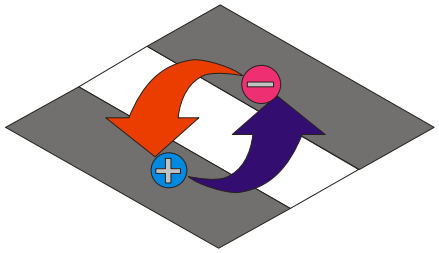
Development of Thermoelectric Devices at Cardiff

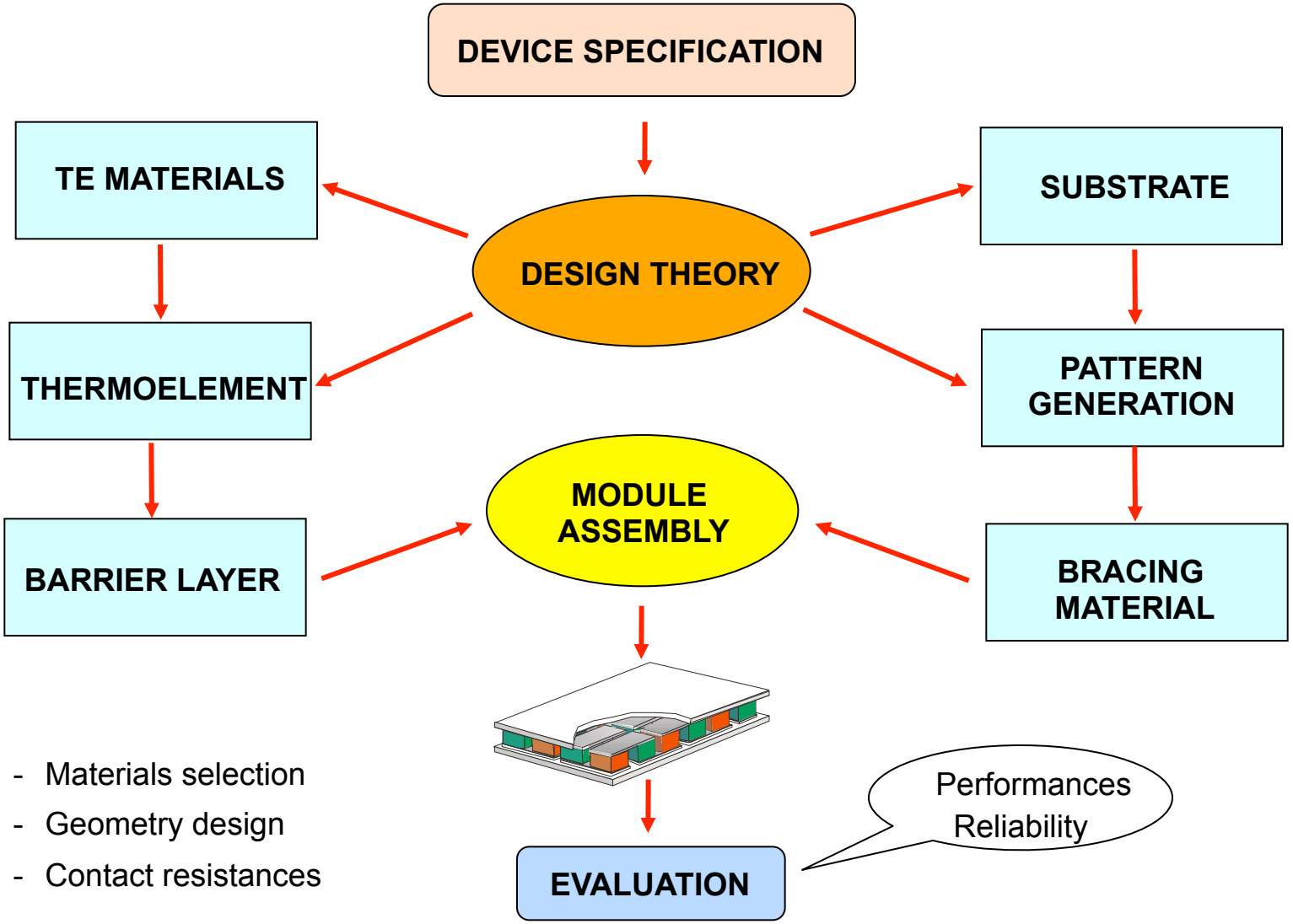
- *Design, Fabrication and Evaluation* -



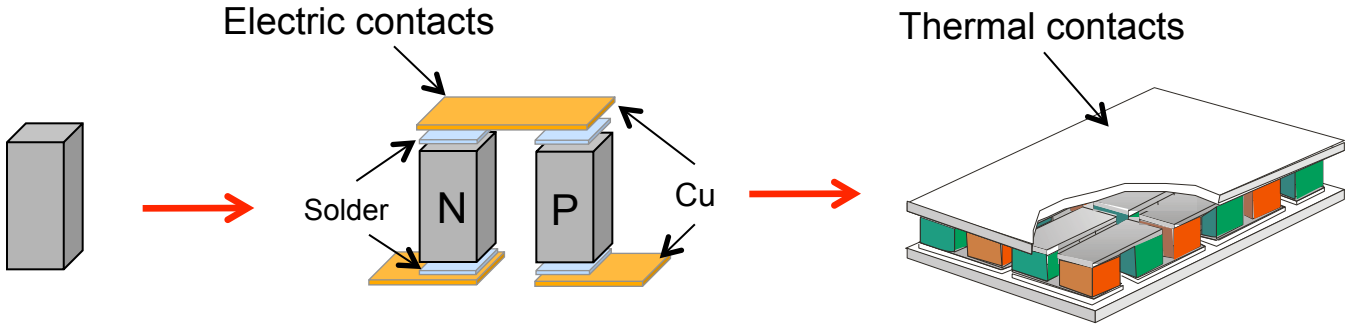
Gao Min

School of Engineering, Cardiff University

Thermoelectric Device Fabrication Processes



From Materials to Device – *Contact problem*



$$P_{\max} = \frac{(\alpha \cdot \Delta T)^2}{4\rho} \frac{A}{l}$$

$$\phi = \frac{\Delta T}{T_H \left(4 - \frac{\Delta T}{2T_H} + \frac{4}{ZT_H}\right)}$$

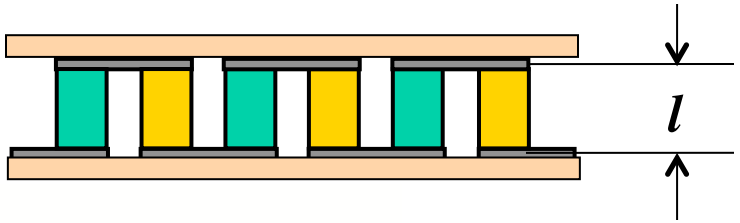
$$P_{\max} = \frac{(\alpha \cdot \Delta T)^2}{4\rho} \frac{A \cdot 2N}{(n+l)(1+2rl_c/l)^2}$$

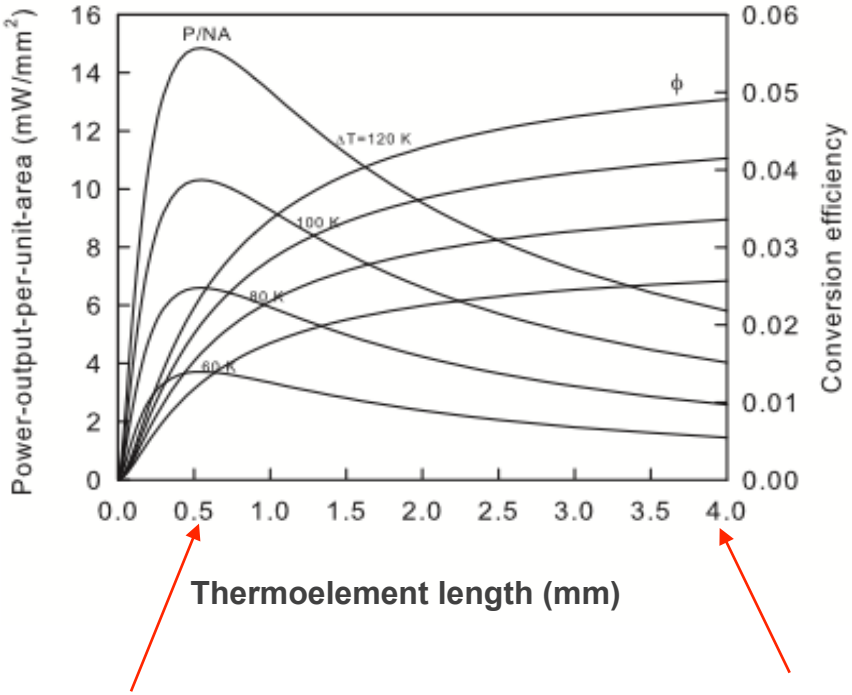
$$\phi = \frac{\left(\frac{\Delta T}{T_H}\right)}{\left(1+2r\frac{l_c}{l}\right)^2 \left(2 - \frac{1}{2}\left[\frac{\Delta T}{T_H}\right] + \left[\frac{4}{ZT_H}\right]\left[\frac{l+n}{l+2rl_c}\right]\right)}$$

A.F. Ioffe, *Semiconductor Thermoelements and Thermoelectric Cooling* (1957).

