Nanoscale Thermoelectric Materials and Devices

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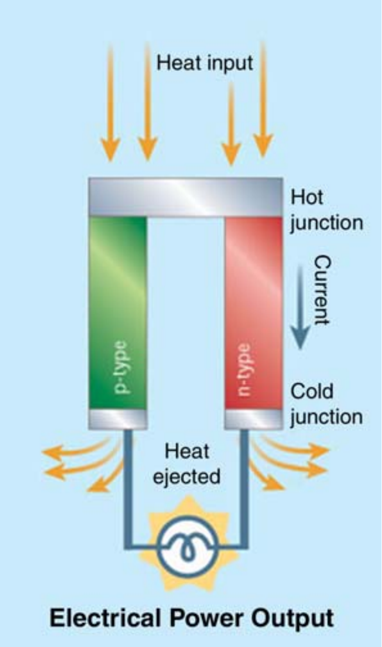
Outline

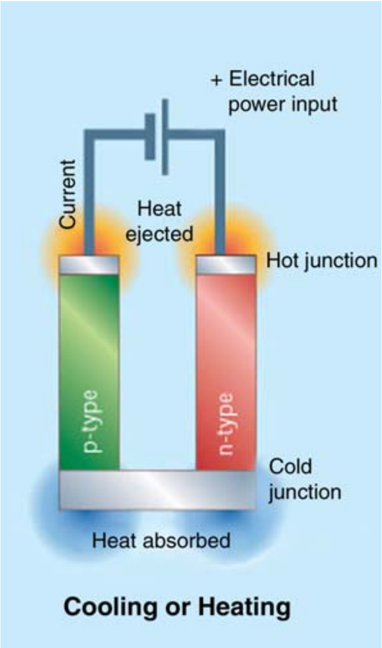
- Recent News on Ozone Depletion and Climate Change
  - Need alternate refrigeration and air-conditioning technologies
- Nearly 60% of the world's useful energy is wasted as heat – in automobiles, several process industries like aluminum, glass, etc.
  - Recovery of even a fraction of this heat by converting to useful electric power can be big for energy efficiency and pollution reduction
- Thermoelectrics
- Nanoscale Thermoelectric Materials – advantages & benefits
  - Site-specific Cooling from electronics to automobiles
  - Energy Harvesting
  - 1/40,00th Materials Usage compared to conventional thermoelectrics- less materials to produce, life-cycle thinking

Recent News

- MONTREAL, Quebec, Canada, September 22, 2007
- Historic Agreement Safeguards Both Climate and Ozone Layer
  In an unprecedented agreement, industrialized and developing countries have decided to accelerate the phase out of coolant chemicals that are harmful to the ozone layer
- The agreement is unique in that it focuses on ozone recovery and also aims to reverse climate change, a benefit that was not foreseen in earlier understandings of how the stratospheric ozone layer relates to the planet's temperature and climate.
- Didier Coulomb of the International Institute of Refrigeration told delegates that environmentally friendly refrigerants have been developed
  - Alternative cooling technologies such as thermoelectrics, thermoacoustics, acoustic compression, magnetic cooling, and gas cycles such as the Stirling cycle open up more possibilities

