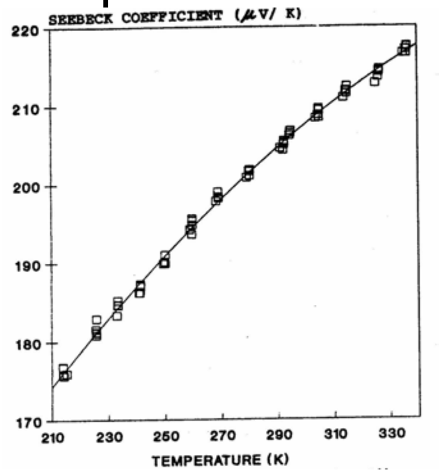
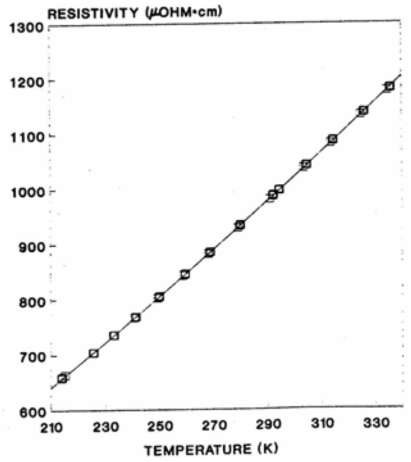
Thermoelectric Characterization

Measurement and Characterization of Thermoelectric Materials

- Properties of interests for *TE* materials
  - Seebeck coefficient (S)
  - Electrical resistivity/conductivity (?/?)
  - Thermal conductivity (?)
  - Carrier mobility (?)
  - Carrier concentration (*n*)
- Issues
  - Temperature-dependent properties
  - Error estimation for ZT calculation
  - Contact effects (Joule heating, surface oxidation,…)

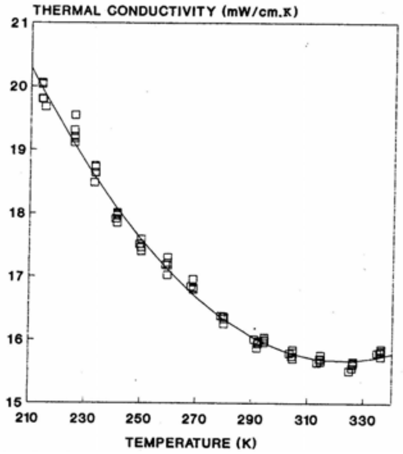
S and ρ Vs. Temperature

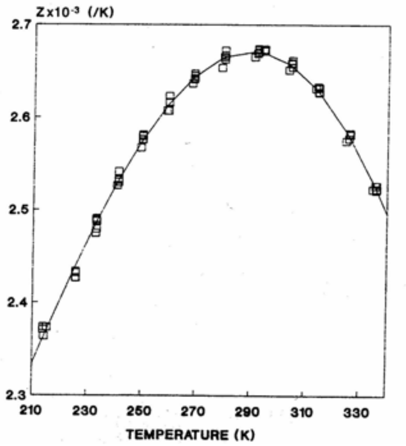




Measure S, ρ, and λ at the same temperature

λ and Z Vs. Temperature





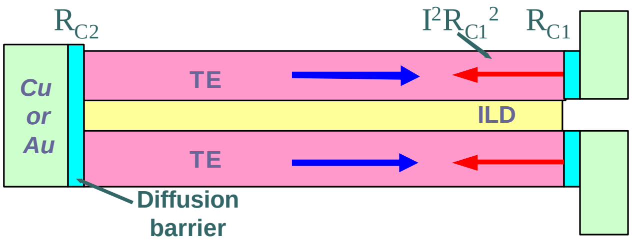
Validate the repeatability and stability of the tests

Error estimation for ZT calculation

- Typical values for Bi_2Te_3 compound:
  S=275 ?V/K, ?=10^3(? -cm)$^{-1}$,?=2 W/mK @300K
  ? ZT=1.13
- Possible measurement error
  S- 10% lower due to ?T error
  ?- 5% higher from sample dimension error
  ?- 10% higher w/ error from ?T , power,…
  ? ZT=0.89 (21% lower)
- To reduce the measurement error
  - Measure all the properties on the same sample
  - Calibrated with the known TE materials

Electrical contact effect

- Contact resistance (Rc) induces extra Joule heating
- Uneven Rc (R_{C1}?R_{C2}) may cause unwanted T gradient
- Au and Cu can readily diffuse into Bi_2Te_3 ; Diffusion barrier may be needed, e.g. Ni



Thermal contact effect

- ✍ Thermal contact resistance induces extra ?T loss into the system (?T =Power•R_{th})