Gao Min, *CRC Handbook of Thermoelectrics*, (2005), Chapter 11

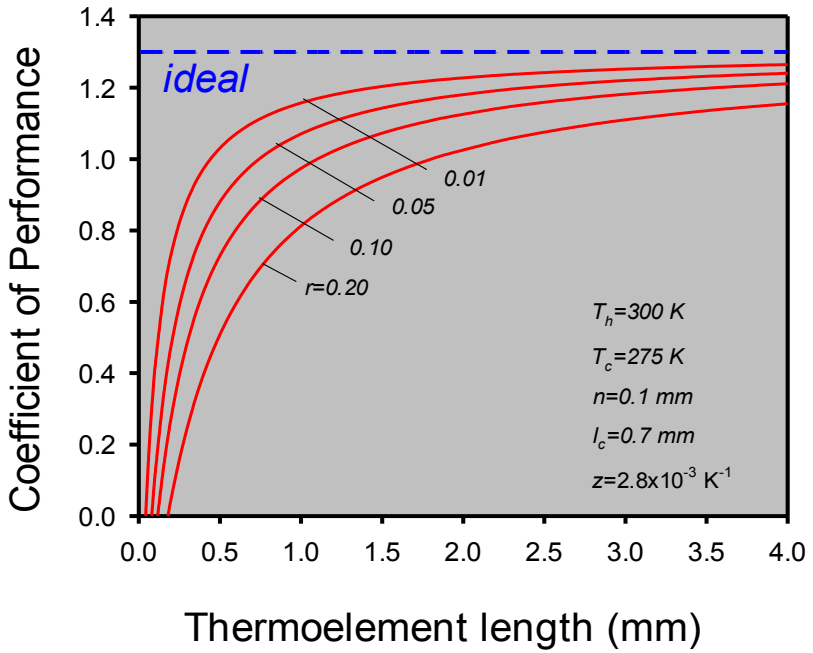
Module Design – Determine *l* for P_{max} or Φ_{max}





Optimal length for P_{max}

Preferred length for ϕ_{max}

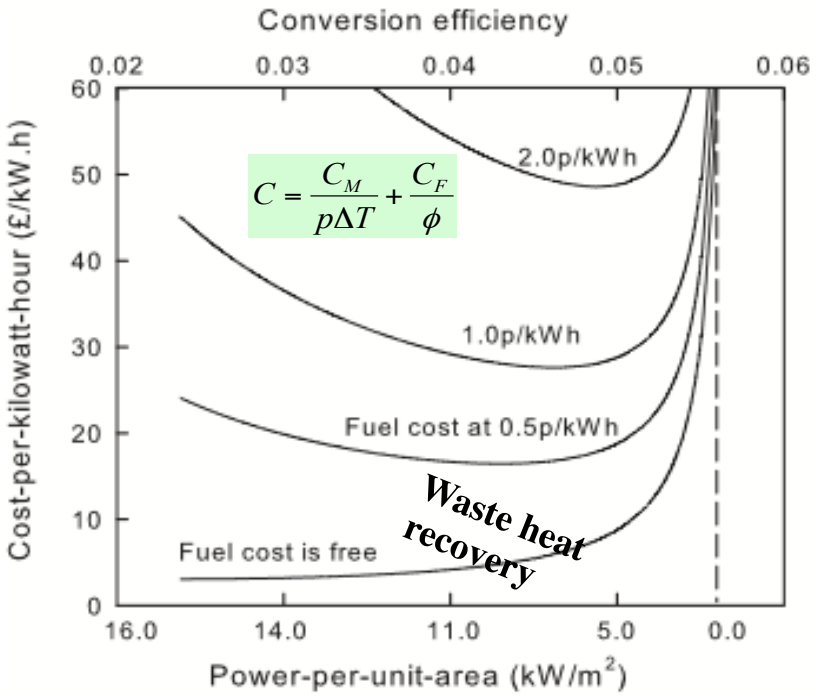


Reduce contact resistance helps to improve performance of short length

Gao Min, *CRC Handbook of Thermoelectrics*, 1996, 11-1

Gao Min and D M Rowe, 2000, *Energy Conversion & Management* , (41) 163-171

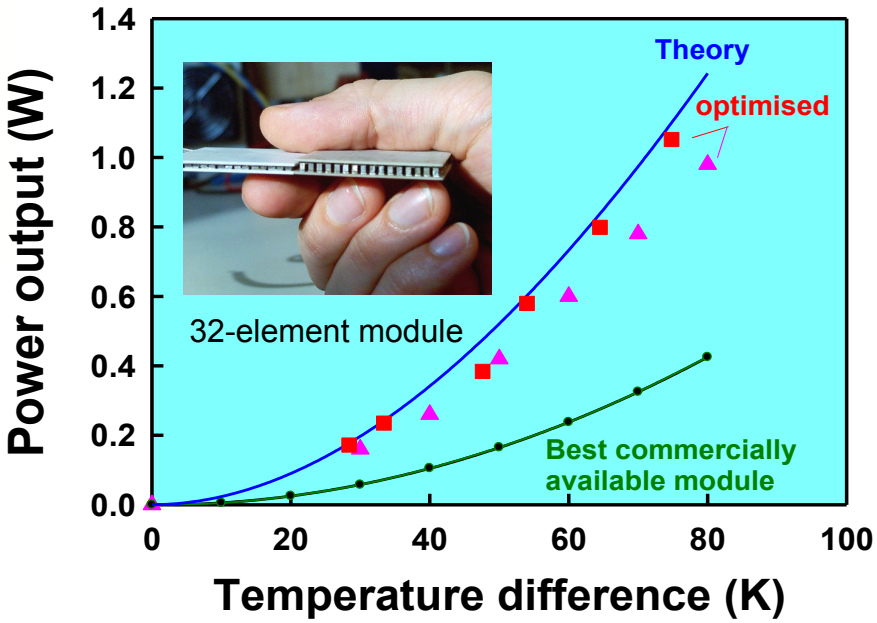
Module Design for Waste Heat Recovery



Suitable for waste heat recovery

Increasing the power output will lead to reduce the cost of power per module

The power output can be increased by reducing the length of thermoelements.