Thermoelectrics

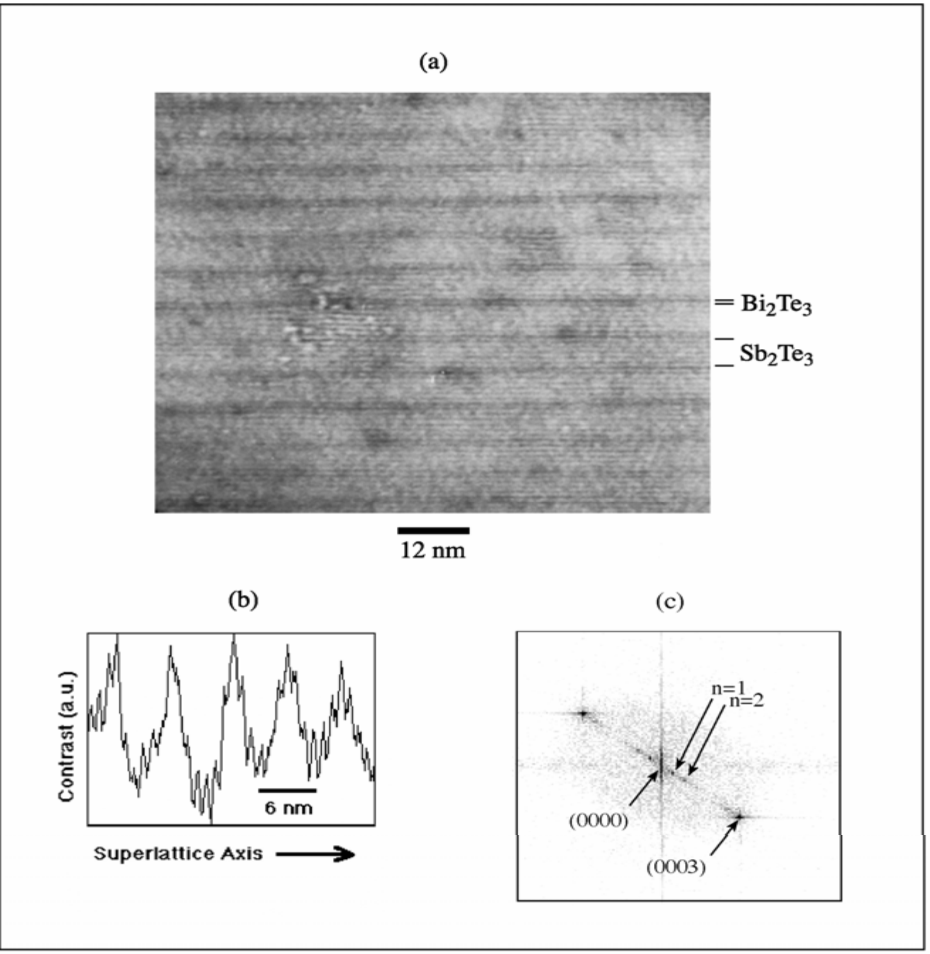


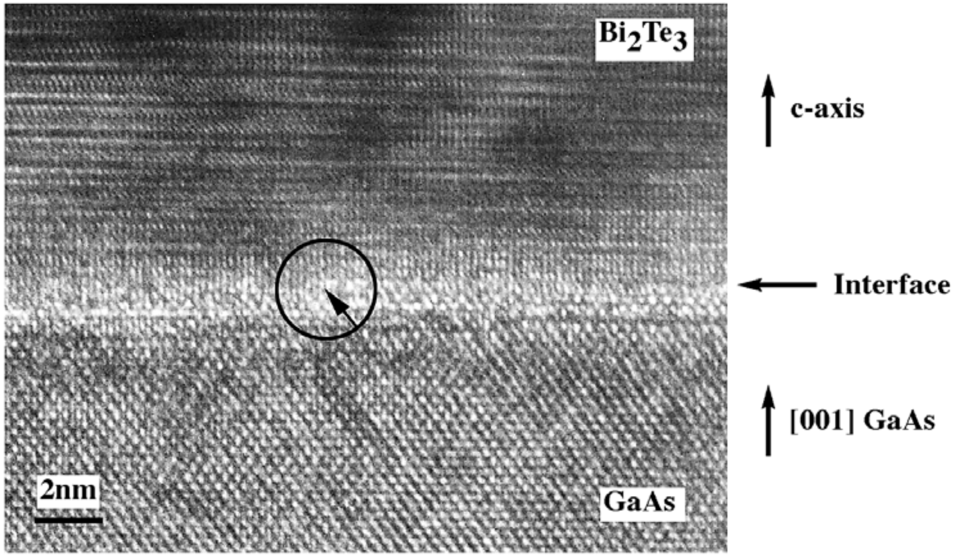


$$ZT = (\alpha^2 \sigma T/k)$$

- **Solid-State Technology**
  - **Solid-state Reliability**
  - **No Moving Parts**
  - **Vibration/Noise free**
  - **CFC-free**
- **Heat or Cool**
- **Power Generation from heat sources**
- **Thermal control functions**
- **Figure of merit (ZT) of materials decide performance to a large extent**
  - **Need low thermal conductivity (k)**
  - **Need high electrical conductivity (s)**
- **How do we do this in conventional materials?**
  - **Dilemma until DoD turned looking at nano-scale approaches in 1992**

1nm/5 nm periodic structured material characterized by TEM and Fast Fourier Transform Image Analysis





<110> GaAs zone axis

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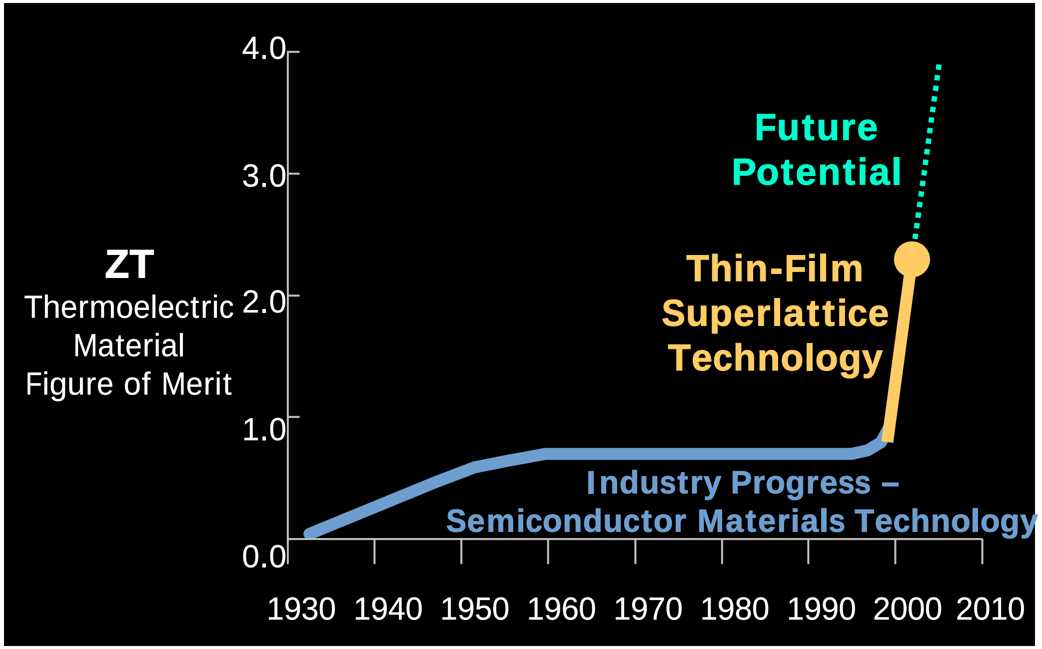
Material >2x Improvement in Intrinsic Figure of Merit (ZT)

