Designing Next-Generation Thermoelectric Materials for Energy Harvesting

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www.energy.hw.ac.uk/docs/**CAESAR**_Leaflet.pdf

Thermoelectric Energy Recovery

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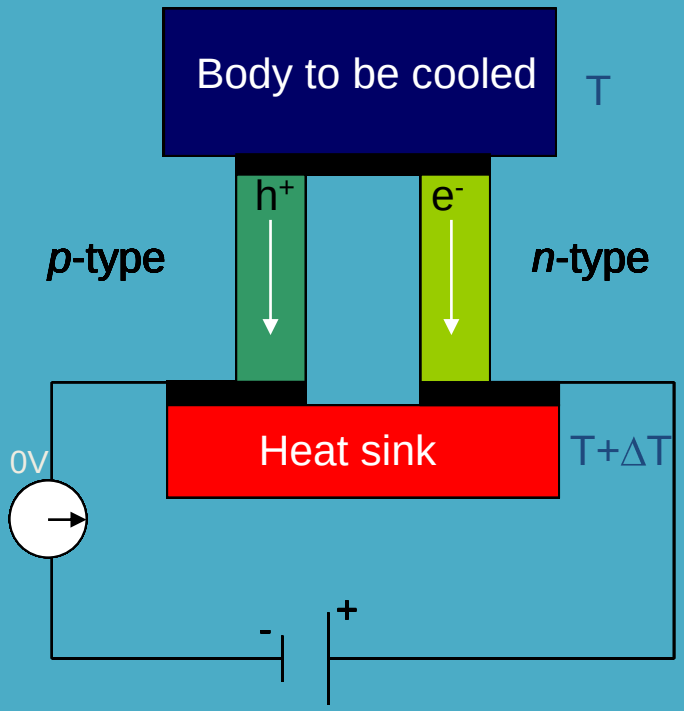
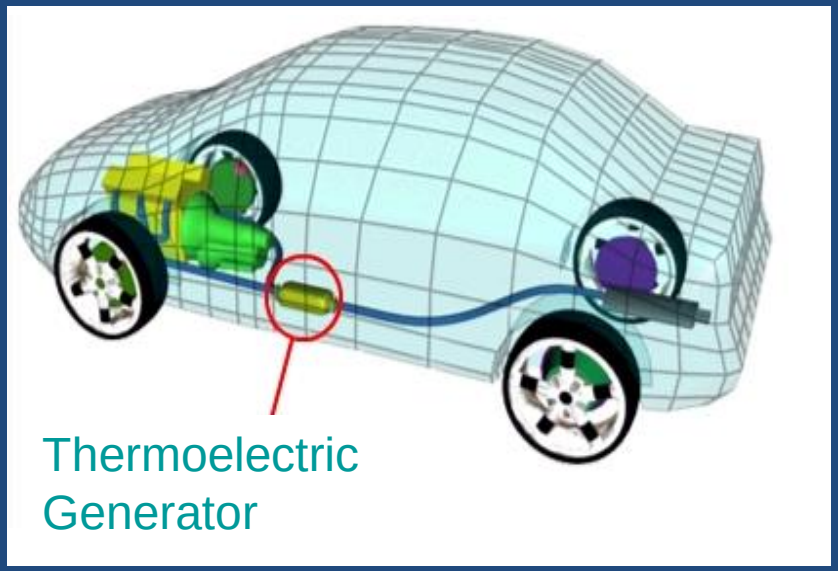
Thermoelectric Couple



Power Generation

- Lightweight and small
- Very reliable

Energy from Waste Heat



Thermoelectric Generator

New car emission standards

160 g CO_2/km (2007)

130 g CO_2/km (2012)

95 g CO_2/km (2020)

Regulation (EC) No 443/2009 (2009)

80% reduction in greenhouse gas emissions(from 1990 levels) by 2050

UK Climate Change Act (2008)

