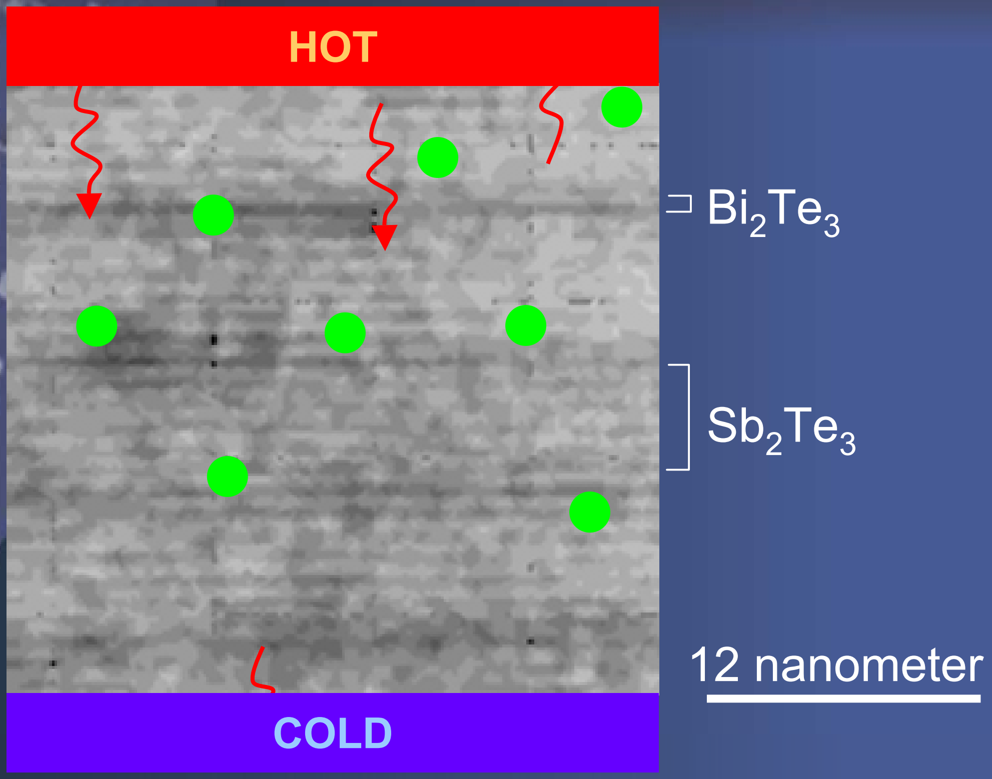
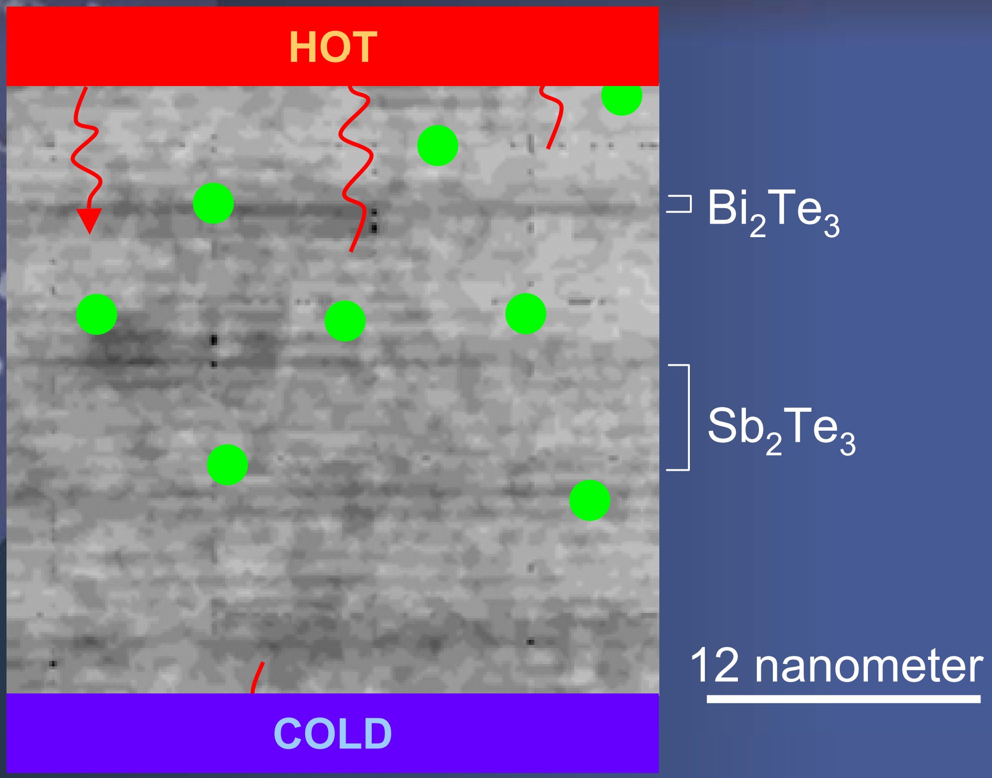
RTI's Superlattice Material