$$ZT = \frac{S^2 T}{\rho\, k}$$

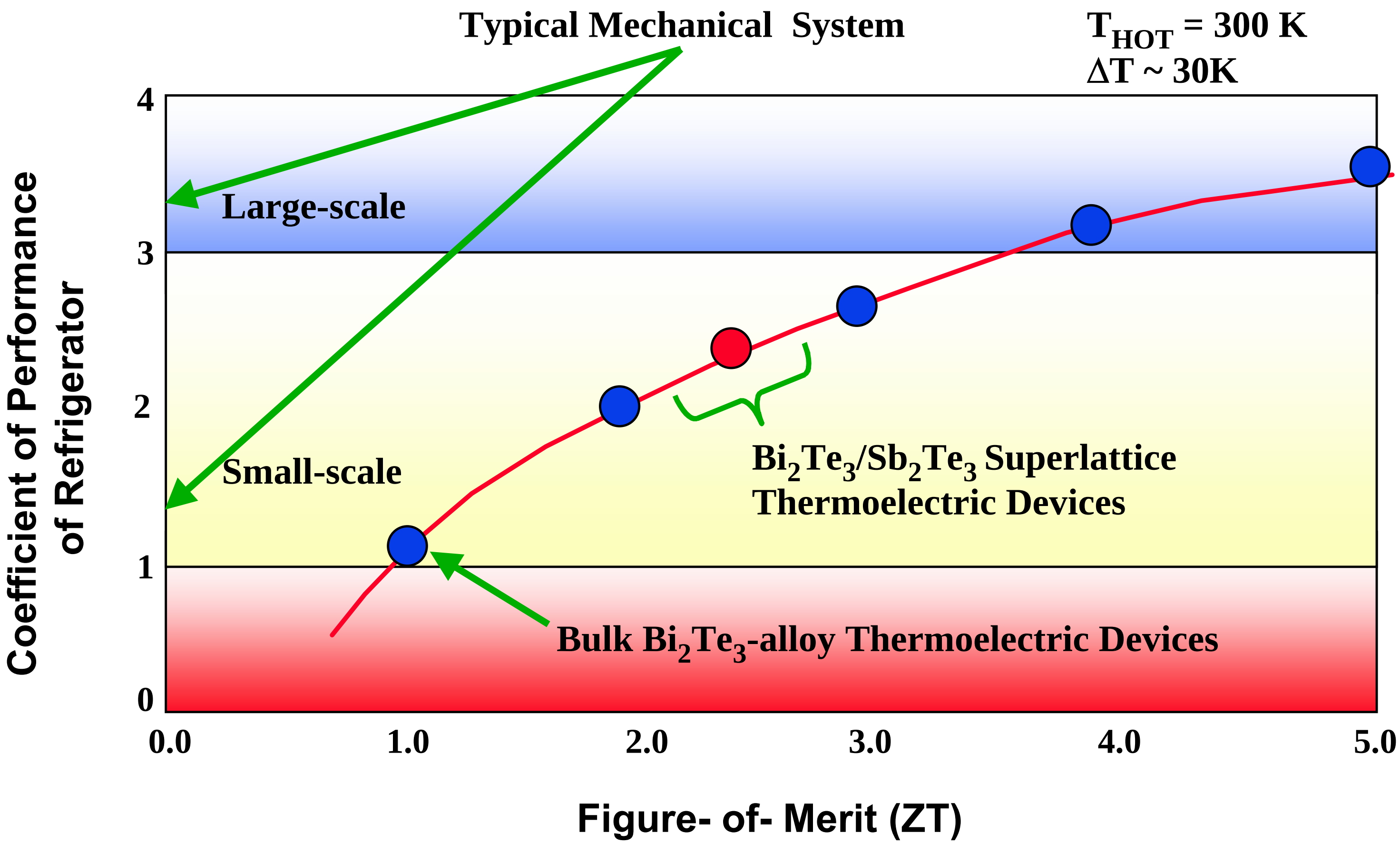


S = Seebeck coefficient
T = temperature

Nature, 413, 597-602 (2001)

Superlattice thin-film material reduces thermal conductivity (k) and improves electronic transport (lower ρ)

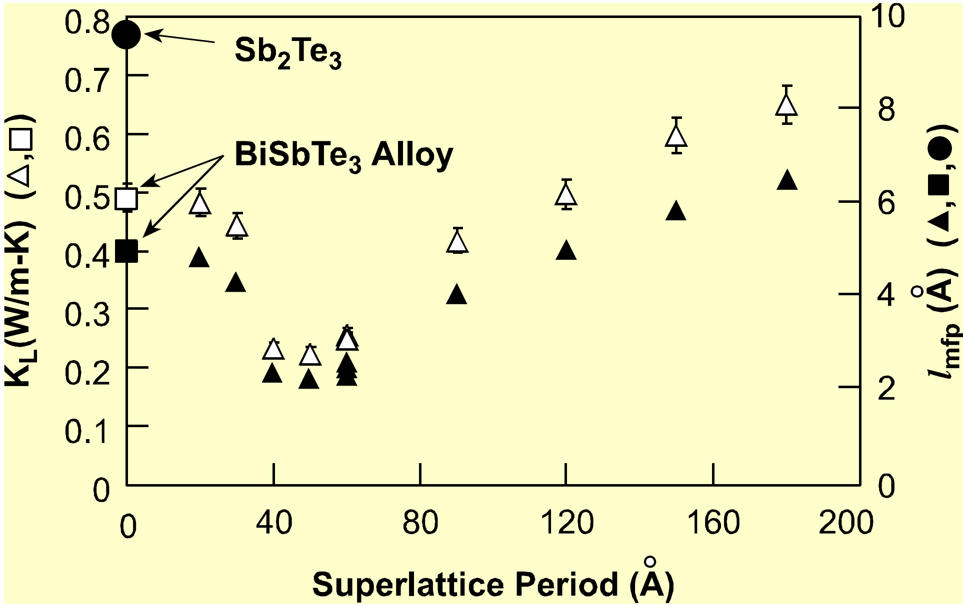
Potential Impact of ZT on Solid State Cooling Efficiency



Nature, vol. 413, Oct. 10, 2001

Nano-scale Materials to Increase ZT

- **Epitaxially grown Bi_2Te_3/Sb_2Te_3 Superlattices (RTI)**
  - **Thermal conductivity reduction with superlattices**
  - **Phonon blocking without hindering electron transport leading to ZT~2.4 at 300K (*Nature* 413, 2001)**

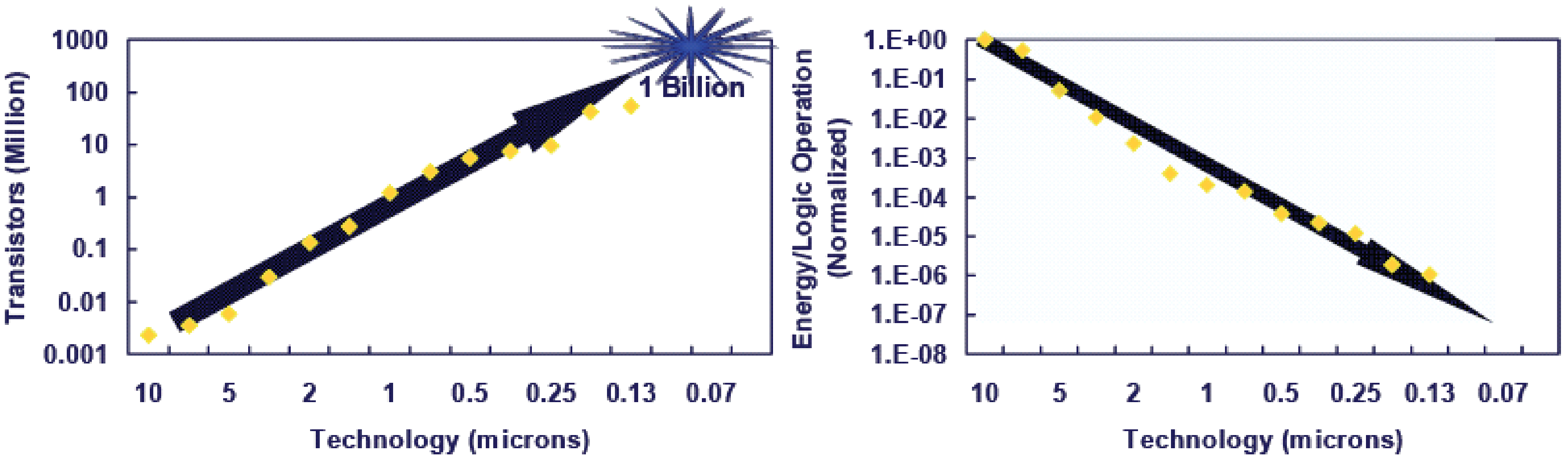


- **Epitaxially PbTe/PbTeSe Quantum-dots (MIT Lincoln)**
  - **Thermal conductivity reduction leading to ZT~ 1.6 at 300K (*Science* 297, 2002)**
- **ErAs nanoparticles in InGaAs alloy (UCSB, UCB, UCSC)**
  - **Thermal conductivity less than solid solution alloy by x2 (PRL 96, 2006)**

How can these nano-materials help immediately?