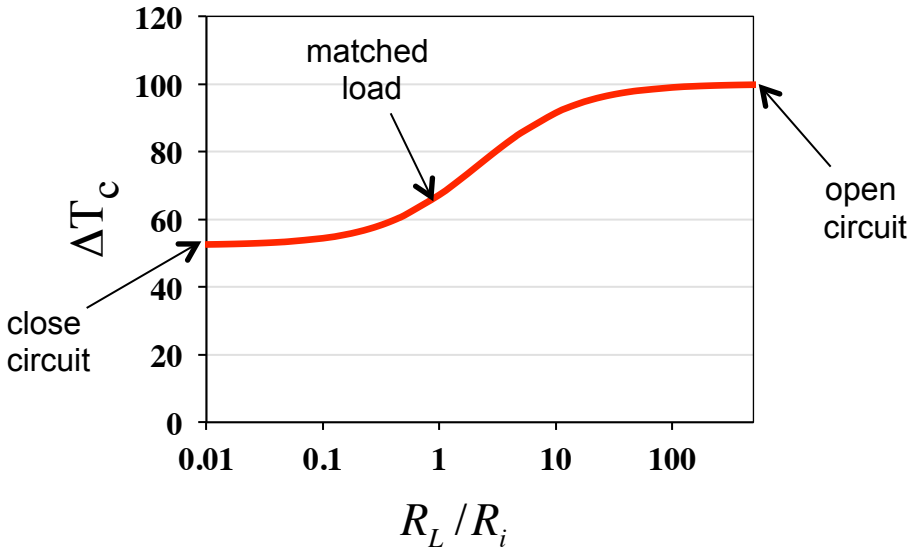


Gao Min and Rowe, 2002, Energy Conversion & Management , (43) 221-228

Module Design Theory for Given Thermal Input

$$\Delta T_c = \frac{\Delta T_o}{1 + ZT_M}$$

$$T_M = \frac{(1+2s)T_H + T_C}{2(1+s)^2}$$

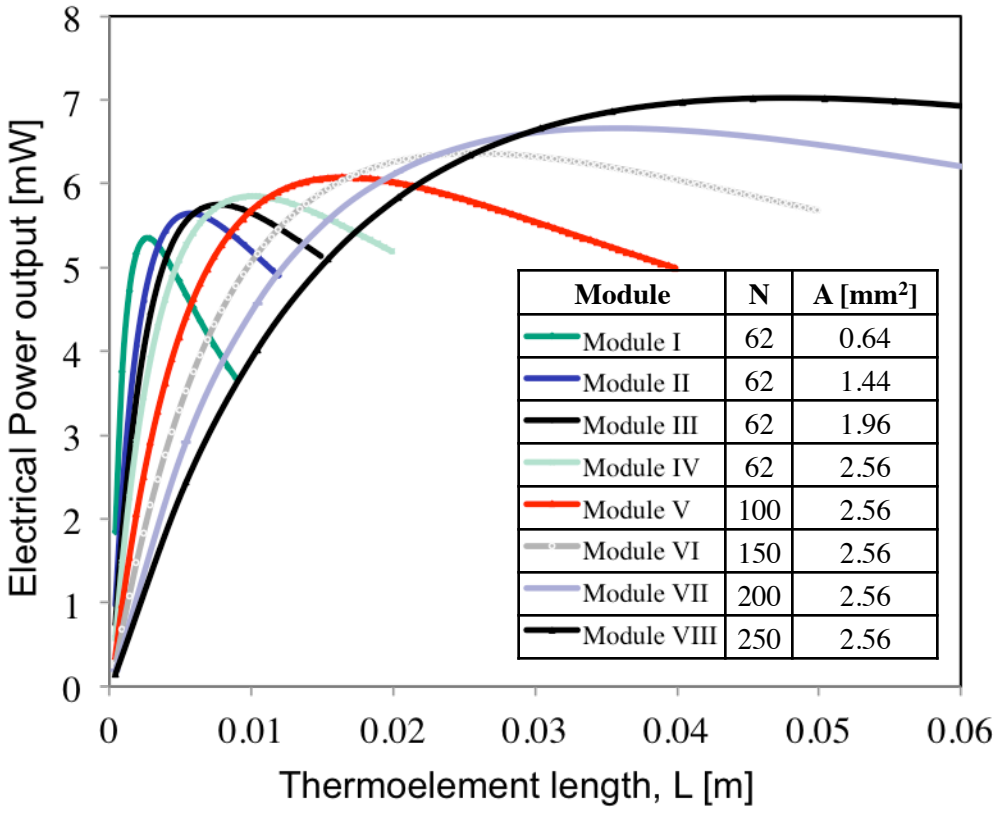


Power output: $$P = \frac{s}{(1+s)^2} \cdot \frac{Z}{(1+ZT_M)^2} \cdot \frac{\dot{Q}^2}{\lambda} \cdot \frac{l}{A} \cdot \frac{l}{(n+l)(1+2rl_c/l)^2}$$

Efficiency: $$\phi = \frac{P}{\dot{Q}} = \frac{s}{(1+s)^2} \cdot \frac{Z}{(1+ZT_M)^2} \cdot \frac{\dot{Q}}{\lambda} \cdot \frac{l}{A} \cdot \frac{l}{(n+l)(1+2rl_c/l)^2}$$

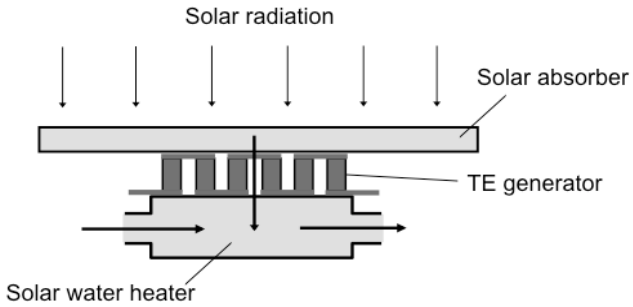
Gao Min, "TE Module Design Under a Given Thermal Input:Theory and Example," J.Electr. Mater. (2013), 42(7), 2239-2242.

Geometry Optimisation for Given Thermal Input



Module	N	A [mm²]
Module I	62	0.64
Module II	62	1.44
Module III	62	1.96
Module IV	62	2.56
Module V	100	2.56
Module VI	150	2.56
Module VII	200	2.56
Module VIII	250	2.56

Solar irradiation: 1000W/m^2

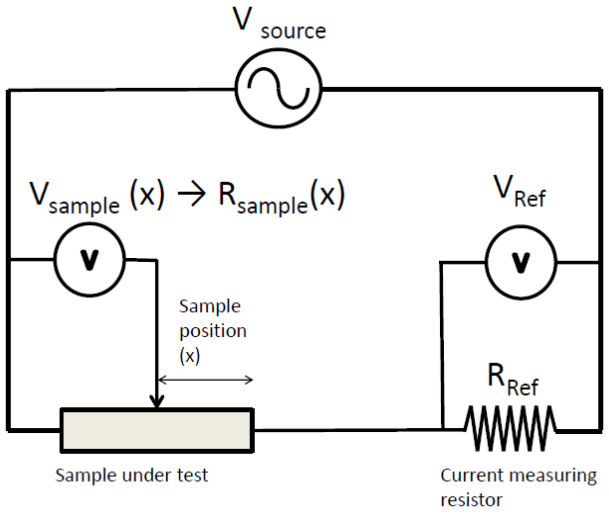


Solar absorber area: 4cm x 4cm

Material Consumption:

Module	Power (mW)	Volume (cm^3)
I	5.2	0.23
VIII	7.0	57.6

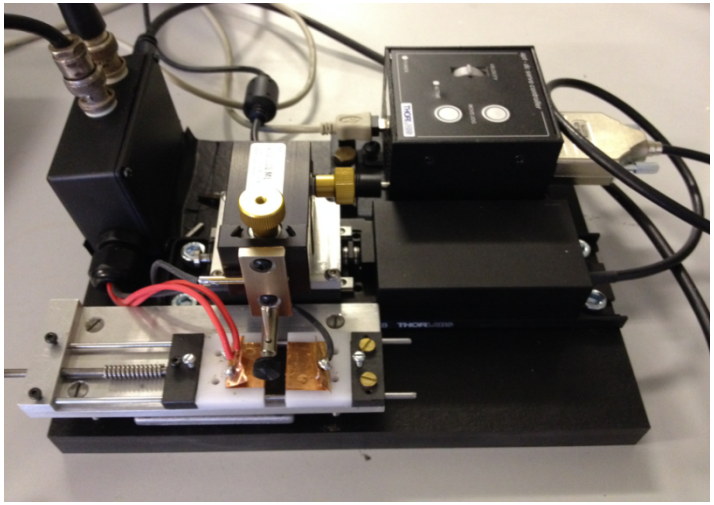
Techniques for Evaluation of Contact Resistance



