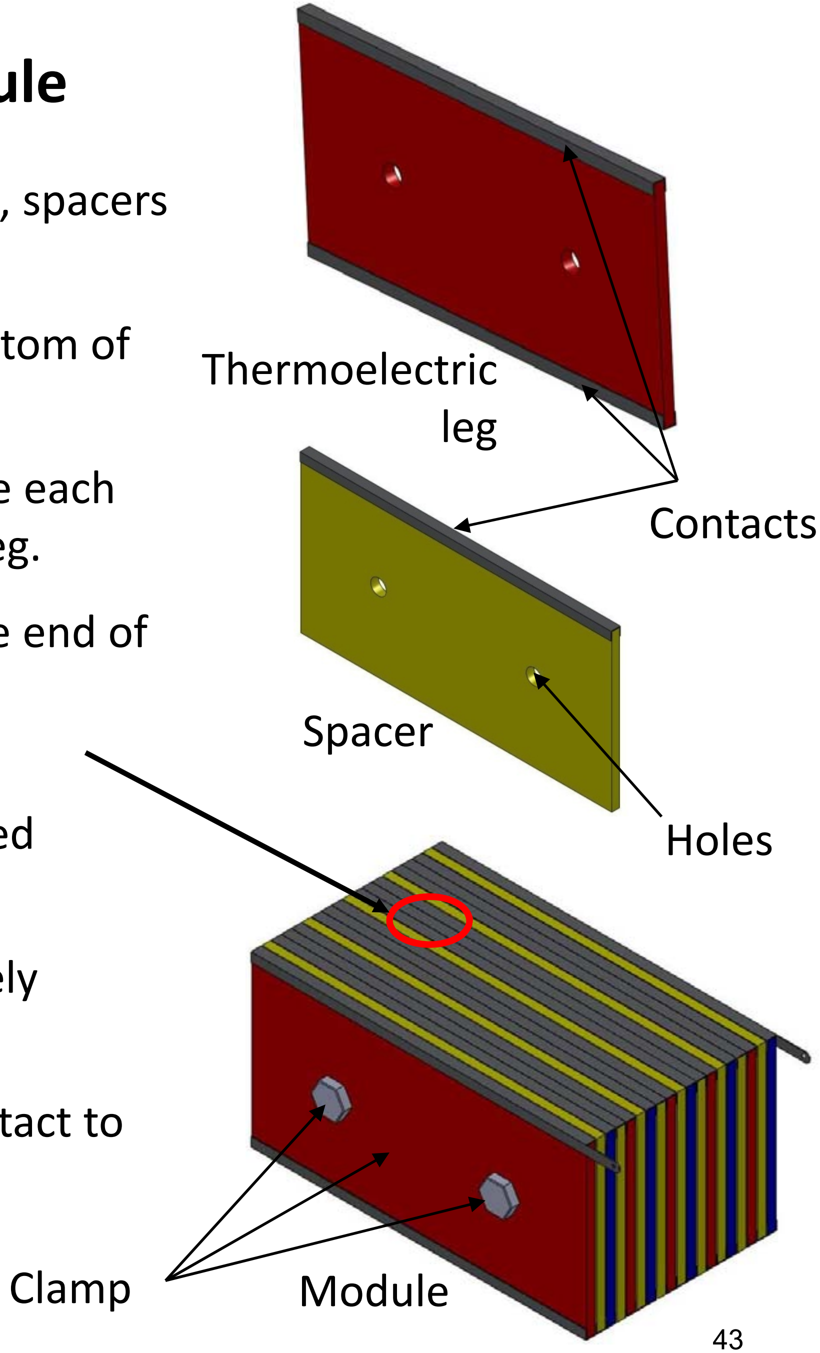
Folded ribbon with N & P facing each other