- Cooling problems in computer industry
- Energy consumption costs are becoming comparable or more than computational equipment capital costs
- Cooling in large data centers determine their design and their operational costs

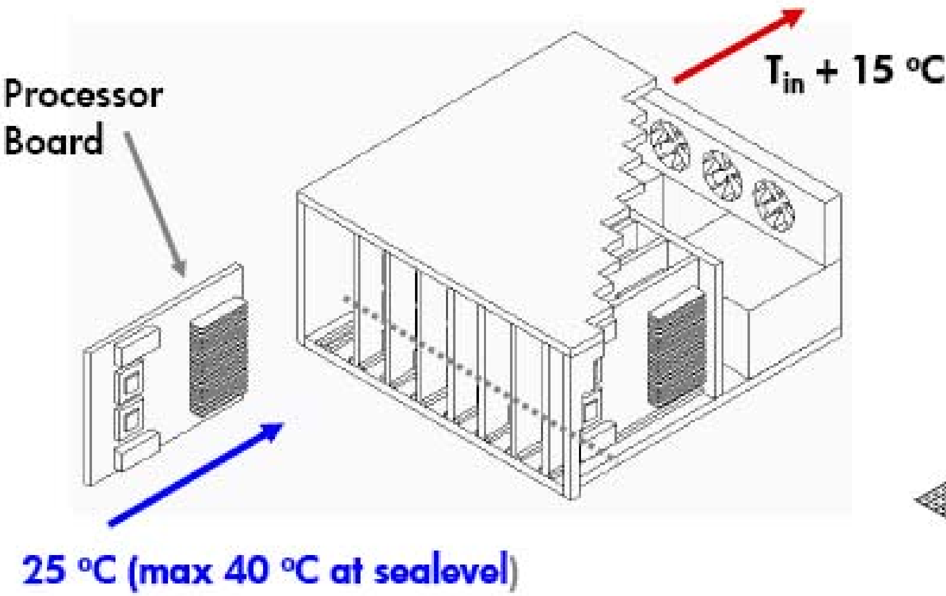
Electronic Chip Industry Facing End of Moore's Law

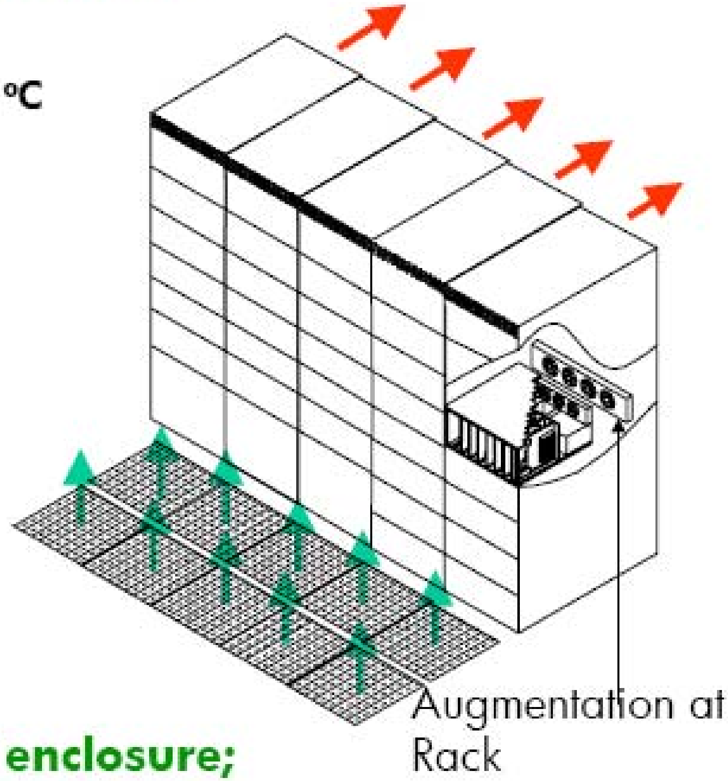


- **Delivering power and removing heat are serious problems**
  - **Multi-core chips have bought time over the next few years**
  - **Thermal Problems have to be addressed to keep the electronic chip industry alive for the long haul**

Servers

Tens of millions of servers

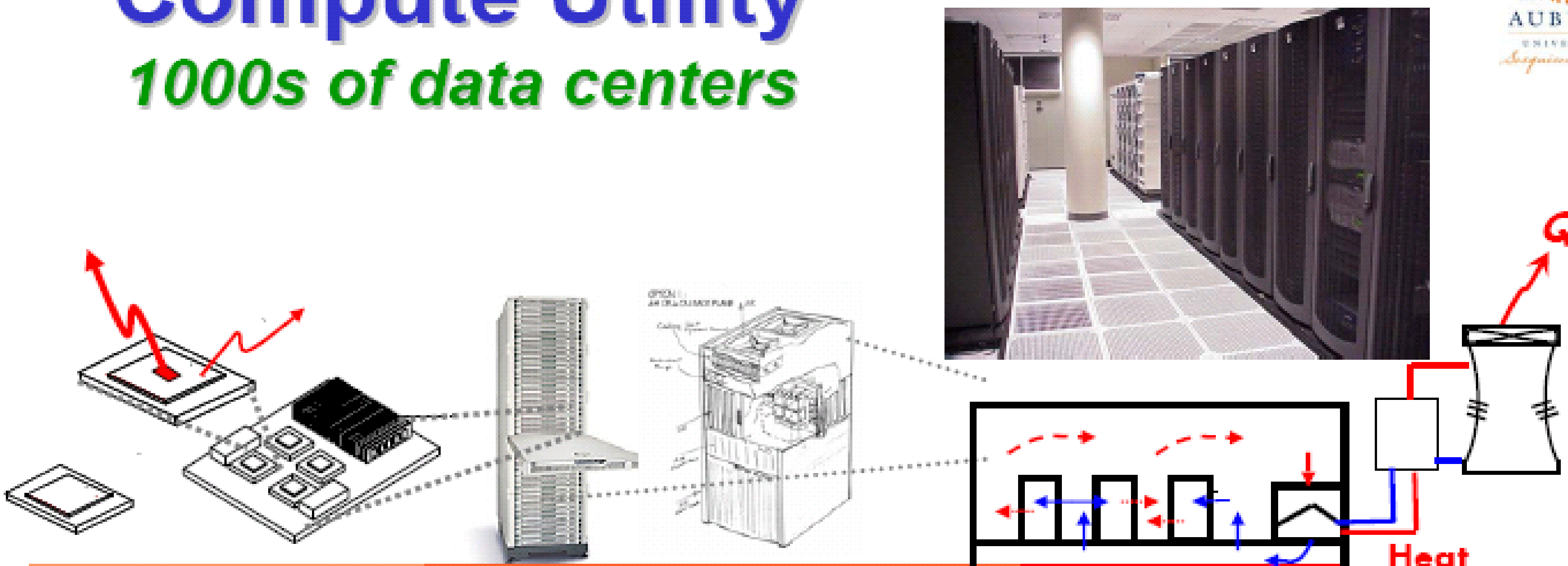




- Single Board Computer: 250 W
- 10X boards per chassis makes a 2.5 KW enclosure;
- Flowrate ~ 150 litres/sec High pressure drop 150 Pa to 200 Pa
- 200 W Fan power
- 6 enclosures per rack; 15 KW rack, 900 litres/sec (~1800 CFM) minimum flow rate