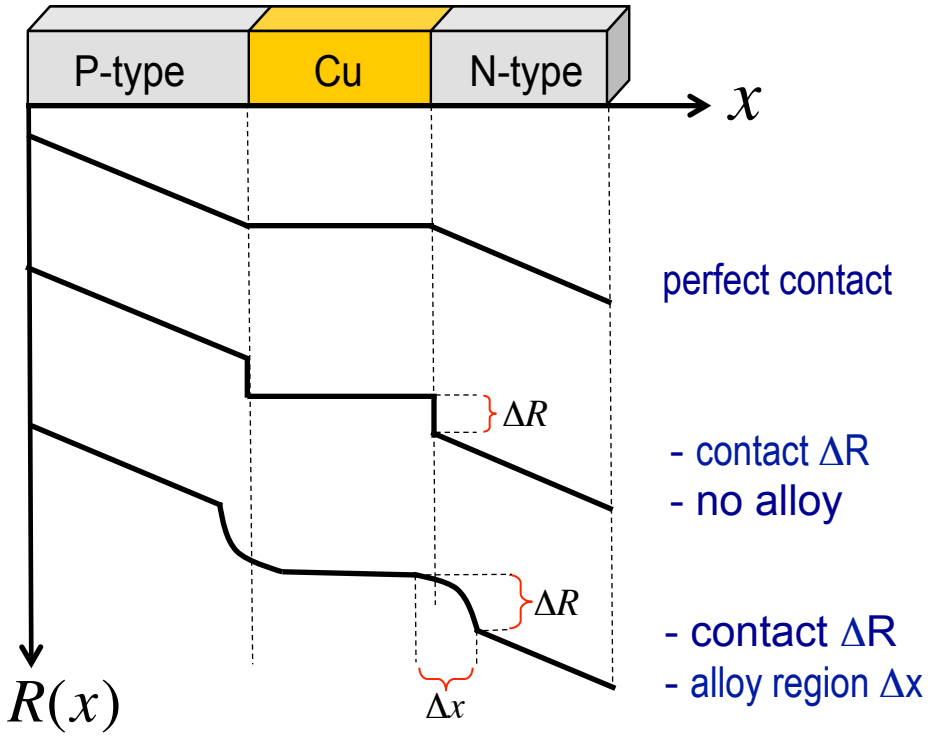
$$R(x) = \frac{V_S(x)}{V_{ref}} \cdot R_{ref}$$

$$\rho_c = \Delta R \cdot A$$

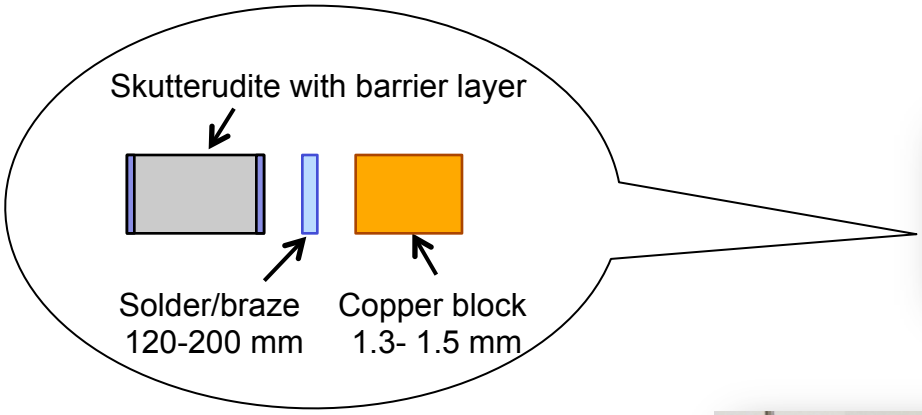
$$\rho = dR(x)/dx$$

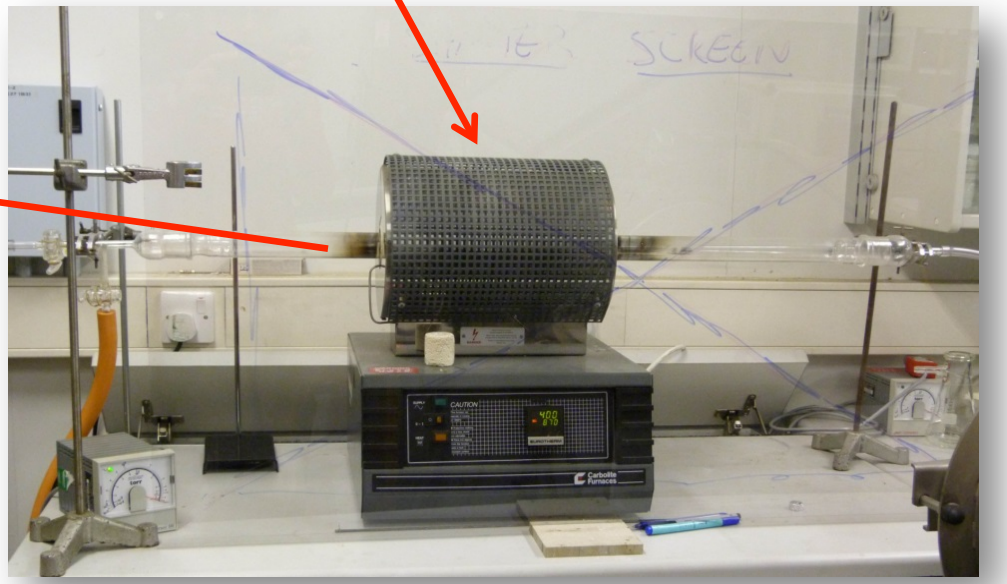


Spatial resolution: 5 μm

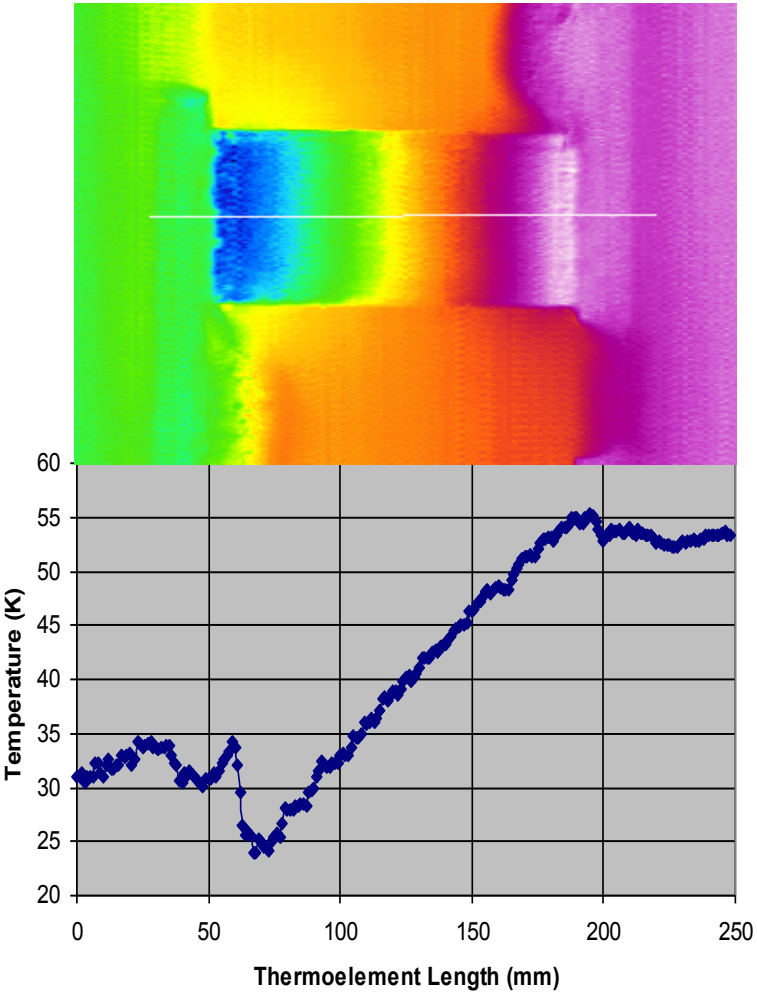


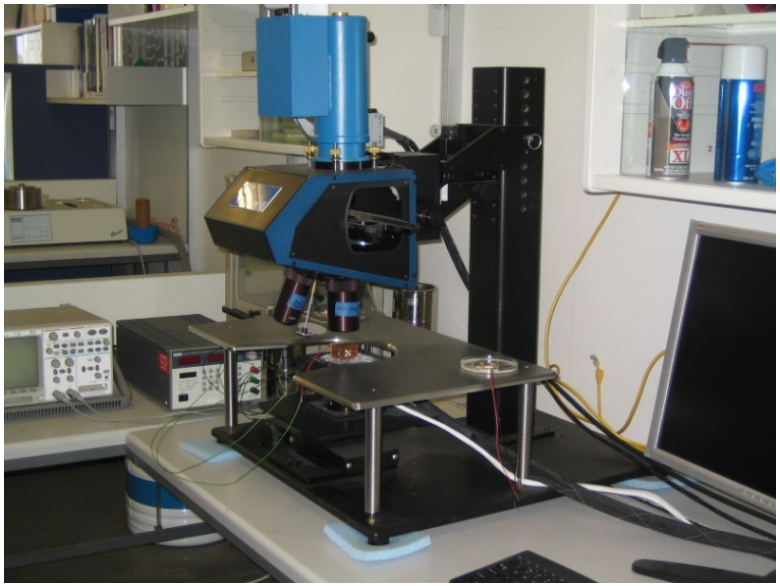
Contact Resistance of Skutterudite interfaces