  ? lower cooler capability

  Assume a perfect TE cooler can attain maximum cooling temp T_C versus heat sink temp T_H, the real $T_{C\text{-Real}}$ will be higher than T_C due to thermal contact loss ?T

Electrical measurements

- ✍ Resistivity / Conductivity meas. :

  4-point probe, Van der pauw method

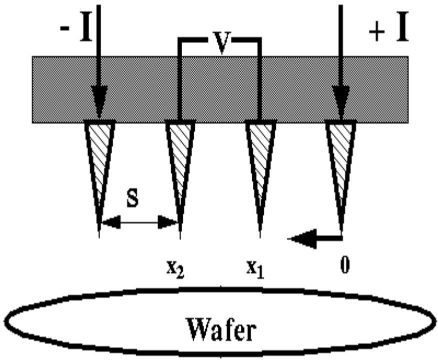
- ✍ Carrier conc./ mobility meas. :

  Hall- bar, Van der pauw method

4-point probe 1

- Measure resistivity (or sheet resistance) of bulk and thin film materials
- Four equally spaced metal tips with finite radius
- Typical probe spacing s ~ 1 mm
- Electric current through the outer two probes; a voltmeter measures the voltage across the inner two probes

Schematic of 4-point probe



4-point probe 2

- Bulk sample (t >> s)

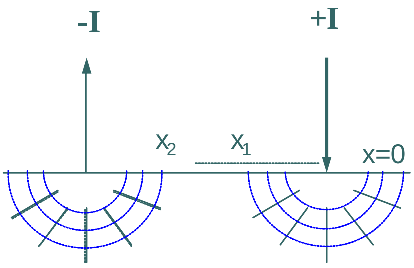
$$\Delta R = \rho\left(\frac{dx}{A}\right)$$

- the integration between the inner probe tips

$$R = \int_{x_1}^{x_2} \rho \frac{dx}{2\pi x^2} = \frac{\rho}{2\pi}\left(-\frac{1}{x}\right)\Bigg|_{x_1}^{x_2} = \frac{1}{2s}\frac{\rho}{2\pi}$$

- Superposition of current at 2 outer tips, V=IR–(-IR)=2IR

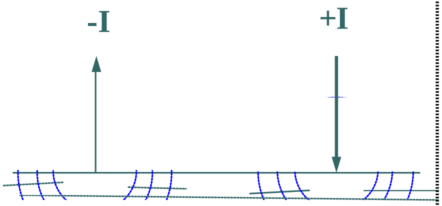
R=V/2I= ρ /(4s π)



- the metal tip is infinitesimal
- samples are semi-infinite in lateral dimension

$$\rho = 2\pi s\left(\frac{V}{I}\right)$$

4-point probe 3



- Thin film sample (t << s)
  $A = 2\pi x t$
- the integration between the inner probe tips

$$R = \int_{x_1}^{x_2} \rho \frac{dx}{2\pi x t} = \int_{s}^{2s} \frac{\rho}{2\pi t}\frac{dx}{x} = \frac{\rho}{2\pi t} ln(x)\Big|_{s}^{2s} = \frac{\rho}{2\pi t} ln2$$

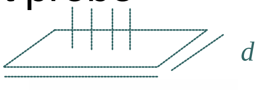
- Superposition of current at 2 outer tips, V=IR–(-IR)=2IR
  R=V/2I= ρ ln2/(2 π t)

$$\rho = \frac{\pi t}{ln2}\left(\frac{V}{I}\right)$$

$$R_S ? \frac{?}{t} ? \frac{?}{\ln 2}\frac{V}{I}$$

Correction factor for the sheet resistance measurement with 4-point probe

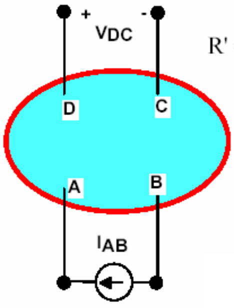
Rs=(V/I)(CF1))(CF2)



		Square	Rectangle		
d/s	Circle	*a/d=1*	*a/d=2*	*a/d=3*	*a/d=4*
1.0				0.9988	0.9994
1.25				1.2467	1.2248
1.5			1.4788	1.4893	1.4893
1.75			1.7196	1.7238	1.7238
2.0			1.9475	1.9475	1.9475
2.5			2.3532	2.3541	2.3541
3.0	2.2662	2.4575	2.7000	2.7005	2.7005
4.0	2.9289	3.1127	3.2246	3.2248	3.2248
5.0	3.3625	3.5098	3.5749	3.5750	3.5750
7.5	3.9273	4.0095	4.0361	4.0362	4.0362
10.0	4.1716	4.2209	4.2357	4.2357	4.2357
15.0	4.3646	4.3882	4.3947	4.3947	4.3947
20.0	4.4364	4.4516	4.4553	4.4553	4.4553
40.0	4.5076	4.5120	4.5129	4.5129	4.5129
infinity	4.5324	4.5324	4.5325	4.5325	4.5324