Compute Utility

1000s of data centers



5 W	100 W	15 KW	20 KW	1 MW	Heat Generated
	10-30 W	1.5KW	2KW	.1MW	Energy to Remove Heat

Accessing Services →

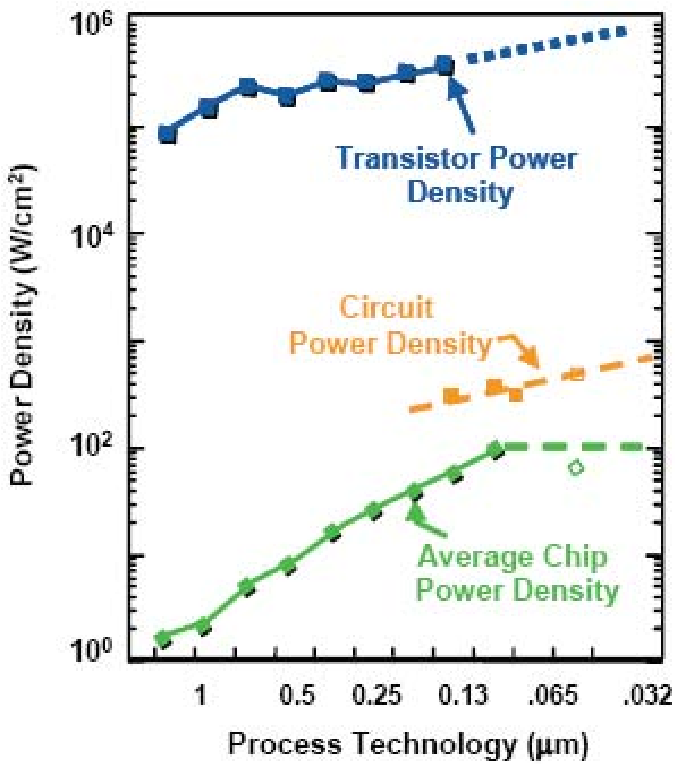
Thin Client Accessing Data Center →

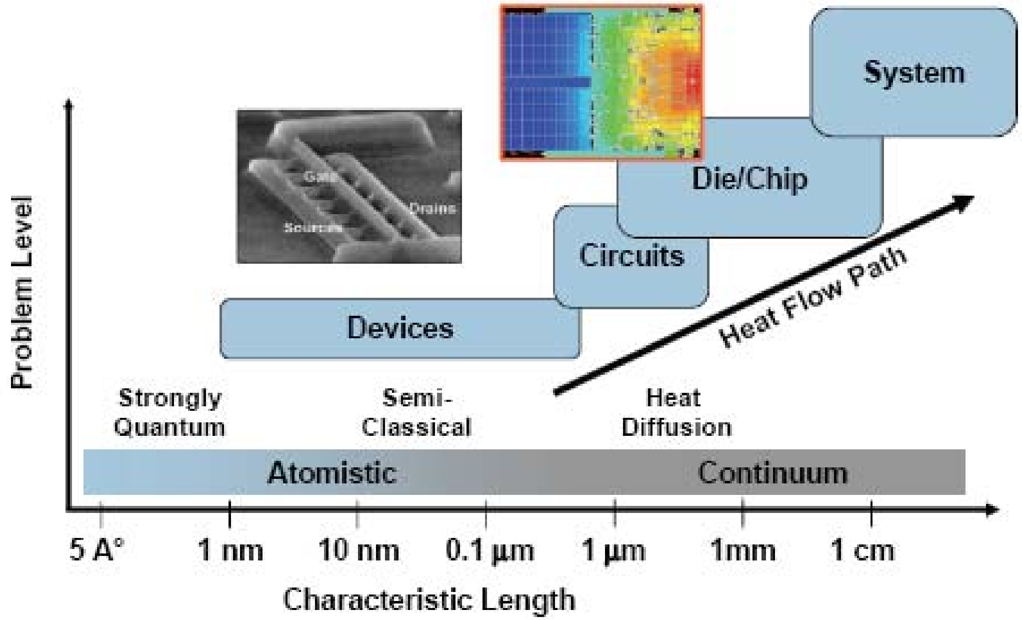
10 + 2 GW	40 + 7 GW	*Global Power Consumption*	3+3 GW	Heat Generated + Energy to Remove Heat

Annualized Destruction of Available Resources – Coal — **25 million metric tons**