Recent programs:
GM
BMW
VW

} 200 - 600W TEG
ca. 5% Fuel Economy

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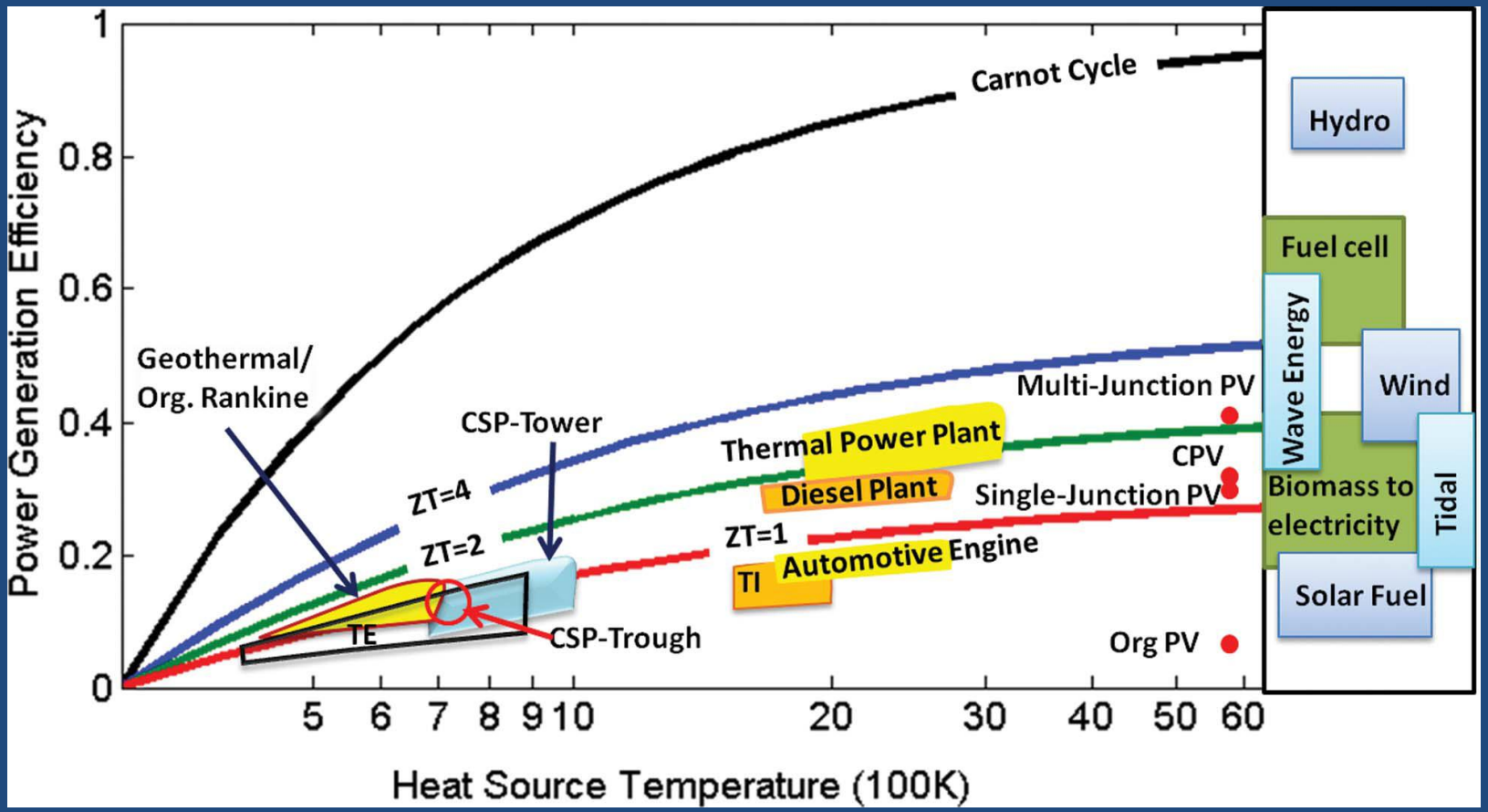
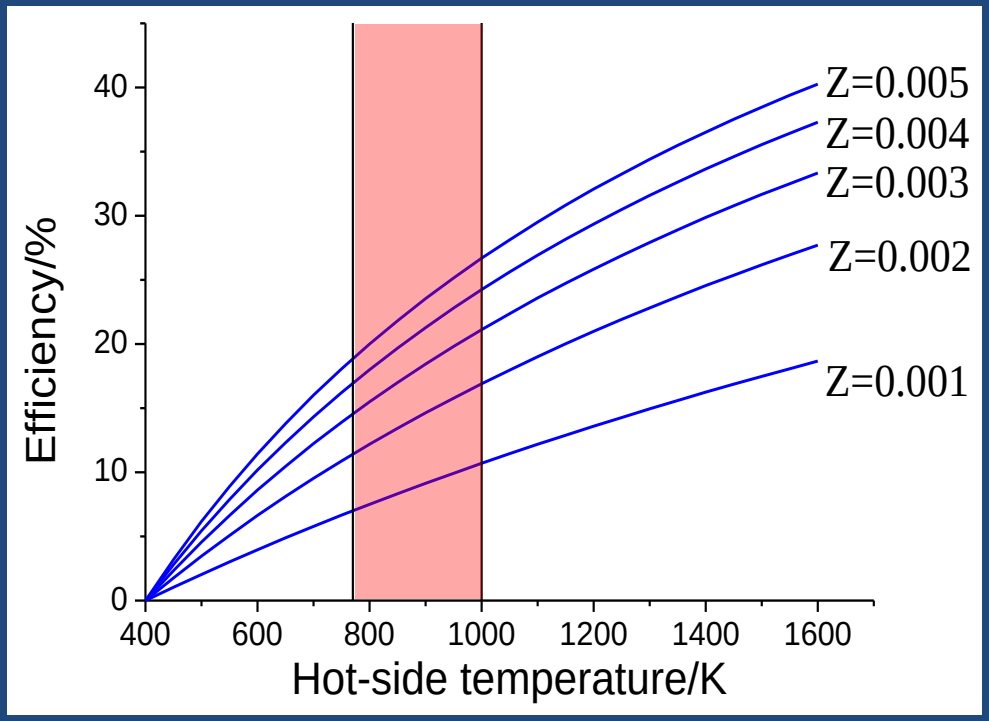
Energy Conversion Technologies

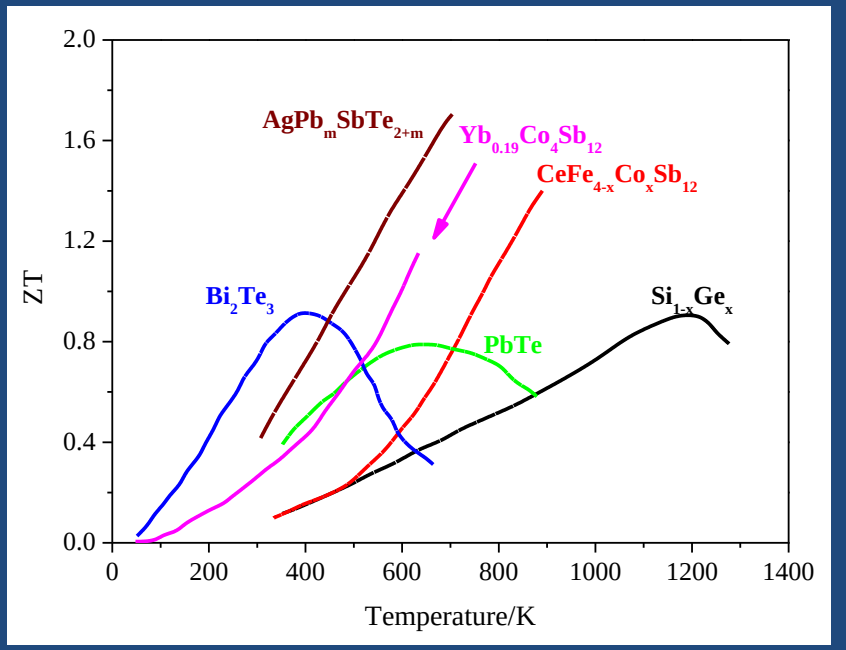


Zebarjadi et al, *Energy Env. Sci.*, **5**, 5147, (2012)