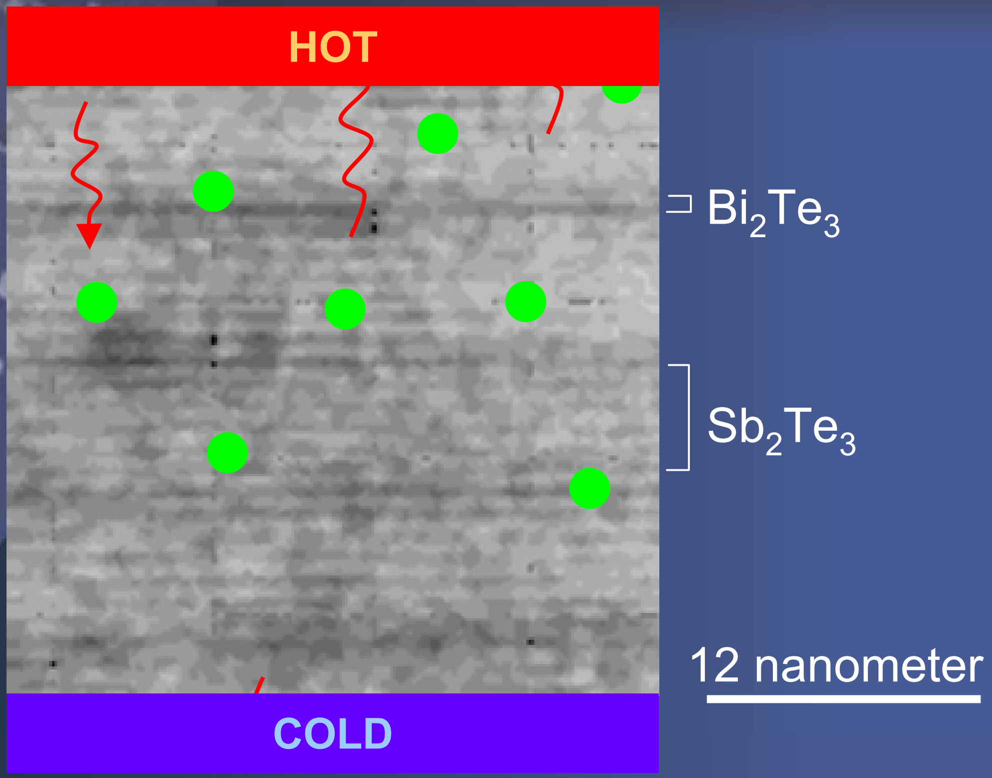
The RTI breakthrough arises from reducing heat transmission without disrupting electron flow

RTI's Superlattice Material



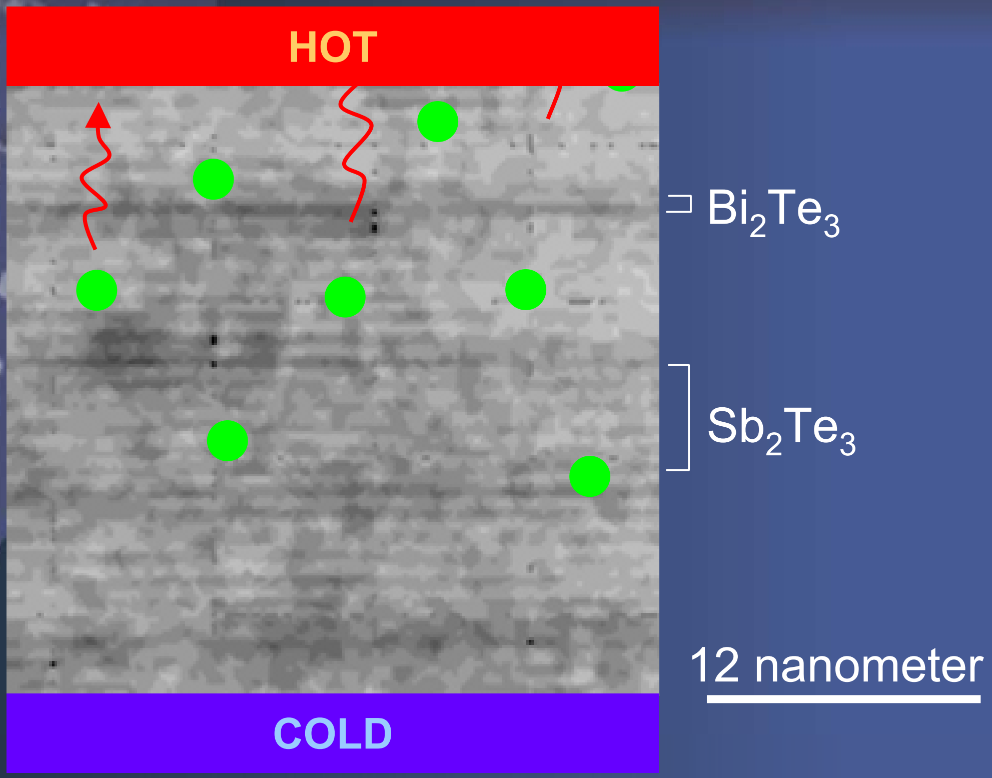
The RTI breakthrough arises from reducing heat transmission without disrupting electron flow