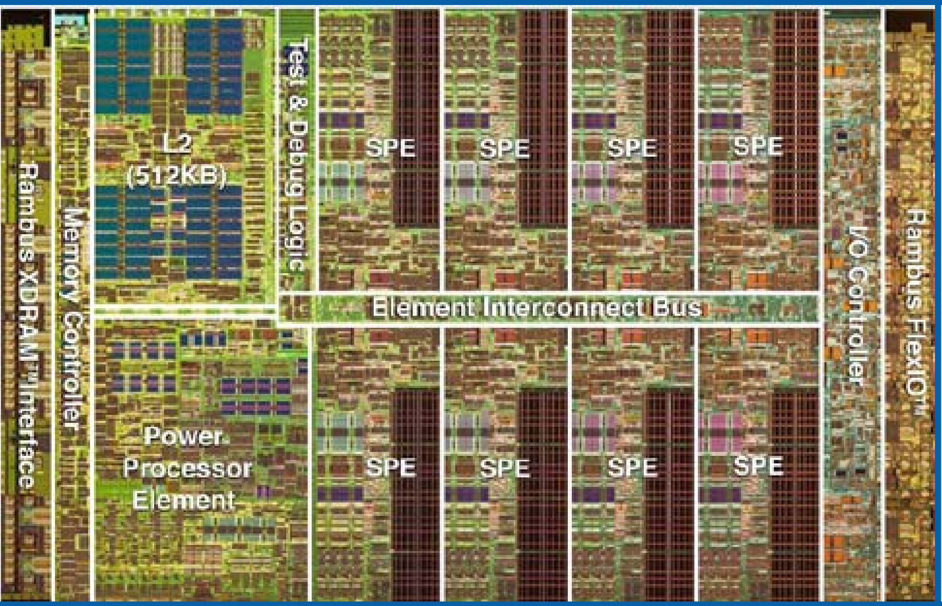
Flow Work + Thermodynamic Work

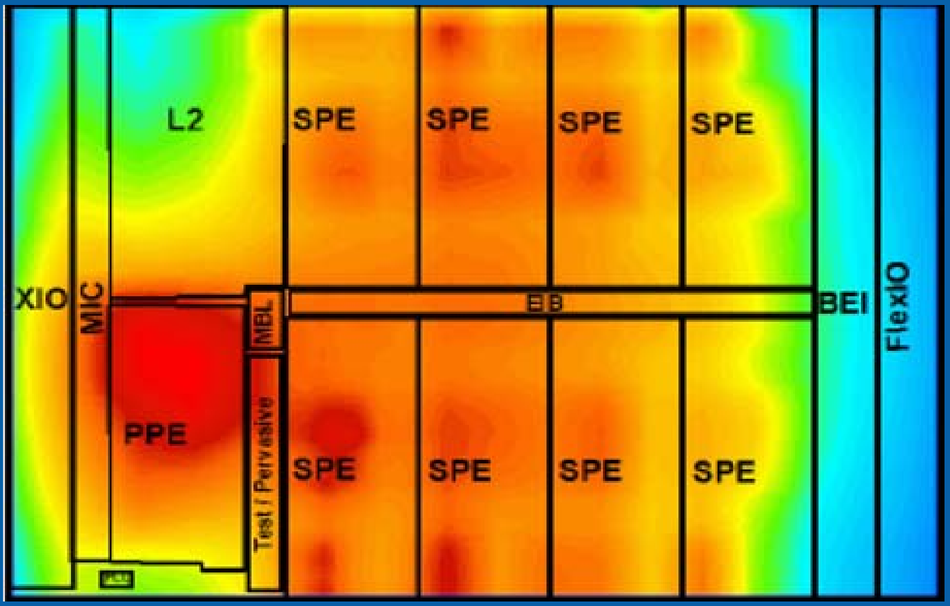
Chip Power Densities (Ref: Intel, 2007)





Hot Spots on IC Die Constrain Performance



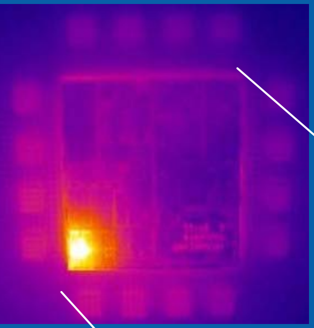


Die Layout

Temperature Map

IBM Cell Processor
Thermally Constrained to 3 GHz (Versus 4 – 5 GHz Target)

Micro vs. Macro Active Cooling



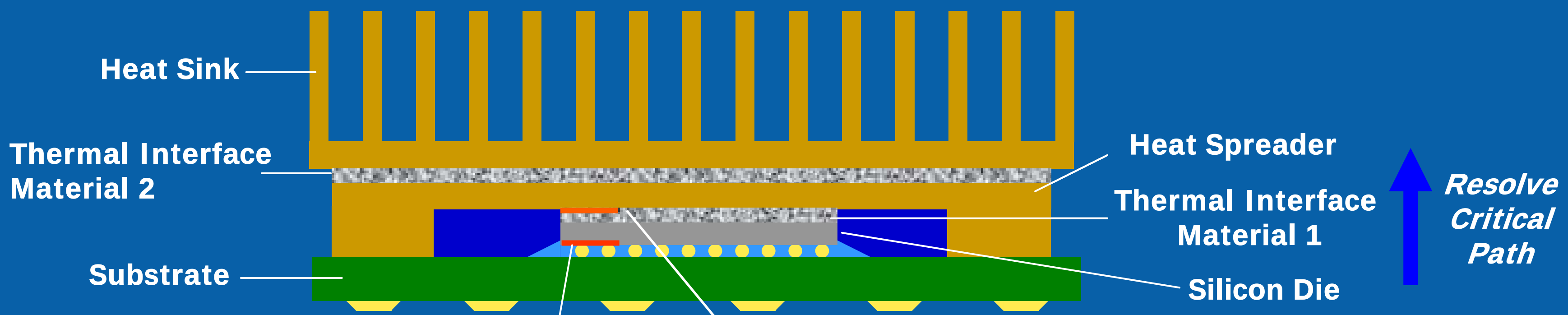
	Heat Profile		Cooling Profile	Resulting Thermal Profile	Thermal Load at Heat-sink
Micro Cooling	100W / 3W	+	3^{+} W		= 106^{+} W
Macro Cooling	100W / 3W	+	103W		= 206W

Hot-spot

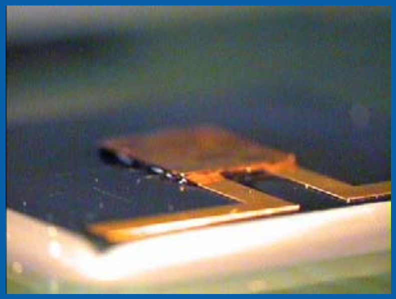
hot — cold

- Model assumes COP of 1 for Active Cooling, independent of ΔT
- Some pumping of background by the spot-cooler

Embedded Thermoelectric Cooler Smoothes Out Hot Spots on ICs to Increase Chip Performance