Limitations of Current Materials

Figure of Merit: $$ZT = \frac{S^2 \sigma T}{(\kappa_L + \kappa_e)}$$

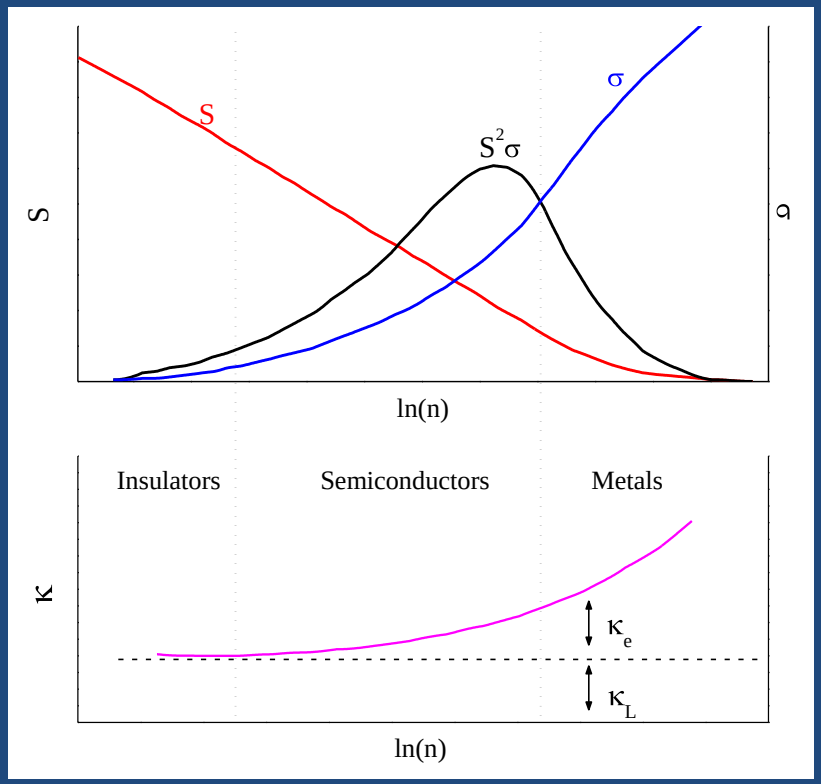




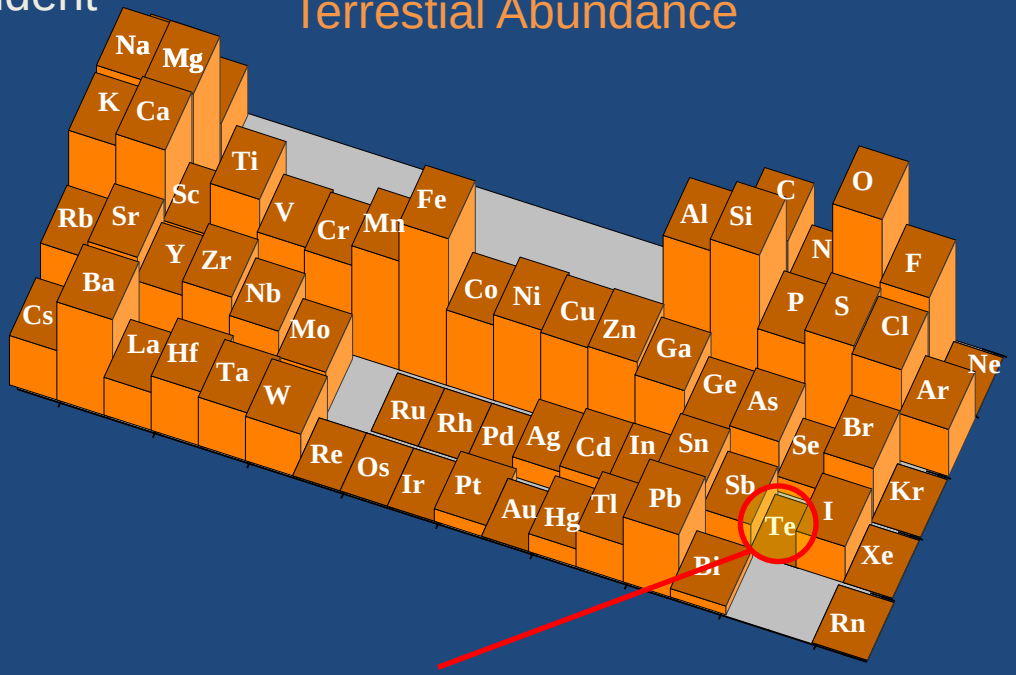
Materials Parameters

Figure of Merit: $$ZT = \frac{S^2 \sigma T}{(\kappa_L + \kappa_e)}$$

- Electrical conductivity (σ), Seebeck (S) and electronic thermal conductivity (κ_e) all inter-dependent



Terrestial Abundance

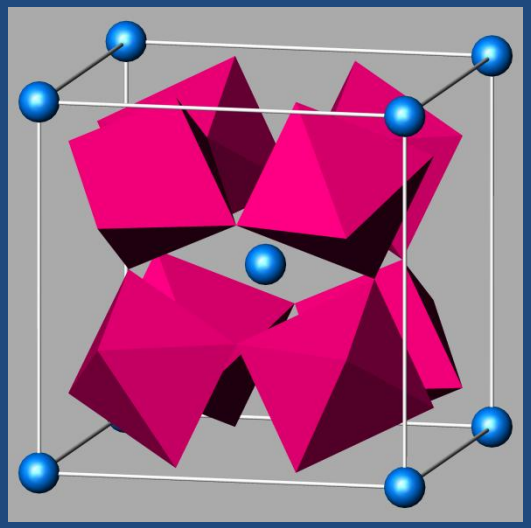


Te: 1 ppb by weight

Requires conduction of electricity like a metal <u>and</u> conduction of heat like an insulator

Materials Design: Phonon Glass Electron Crystal

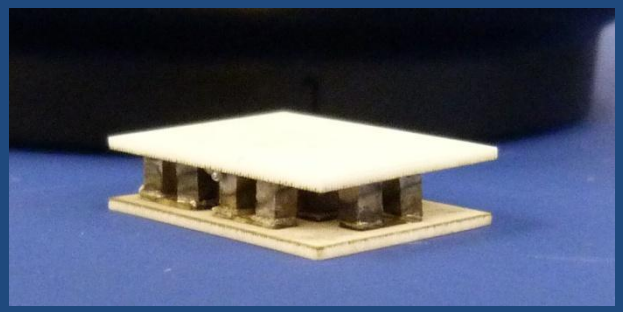
Filled Skutterudites



Rattling vibrations reduce κ_{ph}
$CoSb_3$: 9 $Wm^{-1}K^{-1}$

R(Fe_3CoSb_{12}): 1.2 $Wm^{-1}K^{-1}$

HWU-Cardiff Skutterudite Module
$Yb_xCo_4Sb_{12}$ (*n*-type)
$Ce_xFe_3CoSb_{12}$ (*p*-type)



- 3 W cm^{-3} at $\Delta T \approx 300$ K (T_{cold} = 293 K)
- Compares favourably with Bi_2Te_3

(3 W cm-3 at $\Delta T \approx 100$ K (T_{cold} = 293 K))