Metallized module with contact materials

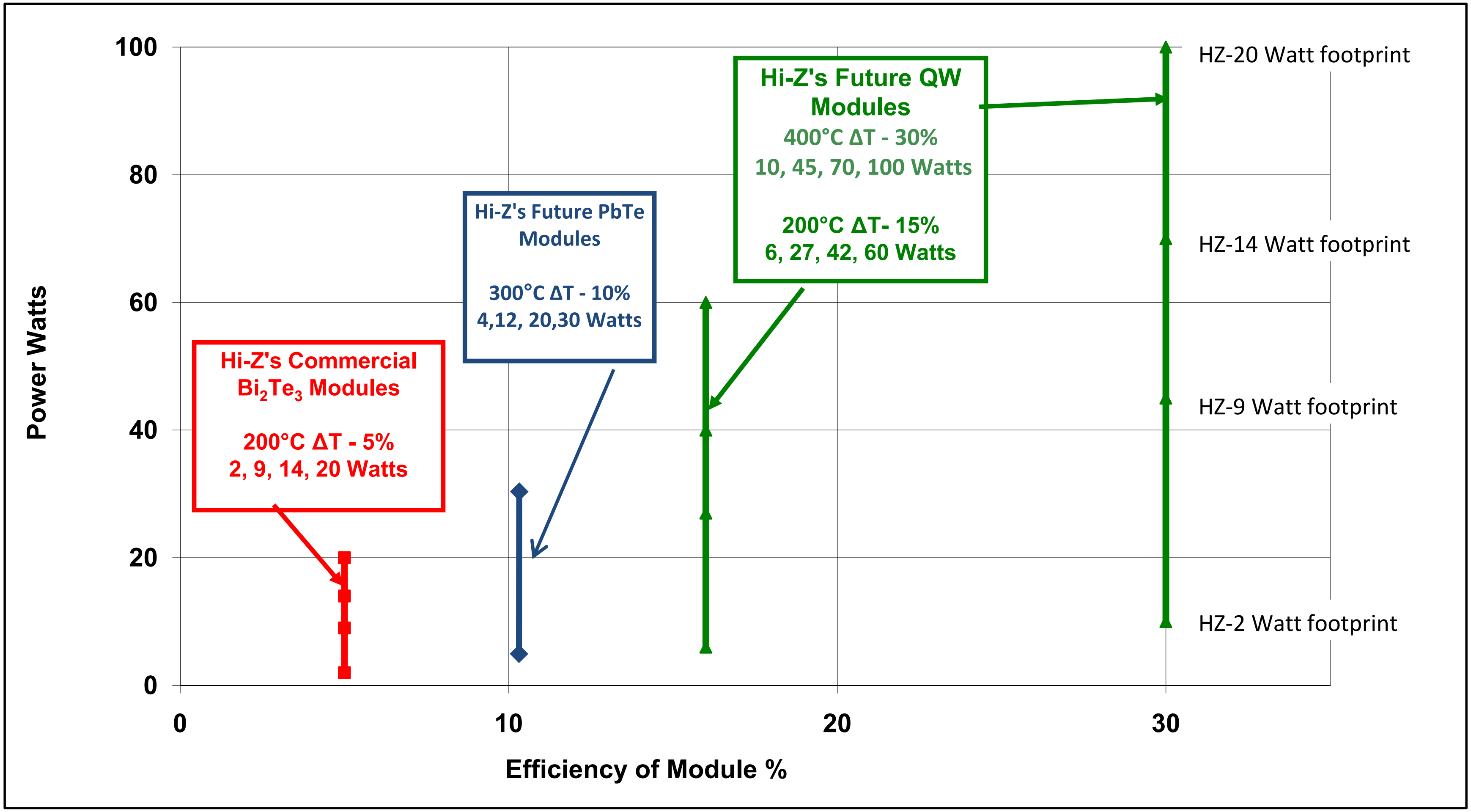
Stacked Thermoelectric Module

- A stacked module consists of P legs, N legs, spacers and a clamp.
- Contacts are deposited on the top and bottom of the legs and on one side of the spacer.
- Alternating N and P legs are stacked beside each other and a spacer is placed between each leg.
- The contact on the spacer will connect one end of the P leg to the adjacent end of the N leg.
- By alternating the side that the contact is positioned on, all of the legs can be connected electrically in series.
- Holes will allow alignment pins to accurately position each leg/spacer.
- A clamp will hold the stack-up in close contact to ensure good electrical continuity.



Forecasted Thermoelectric Progress

Module footprints from HZ-2 to HZ-20 sizes



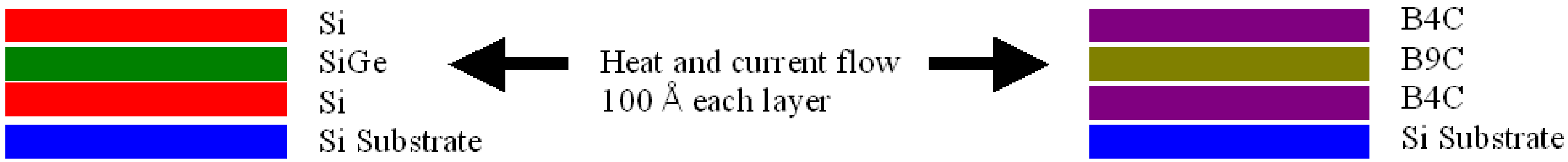
Summary and Future Direction

1. Alternating 100 Å (10 nm) thick layers of N type Si/SiGe and P type B_4C/B_9C were deposited on 5 µm thick Si substrates:v
   - 14% efficiency was measured at a T_H of 250°C and T_C of 50°C
   - Si/SiGe or Si/SiC can also be used as the P type leg.

N Type

QW like behavior is observed "in plane"

P Type can also be Si/SiGe



-Encouraging Seebeck coefficient **α** (1,000µV/°C) and ρ resistivity (1millohm–cm) data has been observed by 4 groups besides Hi-Z

-Measurements by UCSD show the thermal conductivity values are $^1/_3$ to $^1/_2$ of bulk properties which are in agreement with theoretical models

-A new test device developed at Hi-Z, indicates ZT values of ~5 with Si/SiGe alternating layers

2. Good thermal and thermoelectric stability exhibited thus far:
   - In isothermal testing at 600°C, 400 hours and 1000°C, 24 hours
   - Output of a N and P couple at T_H of 300°C and T_C of 50°C remained stable for4000 hours
   - Many more couples to be life tested
3. Joining the QW materials with Mo shows promise. Appears contact resistance can be reduced to low levels. Subcontract with SUNY Albany nano fabrication facility allows us to take advantage of their on going development in this area.

Summary and Future Direction Continued

4. Large area deposition:
    - Sputter QW film onto 6 inch area diameter Si wafers is planned
    - Major coating facility demonstrated multiple layers of Si/SiGe 10 nano meter thick can be deposited over large area. (Several square feet) of Kapton
    - Evaluations of films and further scale up to planned
5. Lower thermal conductivity substrates being pursued with SUNY Albany via several techniques. Kapton and glass may also be suitable as a substrate
6. Several module designs identified and low cost modeling studies indicates ~ $0.50 /Watt is achievable. Module fabrication is planned
7. Large increases in thermoelectric conversion efficiency (>3 times) appear feasible from T_H's of 150°C to 1000°C.
8. With higher efficiencies waste heat recovery markets become economical. Today they are marginal. Plan underway to work with several large companies
9. There are many marketing opportunities for this encouraging QW Technology. Several are multi billion dollar in size
10. Future work oriented towards fabricating couples and modules as well as material optimization.