Investigate Thermal Contact Effect Using Infrared Microscope

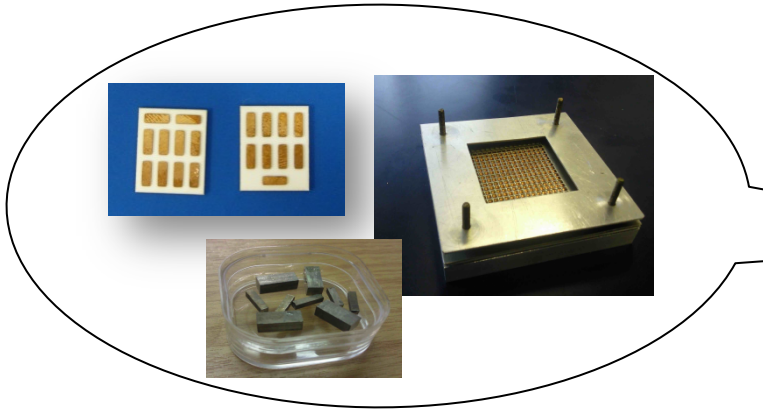


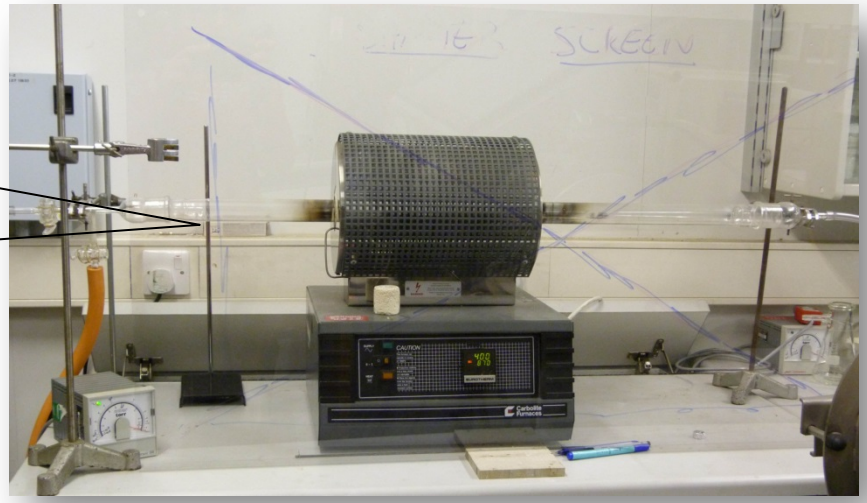


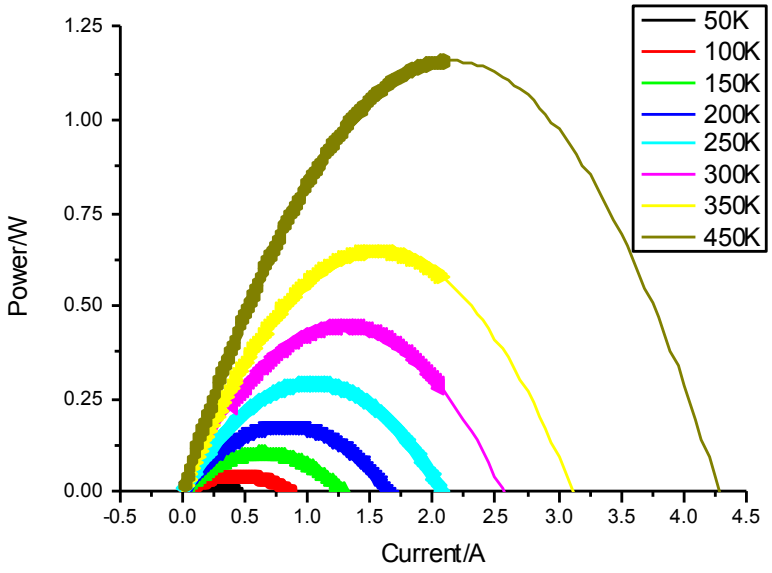
Specifications:

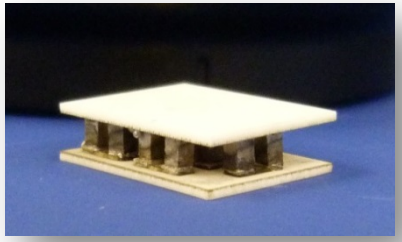
- Spatial resolution: 4 μm
- Temperature sensitivity: 0.1 K
- Temperature range: 300-600K

Fabrication of High Temperature Skutterudite Module





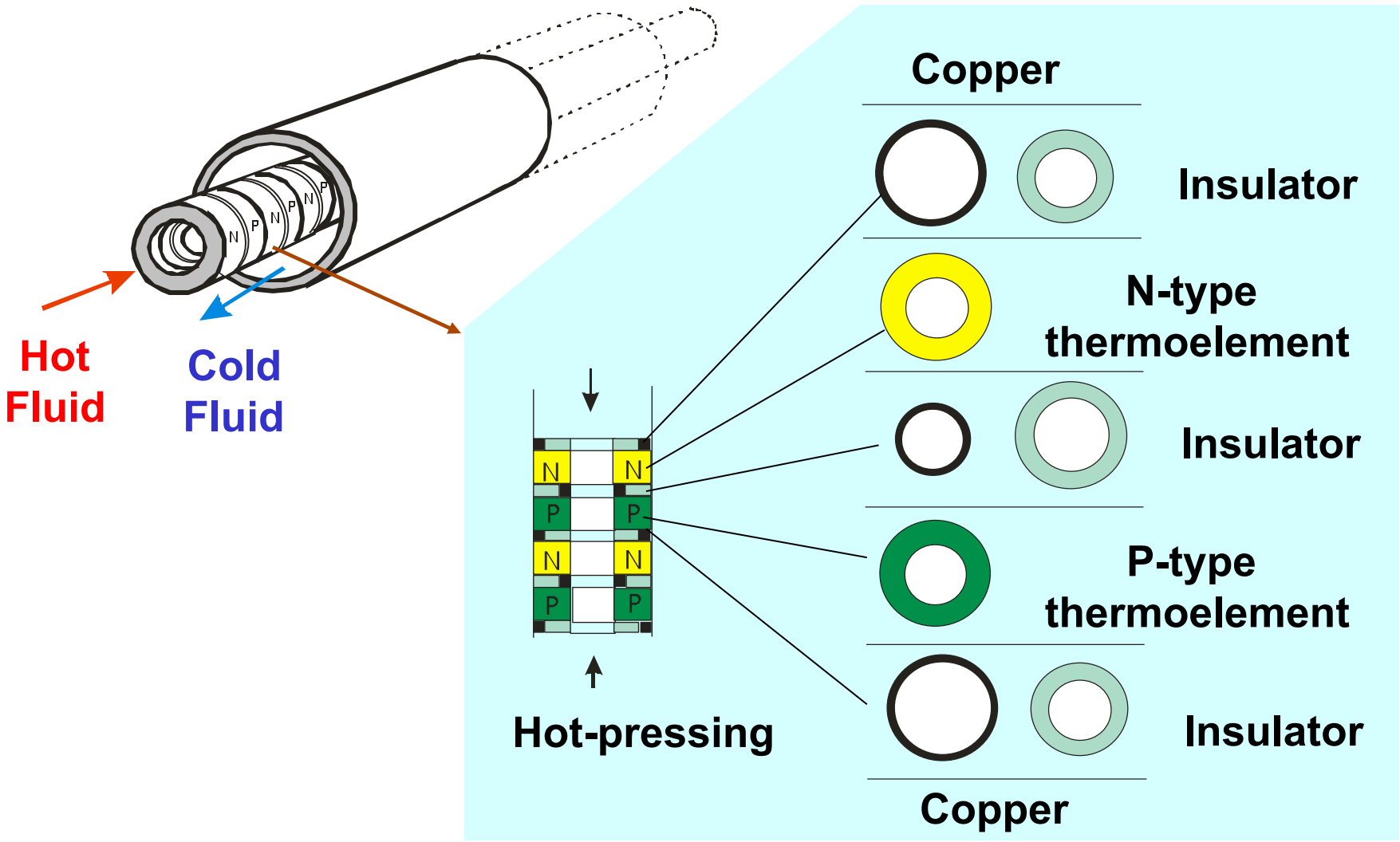




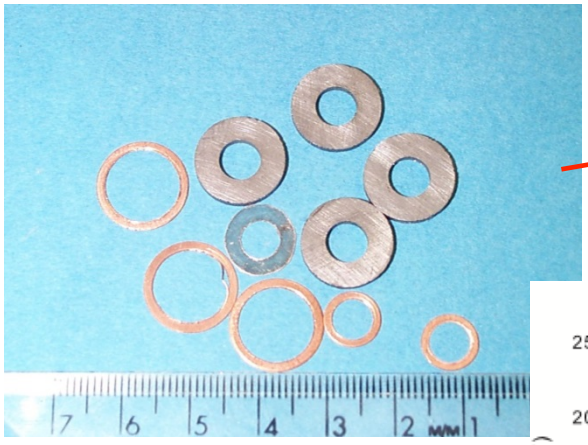
Loughborough-Reading-Cardiff Collaboration