Nanostructured Thermoelectrics

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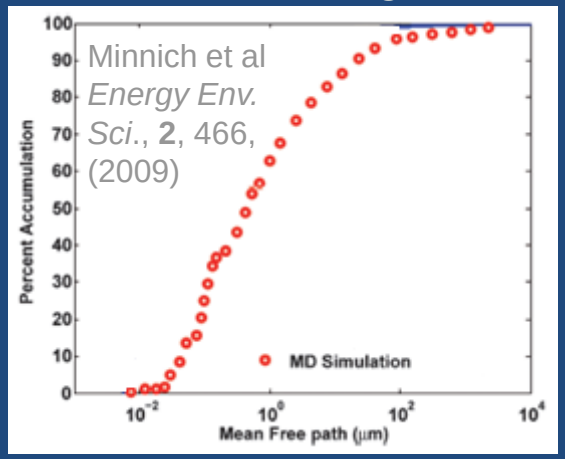
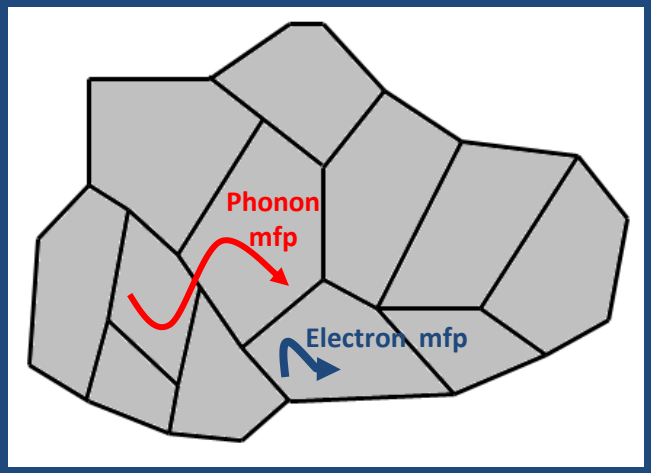
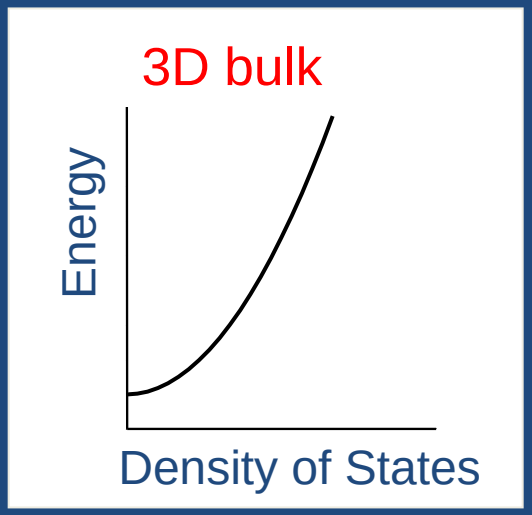
Interface Scattering: Decreases κ_L

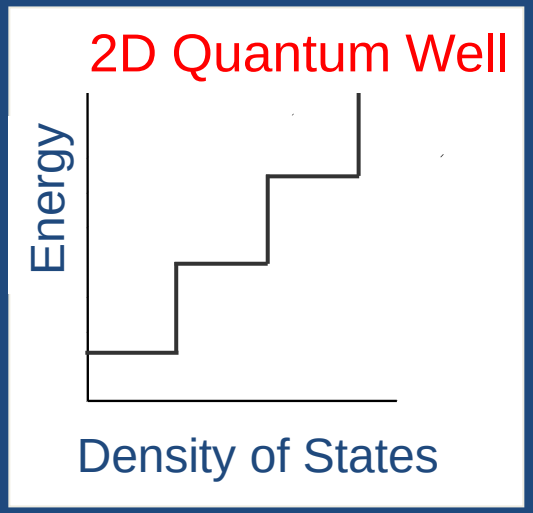


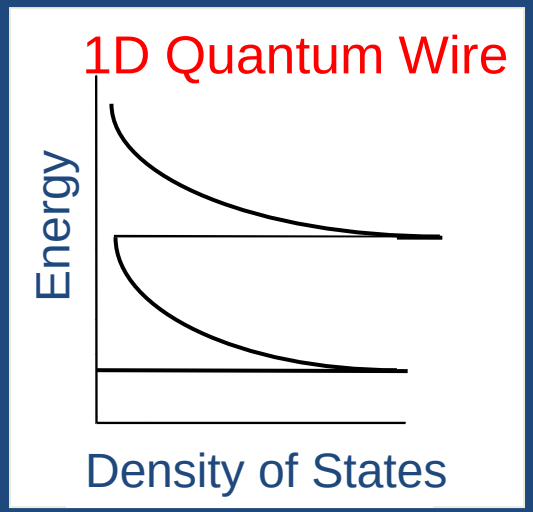


- Interface scattering when mean-free-path > interface spacing

Quantum Confinement: Enhances S







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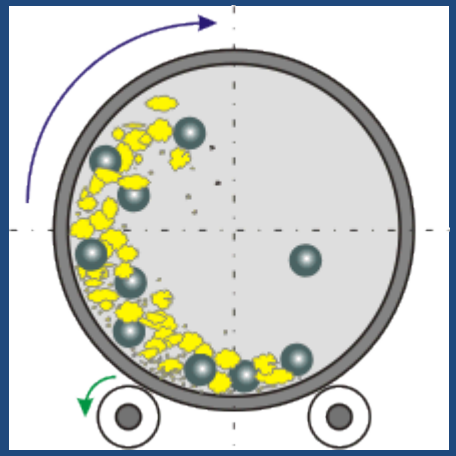
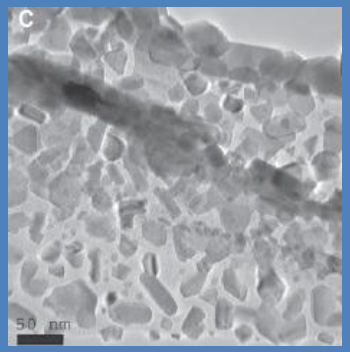
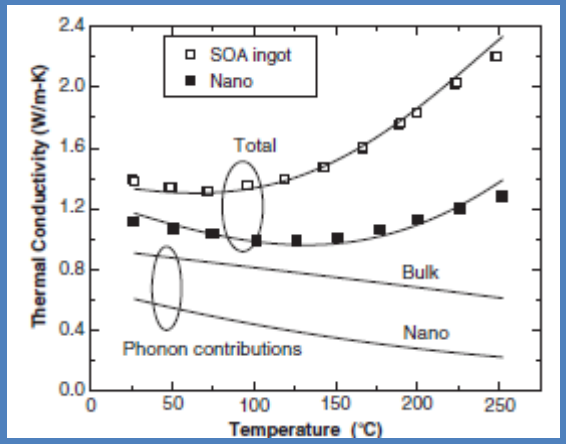
Ball-Milled Thermoelectrics



$(Bi,Sb)_2Te_3$





Poudel et al, *Science*, **320**, 634, (2008)

Material	Bulk		Nanostructured	
	ZT_{max}	Temperature at which ZT_{max} is observed	ZT_{max}	Temperature at which ZT_{max} is observed
Si	0.2	1200	0.7	1200
$Si_{80}Ge_{20}$ (n-type)	1.0	1200	1.3	1173
$Si_{80}Ge_{20}$ (p-type)	0.7	1200	0.95	1073
$(Bi,Sb)_2Te_3$	0.9	293	1.4	373
$CoSb_3$	0.45	700	0.71	700