RTI's Superlattice Material



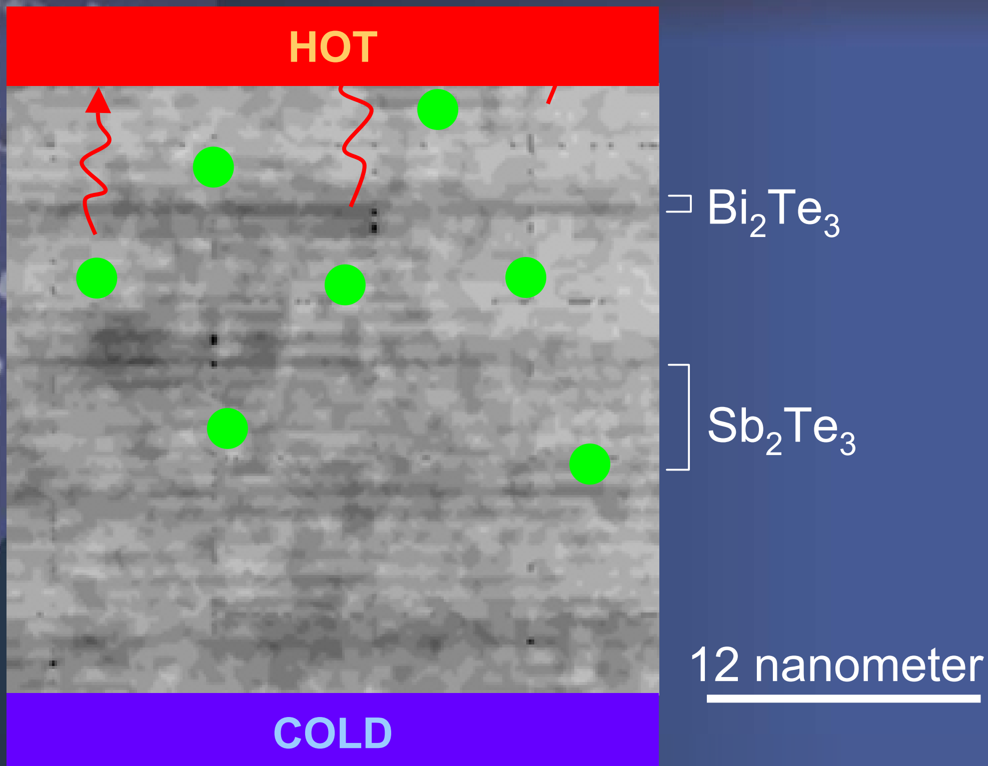
The RTI breakthrough arises from reducing heat transmission without disrupting electron flow