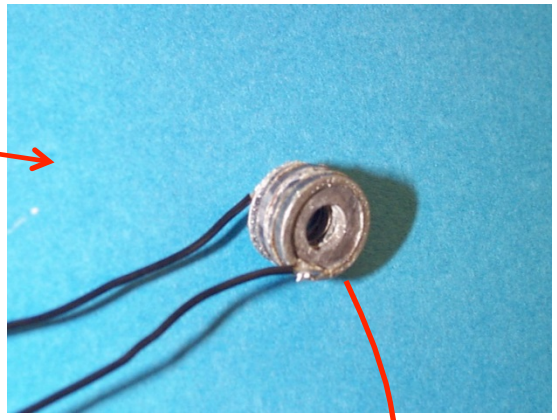
J Garcia-Canadas, A Powell, A Kaltzoglou, P Voqueiro and Gao Min, "Fabrication and Evaluation of a Skutterudite-Based Thermoelectric Module for High-Temperature Applications," Journal of Electronic Materials, (2013), 42(7), 1369-137

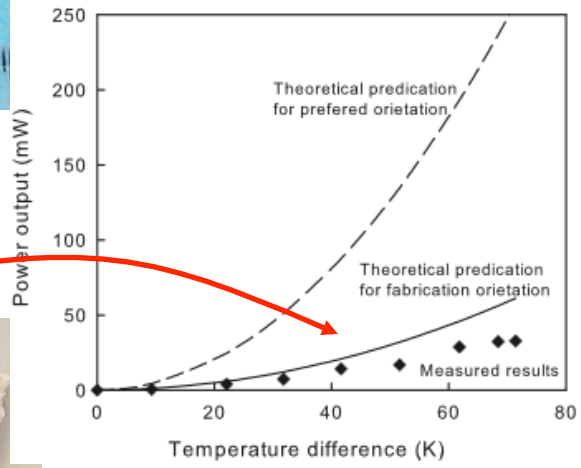
Ring-structured Thermoelectric Module

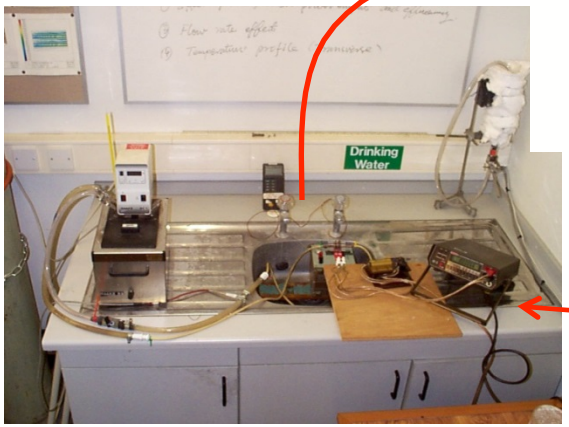


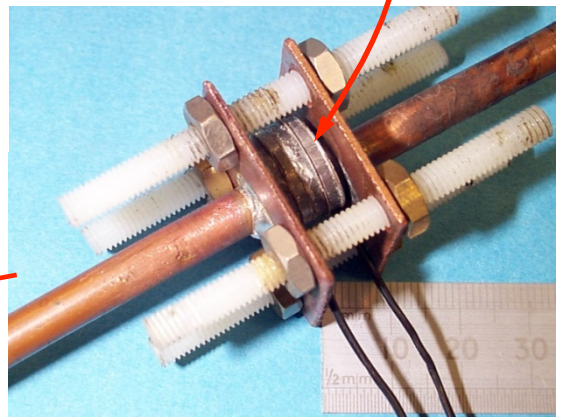
Ring-Structured Thermoelectric Tube







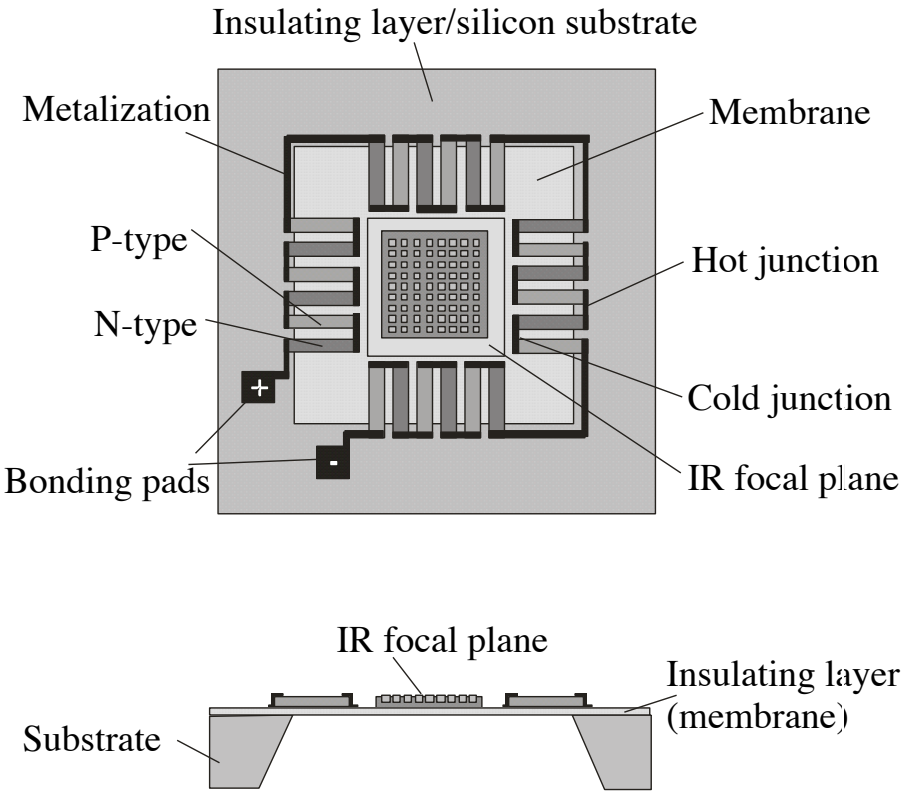


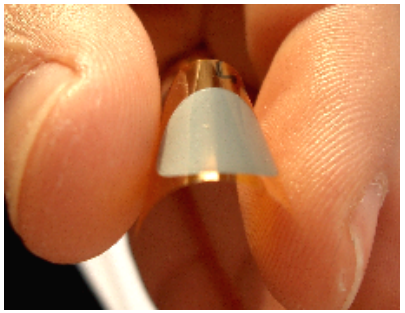


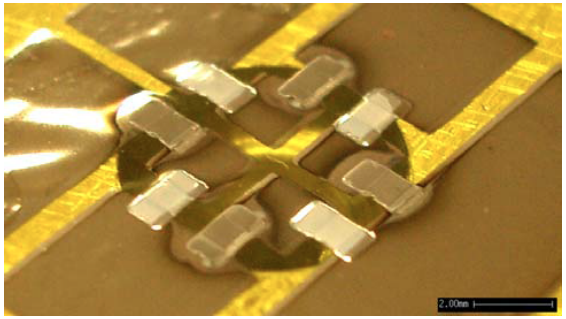
Gao Min and Rowe, 2007, Semicond. Sci. Technol., (27) 21-28

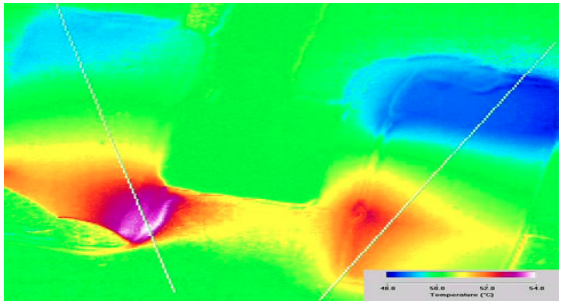
Micro/Nano Converters for Integrated Circuits