Vaqueiro and Powell, *J. Mater. Chem.* , **20**, 9577, (2010)

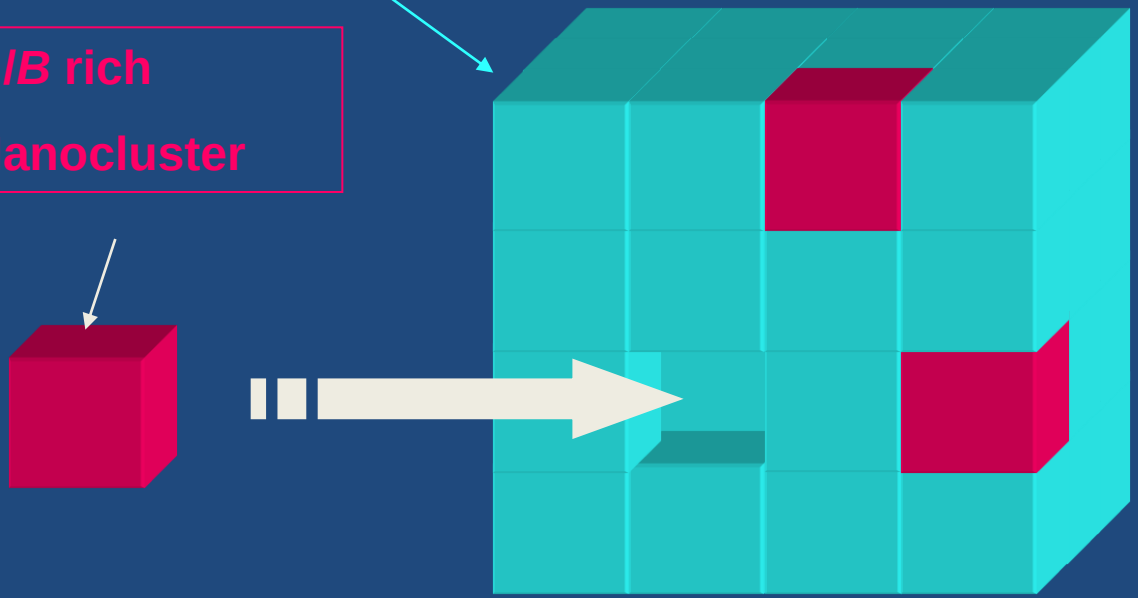
Nanoinclusions in *LAST*-type Phases

APb_mBTe_{m+2}

- Degenerate semiconductors
- Nanoinclusions
- Thermal conductivity reduced from PbTe

Pb rich matrix

***AlB* rich Nanocluster**



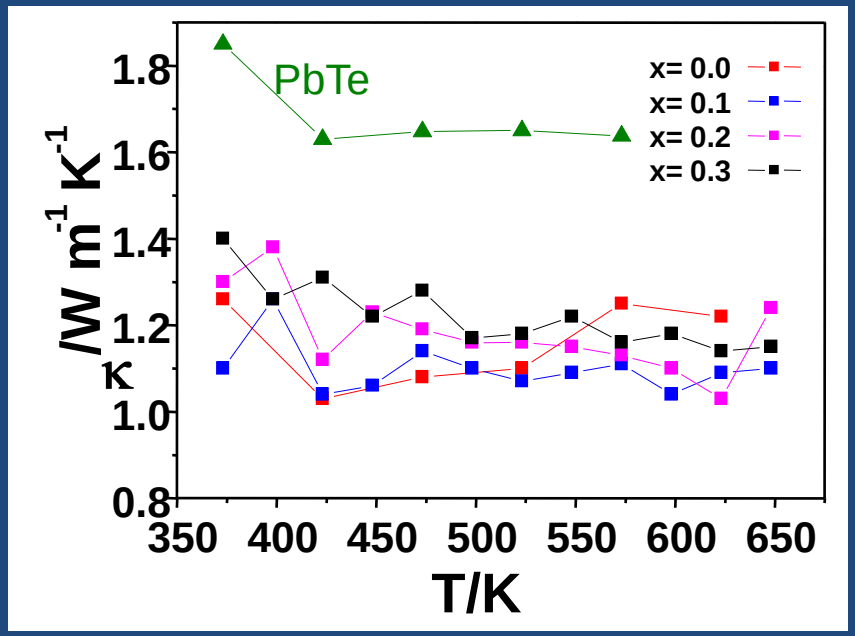
LAST=18

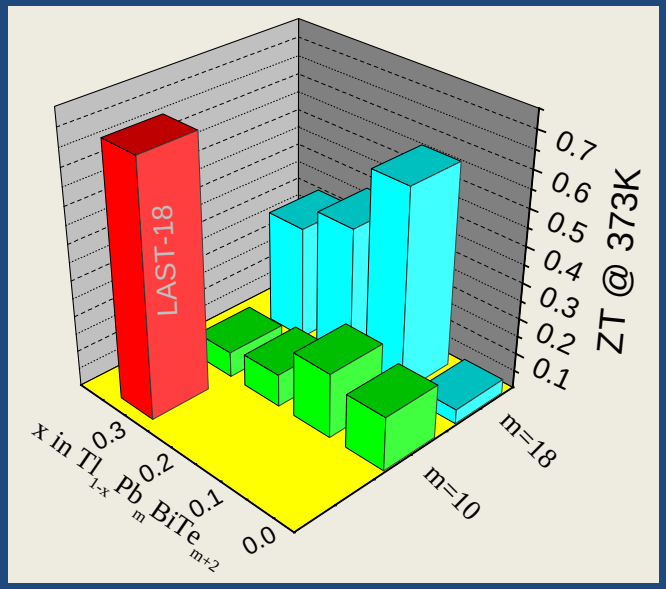
- *n*-type conduction
- ZT_{max} = 2.2 at 800K
- Silver deficient

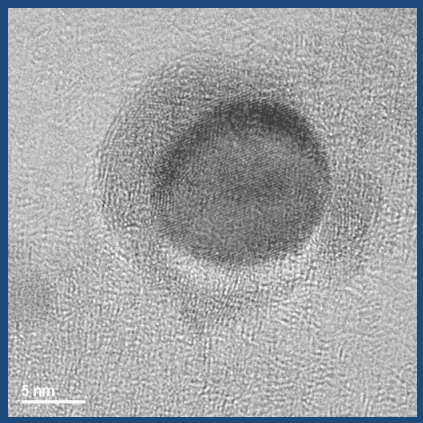
Hsu et al, *Science*, **303**, 818, (2004)