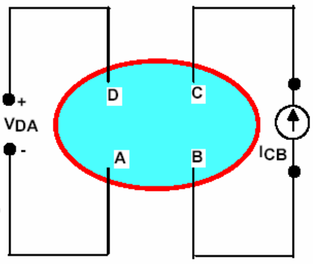
t/s	*CF2*
< 0.4	1.000
0.400	0.9995
0.500	0.9974
0.555	0.9948
0.625	0.9896
0.714	0.9798
0.833	0.9600
1.000	0.9214
1.111	0.8907
1.250	0.8490
1.429	0.7938
1.667	0.7225
2.000	0.6336

Van der Pauw measurement



$$R' = \frac{V_{DC}}{I_{AB}}$$

$$R'' = \frac{V_{DA}}{I_{CB}}$$

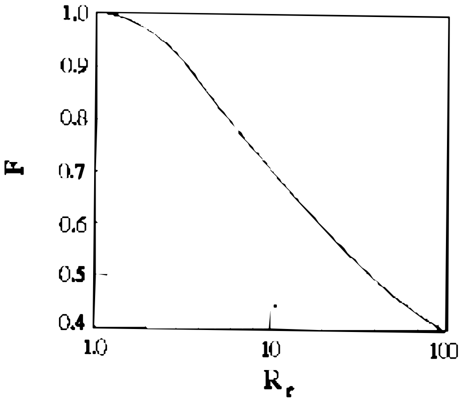


$$R_S ? \frac{?}{t} ? \frac{?}{\ln 2} \frac{R'?R''}{2} F(R'/R'')$$

F 1

- Van der Pauw structures are used for determining sheet resistance
- Four contacts are placed in four corners of a structure (ABCD) and two measurements are taken to measure resistances R’ and R”.
- Current is forced through contacts A & B and the voltage drop between C & D is measured to determine R’.
- Current is forced through contacts C & B and the voltage drop between D & A is measured to determine R”.

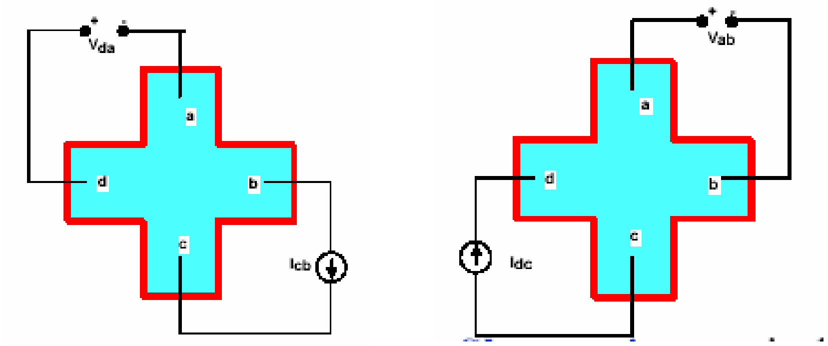
Van der Pauw correction factor



R_r=(R’/R”)

Van der Pauw correction factor F as a function of R_r

Cross-bridge structures

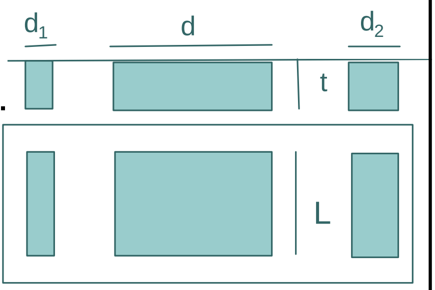


- Using Van der Pauw measurement

$$R_S ? \frac{?}{t} ? \frac{?}{\ln 2} \frac{R_{abcd} ? R_{dabc}}{2}$$

ECD measurement

- Electrical meas. is more precise than physical meas. on feature dimension.
- Measure d, L and sheet rho $R_S(d)$ and then determine d_1 and d_2 by measuring resistance $R(d_1)$ and $R(d_2)$



$R_s(d) = \rho / t$;