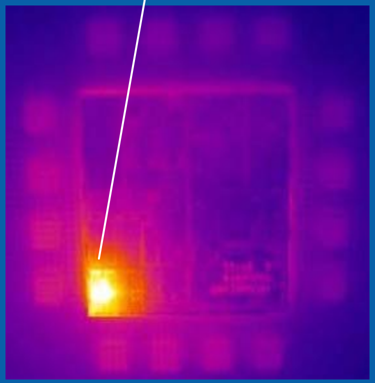
RTI's early solution



100 μm thickness

Hot spots effect

- Reliability
- Performance
- Yield
- Cost

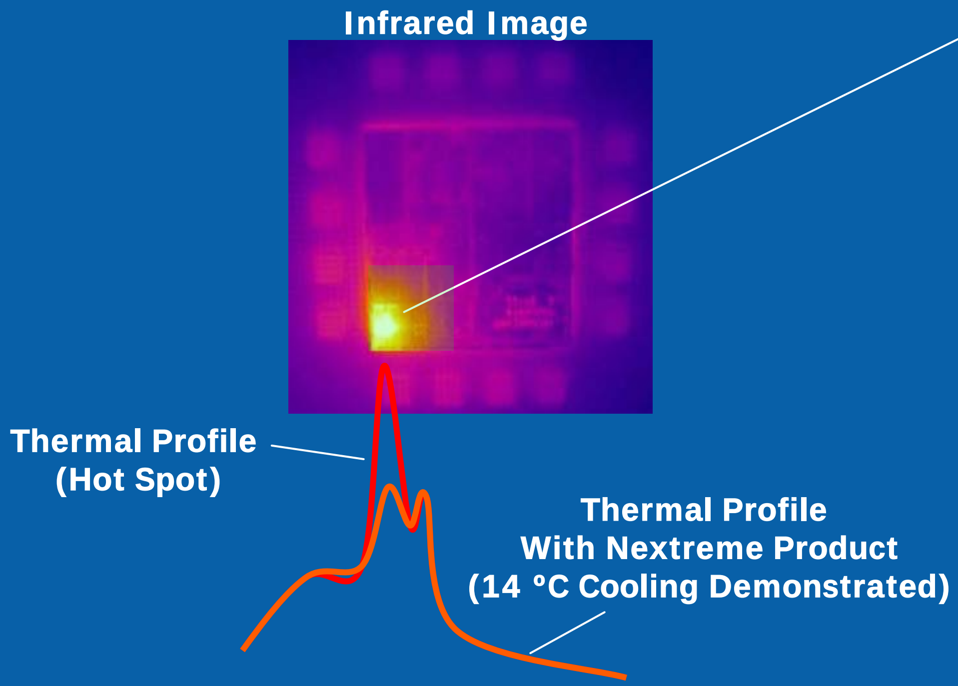


Embedded Thermoelectric Cooler

- Smooths out hot spots
- Increases chip performance
- Easily integrated inside IC package

Solution

- We produce an integrated, solid-state, miniature heat pump to locally cool hot spots in semiconductors.



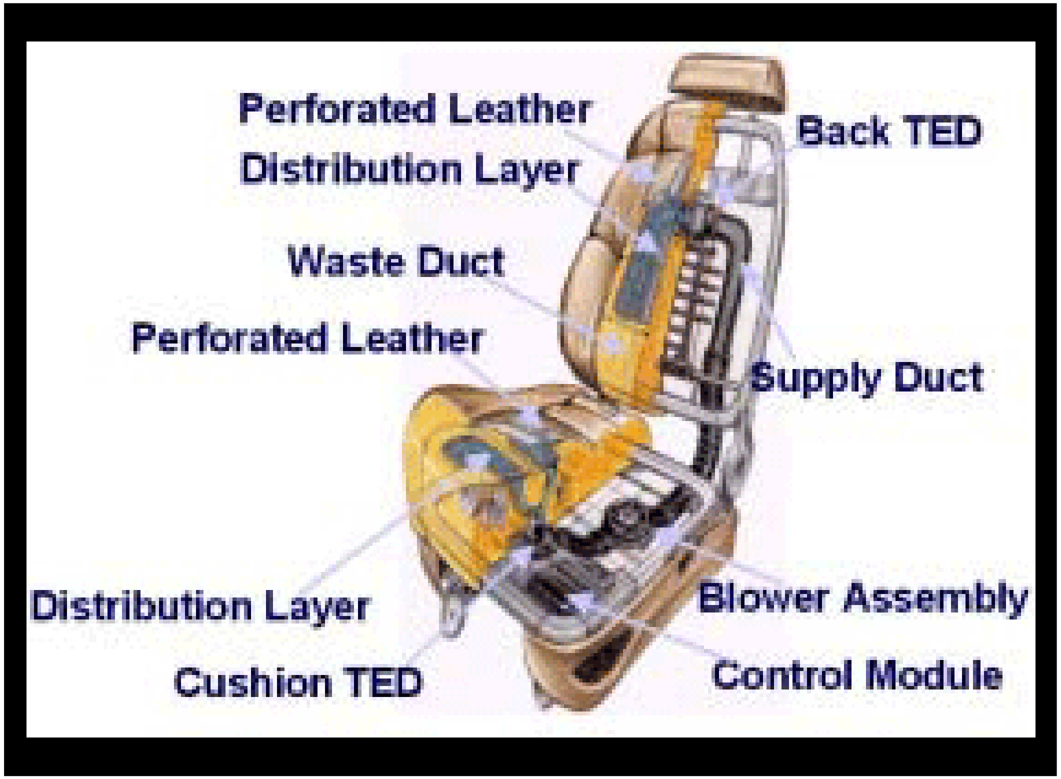
Chip performance limited by peak temperature.

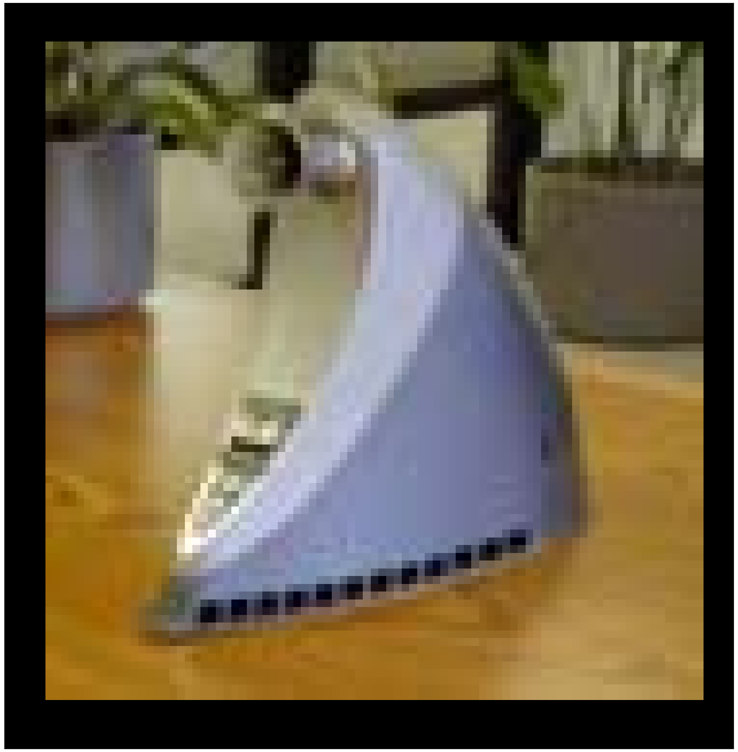
Increasing circuit density makes the problem worse.

Chip performance no longer scales with transistor density.