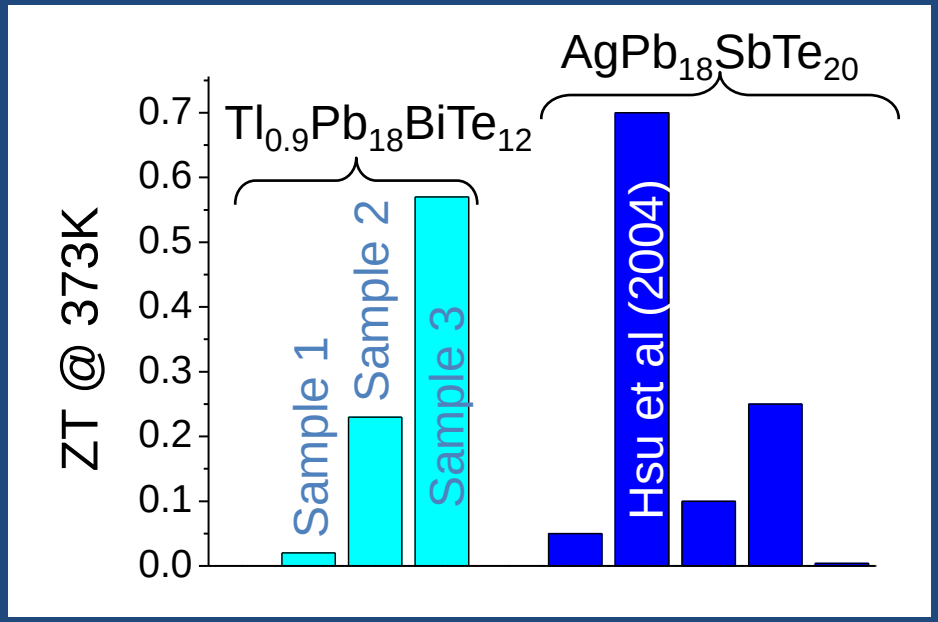
$Tl_{1-x}Pb_mBiTe_{m+2}$

$Tl_{1-x}Pb_{18}BiTe_{20}$



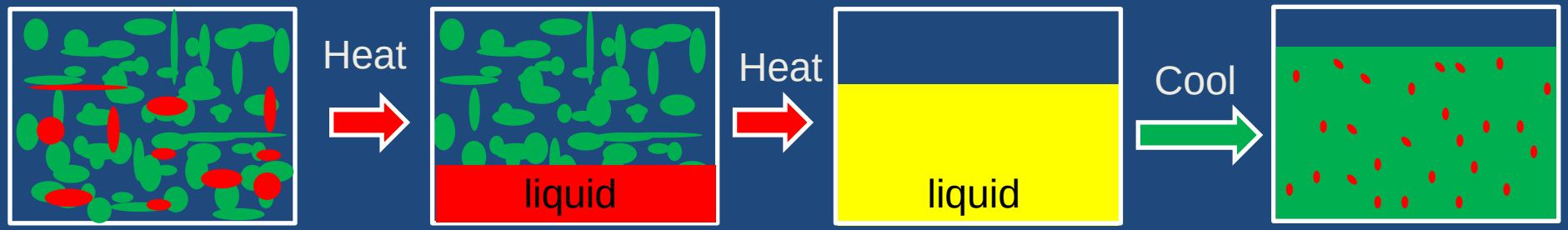






Nanocomposite Materials

Matrix Encapsulation



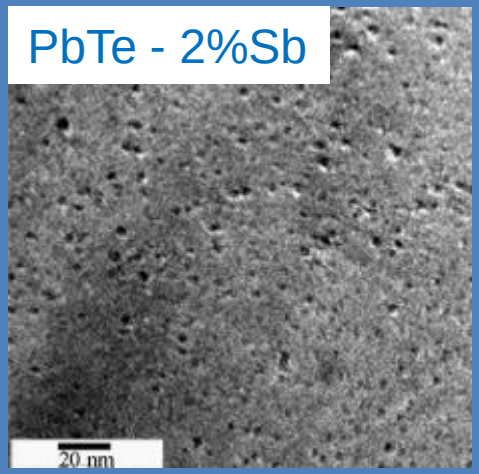
Solid *A* and solid *B*

A melts

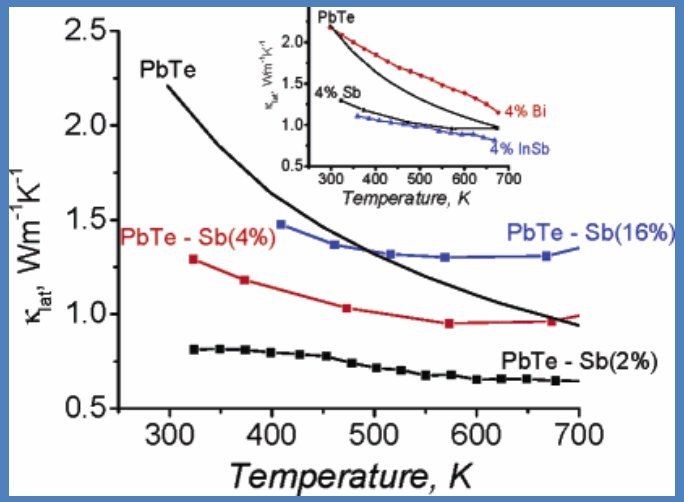
B melts, *A* dissolves in liquid *B*

B solidifies, *A* insoluble in solid *B*, so precipitates

PbTe - 2%Sb



k_L = 0.8 W m^{-1} K^{-1}



Sootsman *et al*, *Chem. Mater.*, **18**, 4994, (2006)

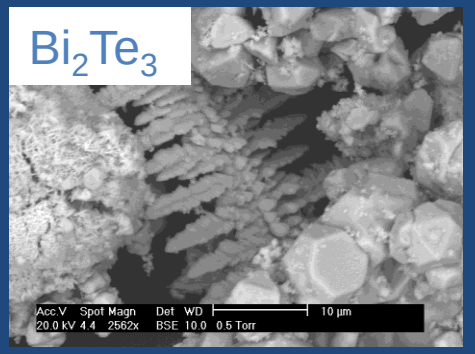
Solvothermal Growth of Nanoparticulate Thermoelectrics

Metal Salts,
Reducing agent
Solvent,
'Template
Molecule'