Horizontal structure





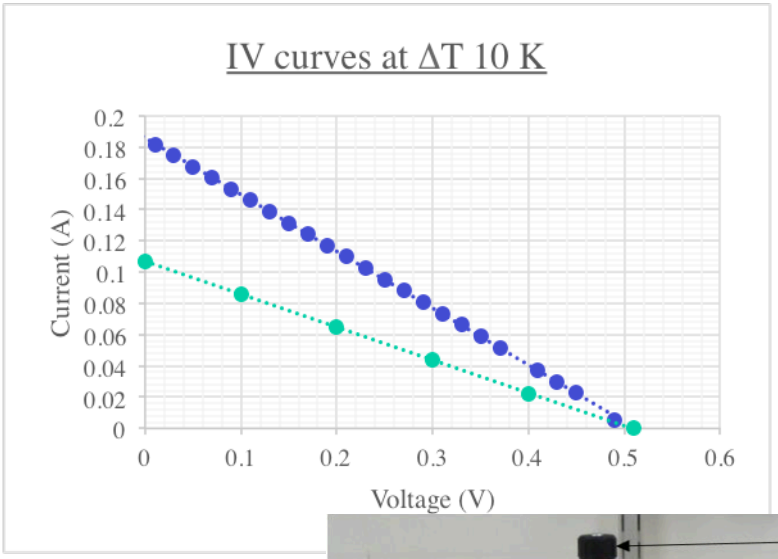


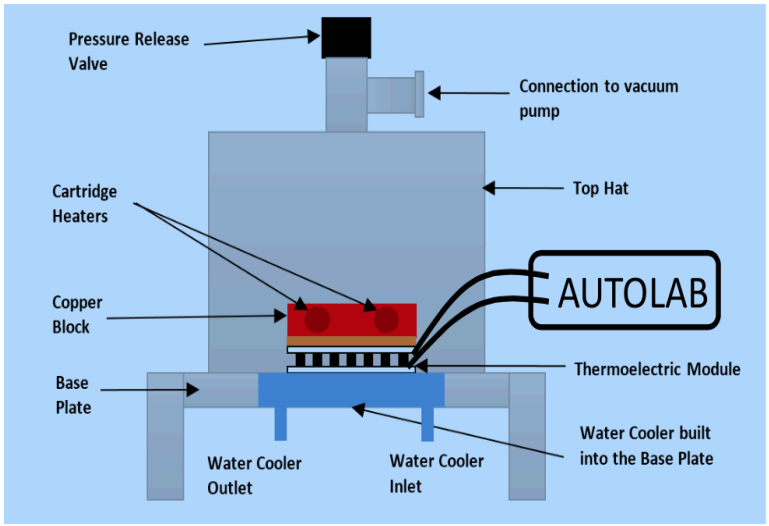


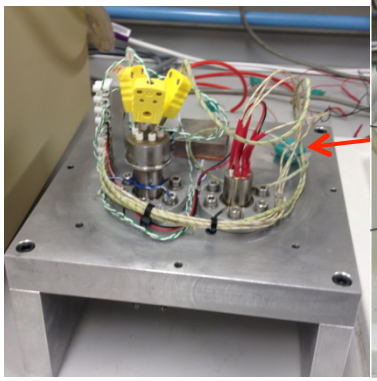
Ref: G Min and D Rowe, Electronics Letter, 1998, 34(2), 222-223

L.M. Goncalves. P. Alpuim, G. Min, D. M. Rowe, C. Couto, and J. H. Correia, "Optimization of Bi2Te3 and Sb2Te3 thin films deposited by co-evaporation on polyimide for thermoelectric applications", Vacuum, 82 (12), (2008), 1499-1502

Evaluation of TE Generators by I-V Curves

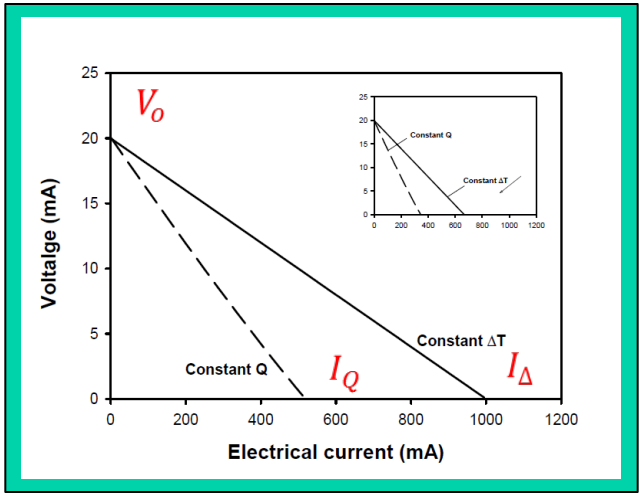


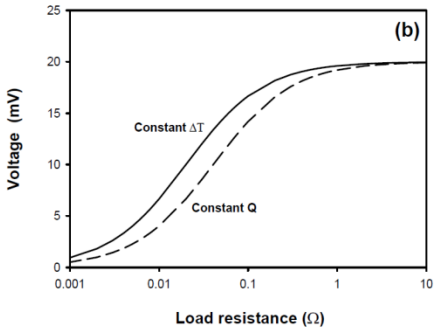


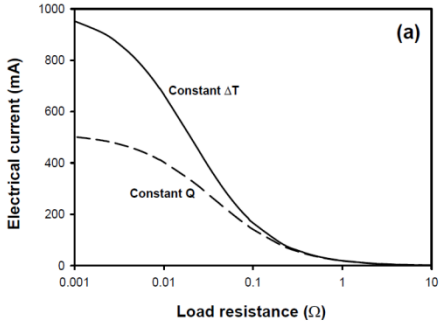


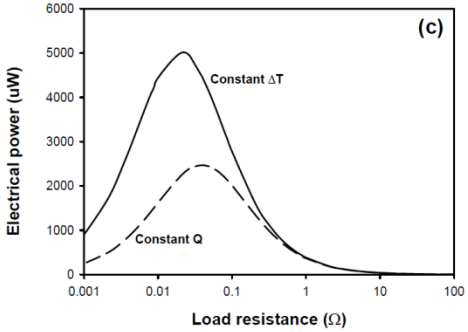
The use of AUTOLAB eliminates requirements for sophisticated temperature control system.

Thermoelectric Parameters Obtainable from I-V Curves









Device parameters

$$Z\bar{T} = \frac{I_\Delta}{I_Q} - 1$$

$$\alpha = \frac{V_o}{\Delta T_o}$$

$$R_i = \frac{V_o}{I_\Delta}$$

$$K = \frac{\bar{T}}{\Delta T_o^2} \cdot \frac{I_Q \cdot V_o}{1 - I_Q / I_\Delta}$$

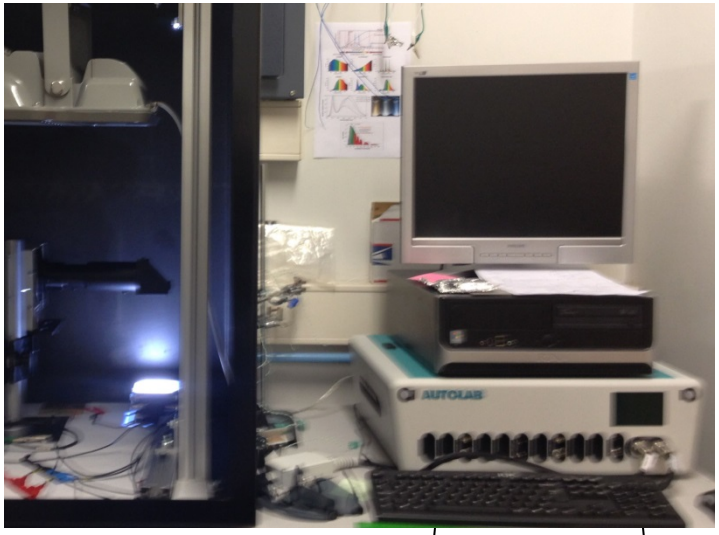
$$\rho = \frac{A}{l} \cdot R_i \qquad \lambda = \frac{l}{A} \cdot K$$