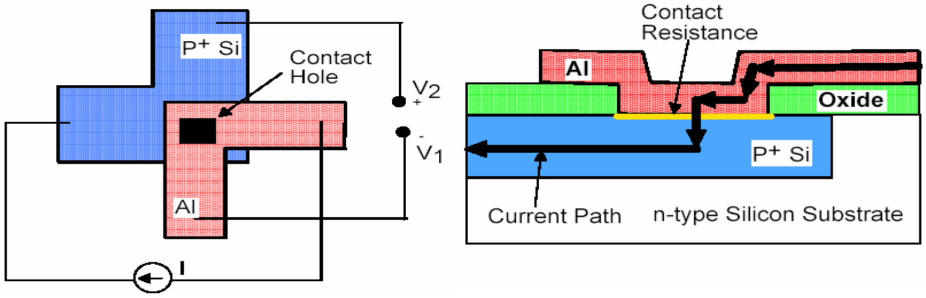
$R(d) = \rho (L/dt) = R_s(L/d)$

$R(d_1) = \rho (L/d_1 t) = R_s(L/d_1)$

$d_1 = R_S L/(R(d_1))$

$d_2 = R_S L/(R(d_2))$

Kelvin structure



- Kelvin structures are used for contact resistance measurement

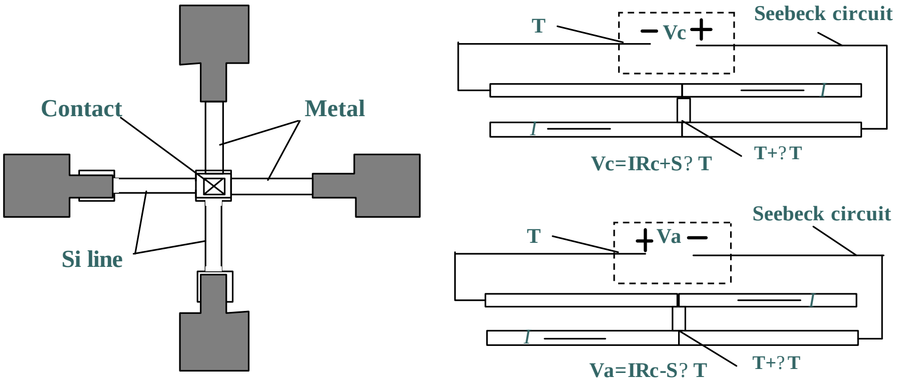
$$R_C ? \frac{V_2 ?V_1}{I} ? \frac{?_C}{A_C}$$

Rc: contact resistance (Ω)

ρ $_c$: specific contact resistance (Ωcm^2)

Ac: contact area (cm^2)

Seebeck effect in contact resistance measurement



$$R_C ? \frac{V_a ? V_C}{2}$$

Hall effect

- Lorentz force drives electrons towards – y
- Hall voltage V_H<0

$$F ? \frac{qV_H}{w} ? qvB ? q\frac{I}{qnwd}B$$

$$n ? \frac{IB}{q|V_H|d}$$

n: carrier conc.

$$? ? \frac{1}{nq?} ? \frac{q|V_H|d}{IB}\frac{1}{q?} \qquad ? ? \frac{|V_H|}{IB}\frac{d}{?} ? \frac{|V_H|}{IBR_S}$$

μ: Hall mobility

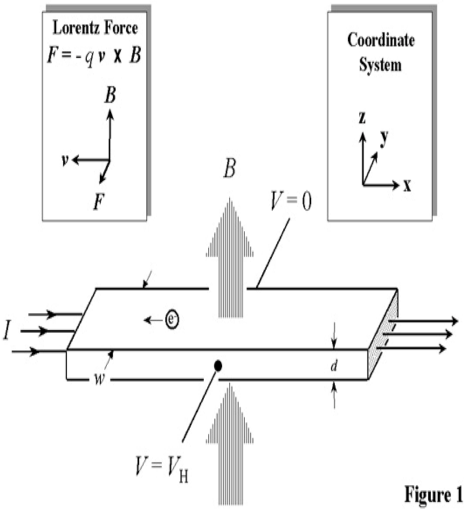


Figure 1

n, μ , R_S measurement using Van der Pauw structure

Hall voltage:

V_H=[V_{24}(B_Z on)-V_{24}($B_Z$off)]

$$n ? \frac{IB}{q|V_H|d}$$

$$? ? \frac{|V_H|}{IB}\frac{d}{?} ? \frac{|V_H|}{IBR_S}$$

$$R_S ? \frac{?}{\ln 2}\frac{(V_{43}/I_{12}) ? (V_{23}/I_{14})}{2}$$

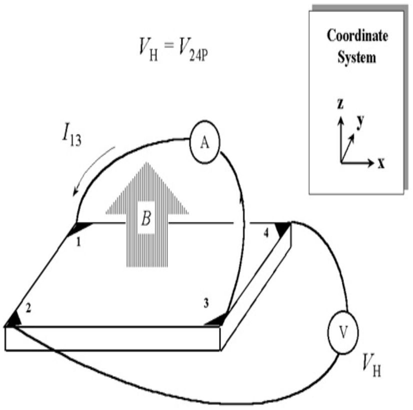


Figure 3