Site-specific cooling is not just applicable to computer chips and servers

Thermoelectrics Enable Site-specific or Personal Space cooling in Automobiles to Desktops



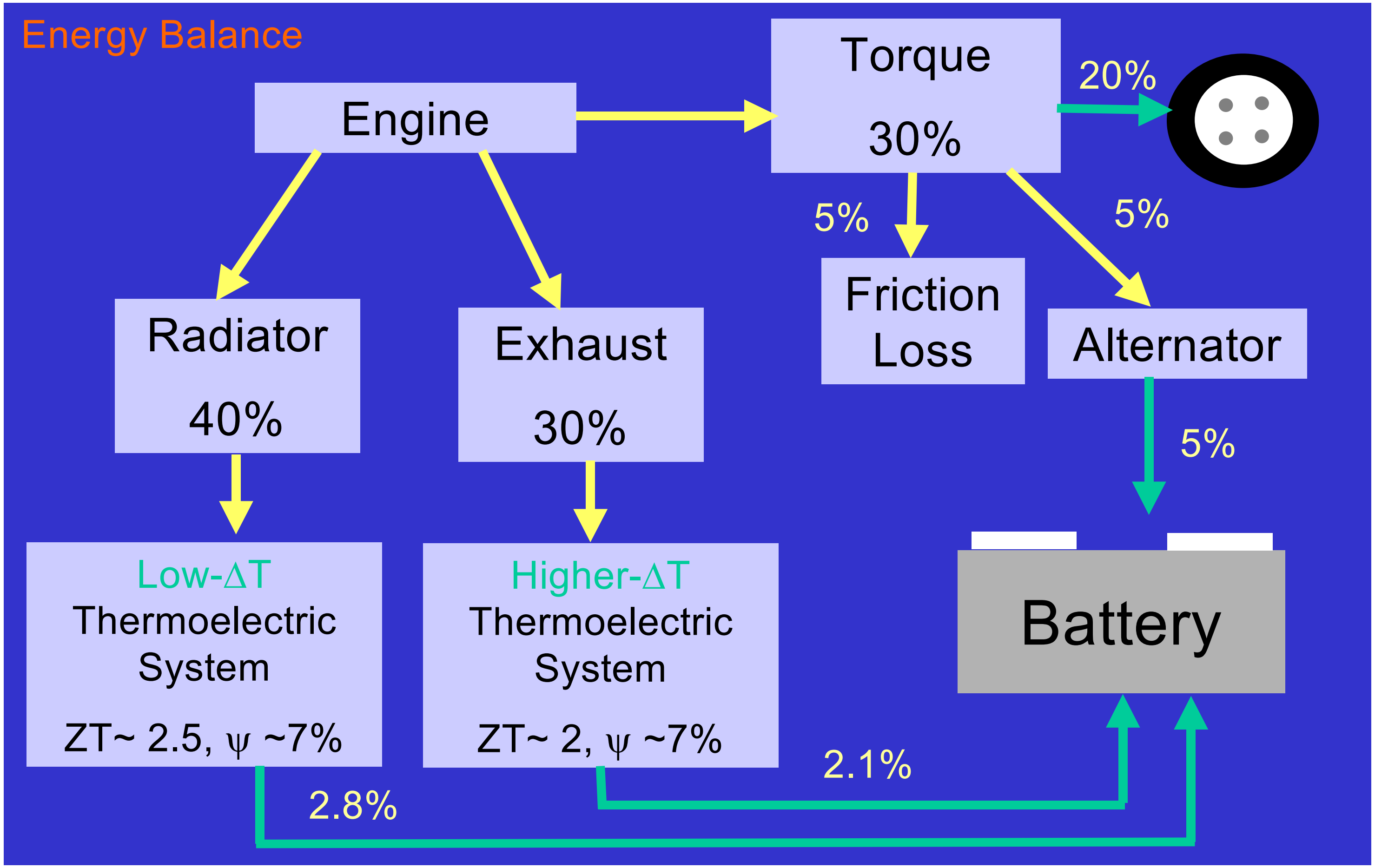


Ref: www.Amerigon.com

Transitioning Nano-materials Research to meeting a Critical Energy Efficiency need

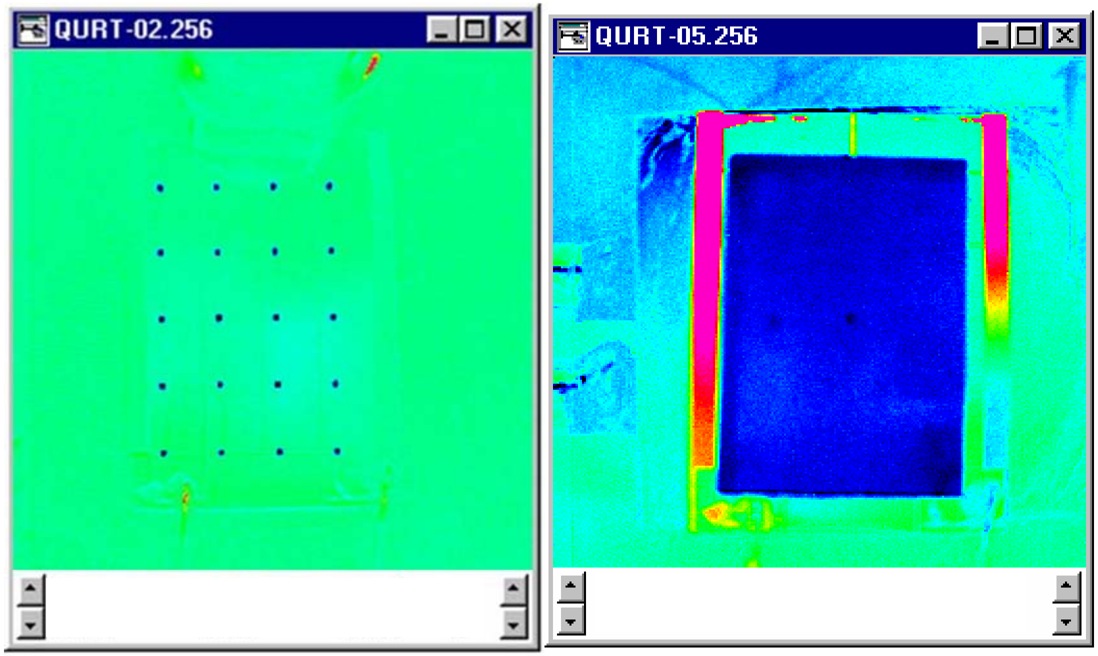
- Improve Fuel Efficiency in automobiles

Potential Capability with Thermoelectrics: recover some of the 70% Wasted Energy in Automotives towards Improving Fuel efficiency



Reduced Material Usage and Recycle Costs

Next Generation Technology with Nano-Materials: 10 cm^2-area cooler plate on 0.072 cm^2- area superlattice couples



- Same functionality with 1/40,000th of active nano-materials compared to commercial non-nano bulk materials

Summary

- Nanoscale thin-film thermoelectrics timely for
  - Electronic chip industry both to keep Moore’s law on track and to reduce cooling costs in servers
  - Energy harvesting for fuel-efficiency in automotives and energy efficiency in some process industries
- Pollution prevention through energy efficiency and reduced energy usage
- Pollution prevention through green cooling technologies
- Reduce materials usage through “nano-materials” approach and reduce lifecycle costs for same or better functionality
  - Will become important if some large commercial applications start happening