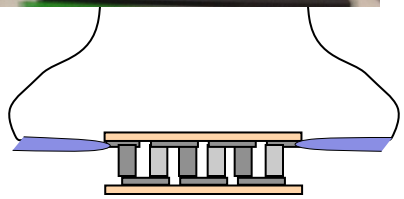
Generator performances

$$P_{\max} = \frac{1}{4} \cdot I_Q \cdot V_o$$

$$\eta_{\max} = \frac{1}{4} \cdot \frac{\Delta T_o}{\bar{T}} \cdot \left(1 - \frac{I_Q}{I_\Delta}\right)$$

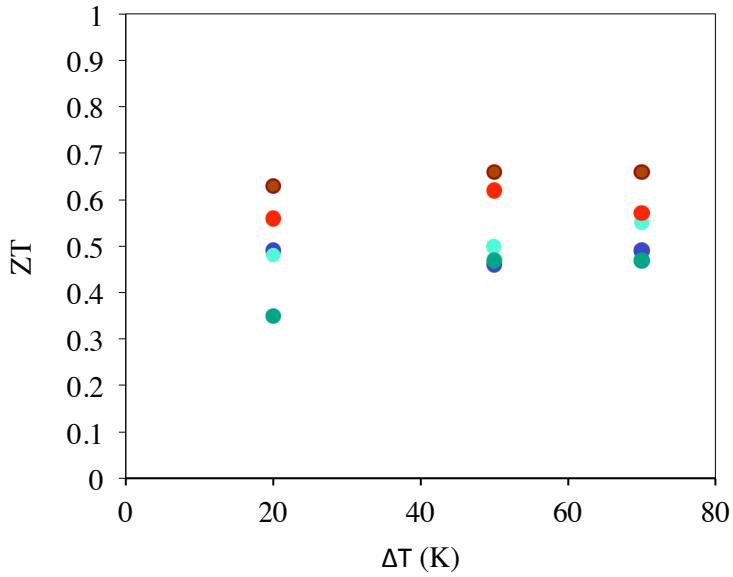
Thermoelectric Impedance Spectroscope

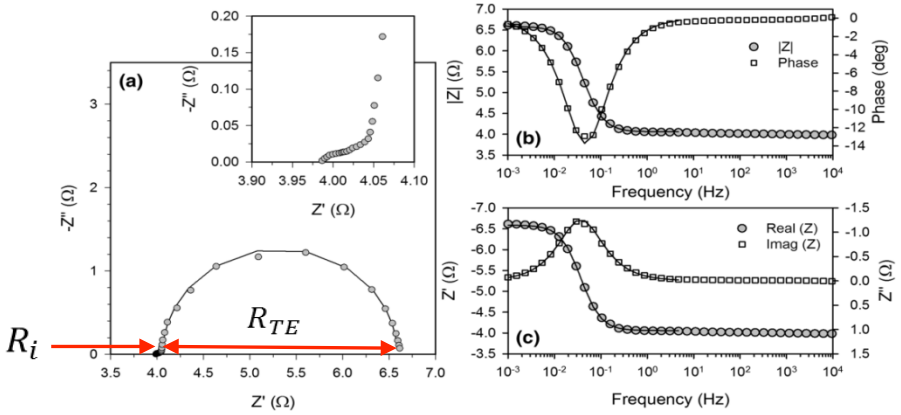




TE module

$$ZT = \frac{R_{TE}}{R_i}$$

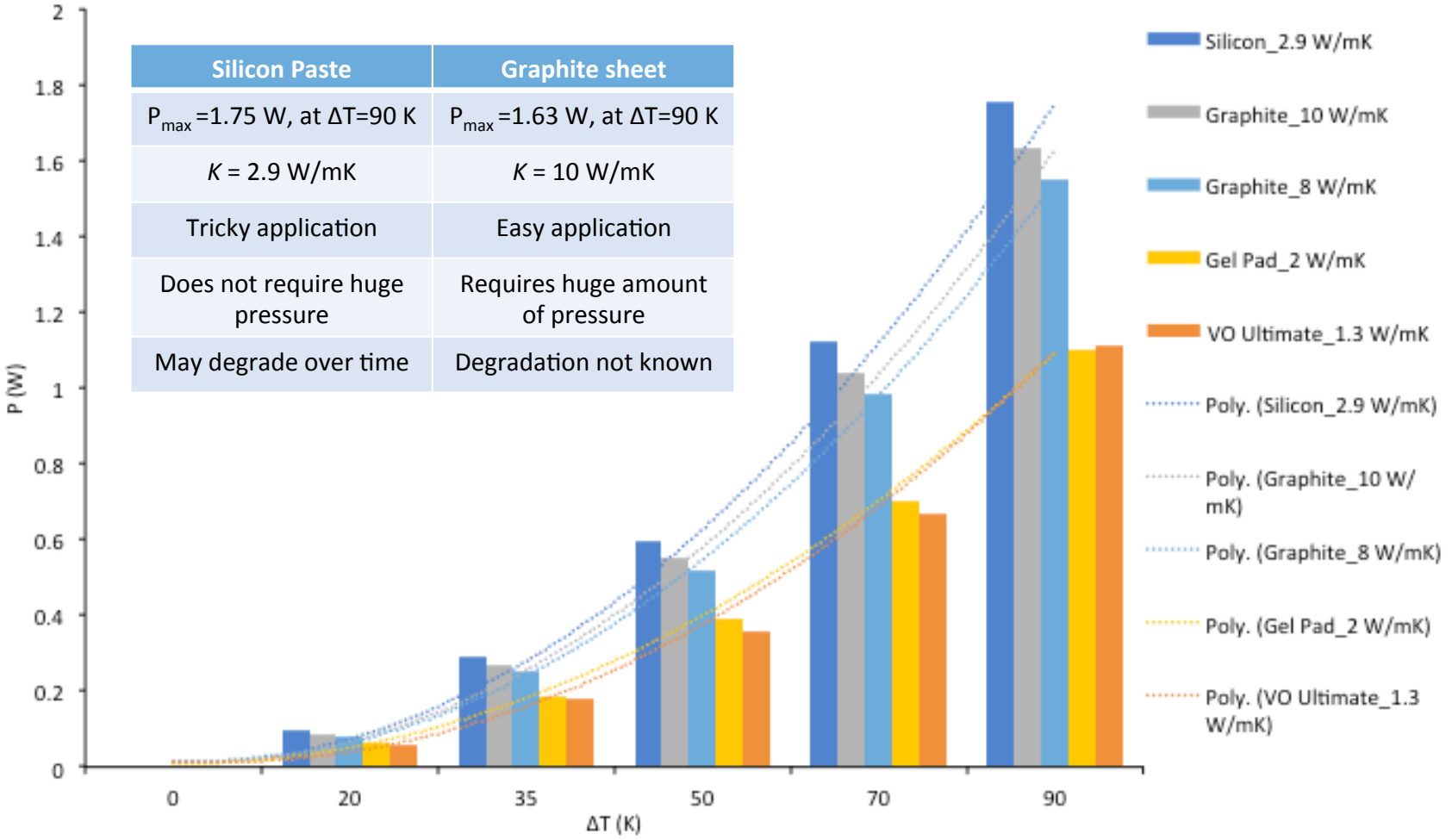




J. Garcia-Cañadas and G. Min, "Impedance Spectroscopy Models for the Complete Characterization of Thermoelectric Materials" Journal of Applied Physics 116 (17), 174510 (2014).

Influence of Thermal Contact Materials

Silicon Paste	Graphite sheet
P_{max} =1.75 W, at ΔT=90 K	P_{max} =1.63 W, at ΔT=90 K
K = 2.9 W/mK	*K* = 10 W/mK
Tricky application	Easy application
Does not require huge pressure	Requires huge amount of pressure
May degrade over time	Degradation not known



Thank You

Acknowledgement

- Matthew Philips
- Jorge G Canadas
- Tanuj Singh
- Jay Bomphrey
- Lourdes M Garcia
- Hasan Hashim
- Martin Prest
- Tracy Sweet
- Mark Robbins
- Matesuz Augustyniak
- W M N WanJaafar
- Hayder Al-Madhachi
- M Al-Bagdadi
- Nadhrad Yatim
- Ramdan Kazuz
- EU-FP7 THERELEXPRO (601545)
- EU-FP7 GLOBASOL (309194)
- EU-FP7 ACCMET (263206)
- EPSRC UKTEG (EP/K029142)
- EPSRC SUNTRAP (EP/K022156)