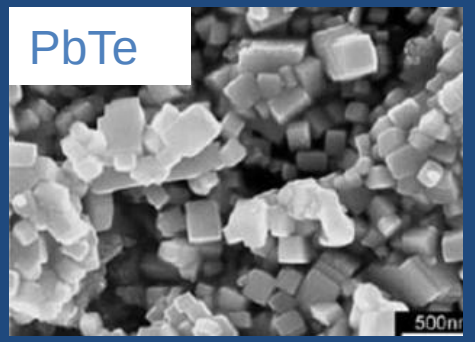
$T > T_{b.p.}$

$P \leq 200$ bar

Bi_2Te_3

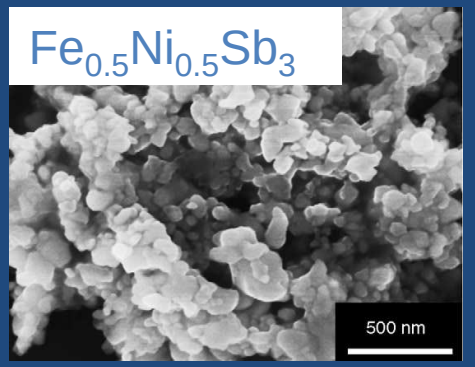


PbTe



Ji *et al*. *J. Electron Mater.*, **36**, 271, (2007)

$Fe_{0.5}Ni_{0.5}Sb_3$



Mi *et al*. *JALCOM*, **399**, 260, (2005)

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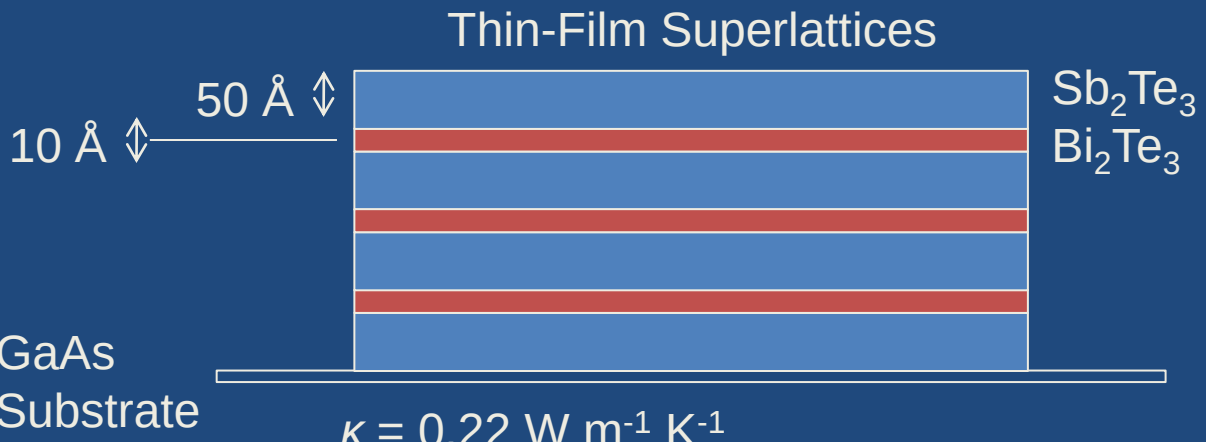
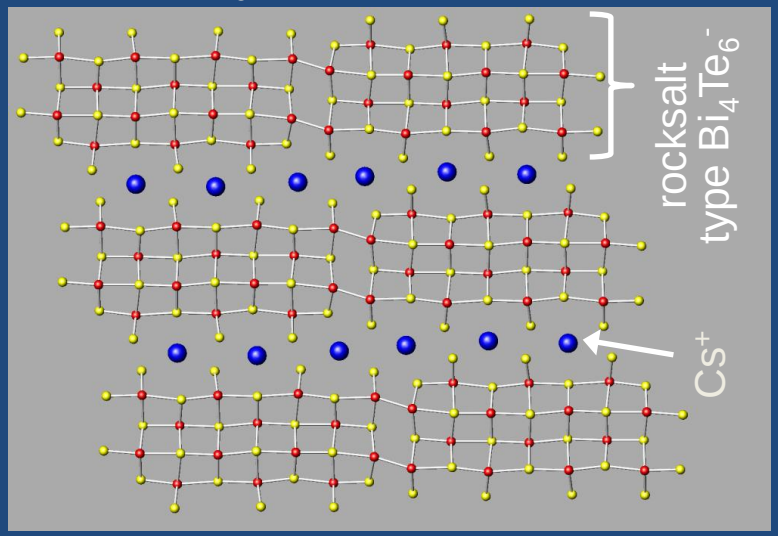
Superlattices and Layered Materials



κ = 0.22 W m^{-1} K^{-1}

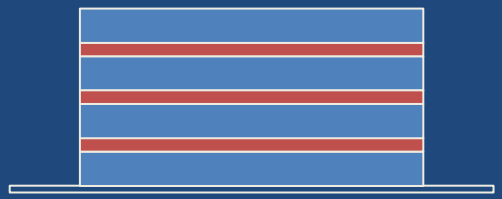
ZT = 2.4 @ 330 K Venkatasubramanian et al, *Nature*, **413**, 597, (2001)

$CsBi_4Te_6$: ZT = 0.8 @ 225 K

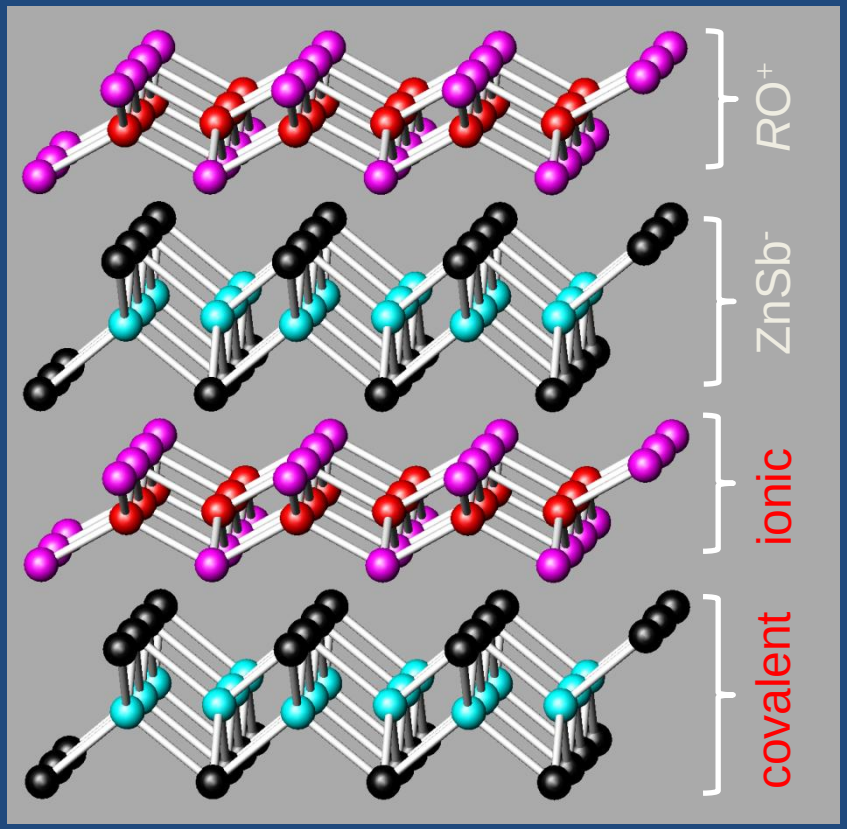


Chung *et al*, *JACS*, **126**, 6414, (2004)

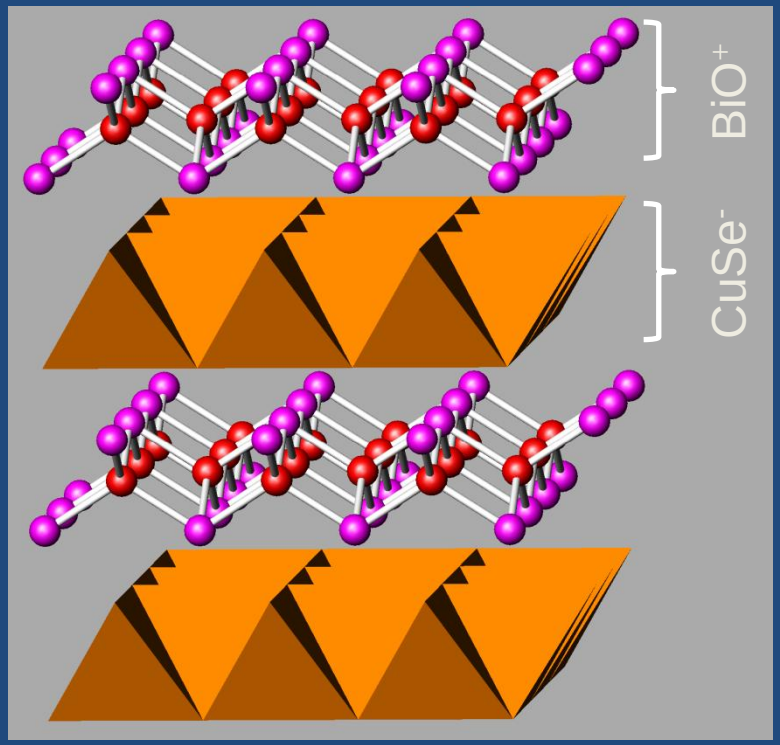
Layered Materials



*R*OZnSb

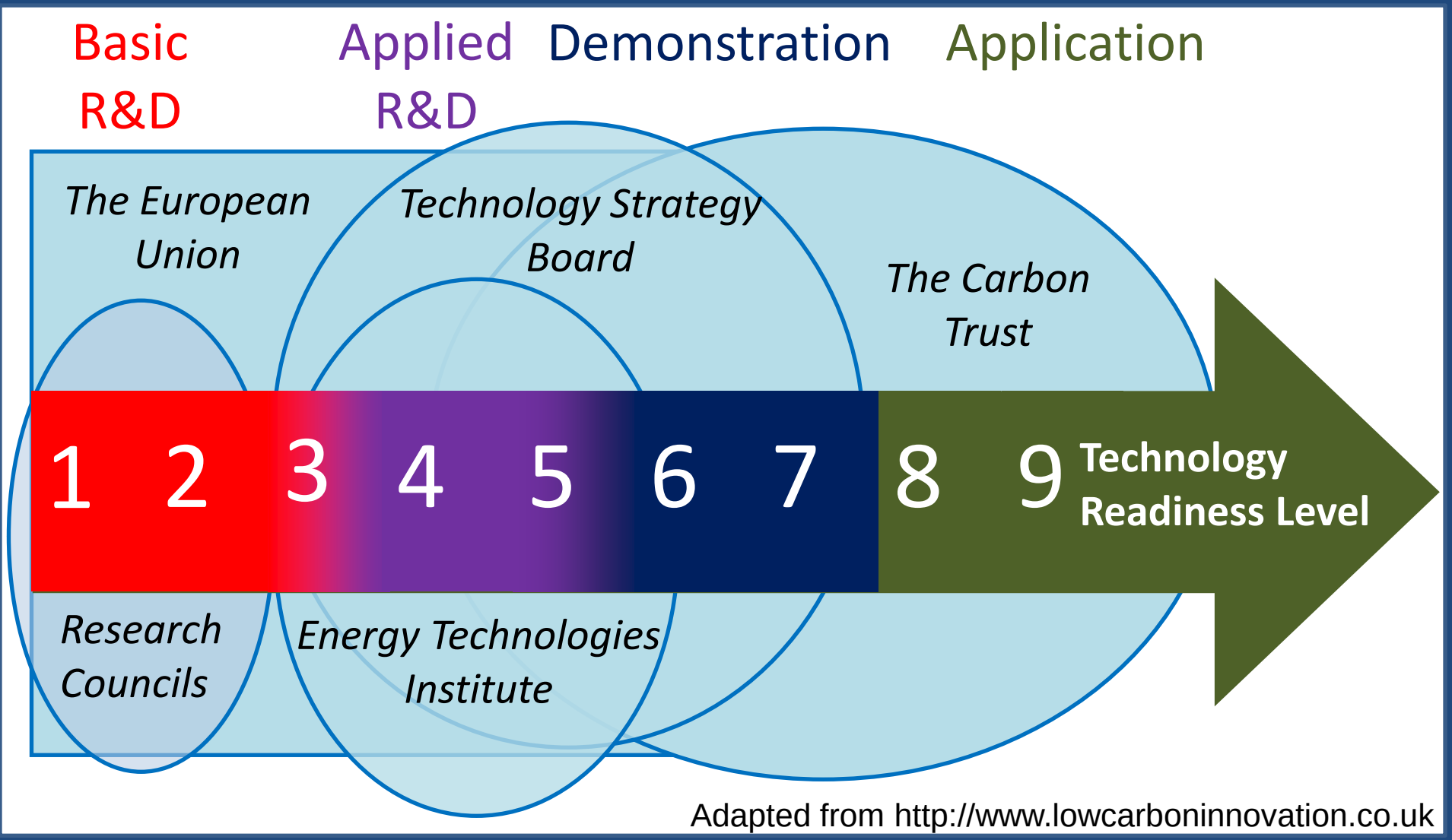


BiOCuSe



- Independent optimisation of $S^2\sigma$ (covalent) and κ_L (ionic)

Pathways to Innovation



Adapted from http://www.lowcarboninnovation.co.uk

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