RTI's Superlattice Material



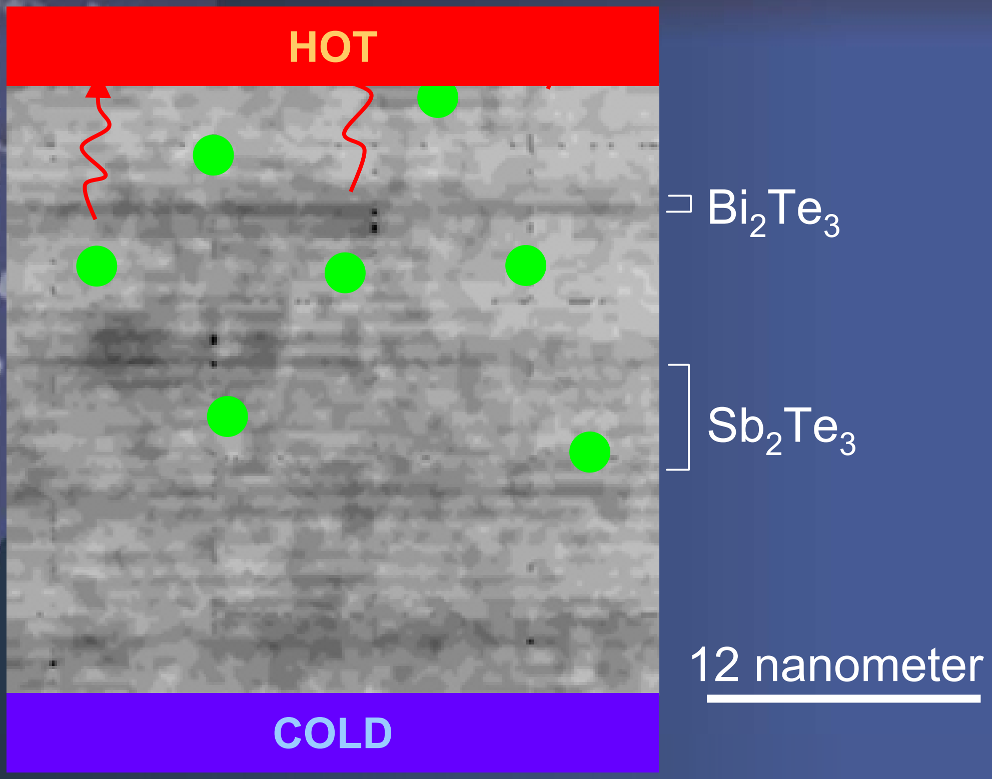
The RTI breakthrough arises from reducing heat transmission without disrupting electron flow

RTI's Superlattice Material



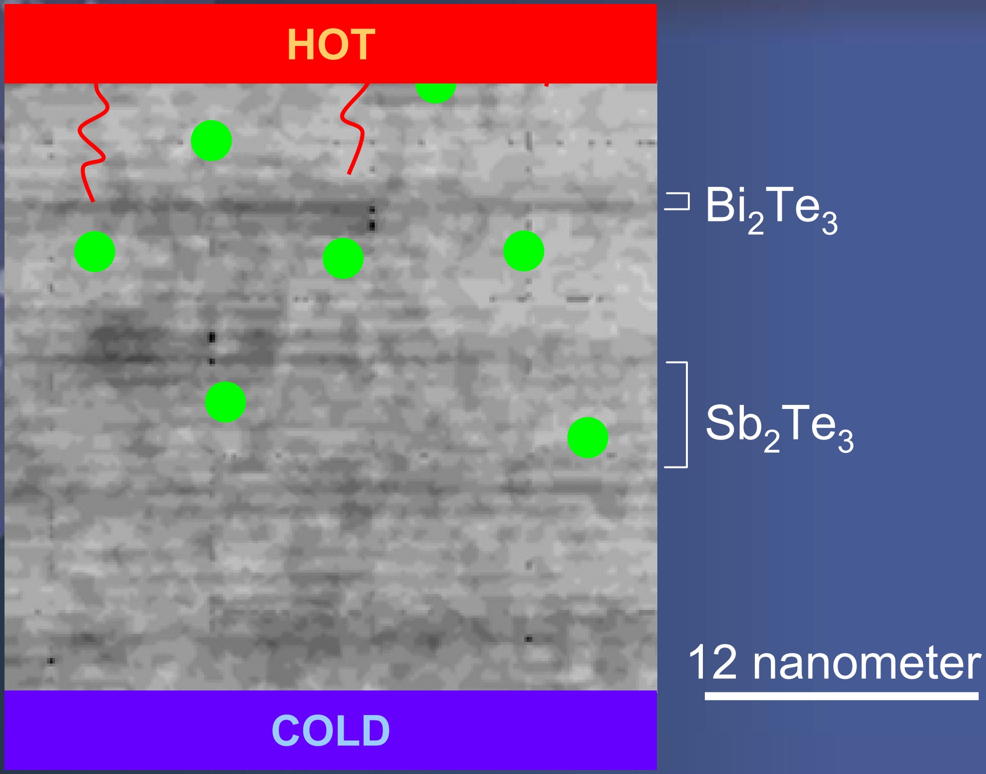
The RTI breakthrough arises from reducing heat transmission without disrupting electron flow

RTI's Superlattice Material



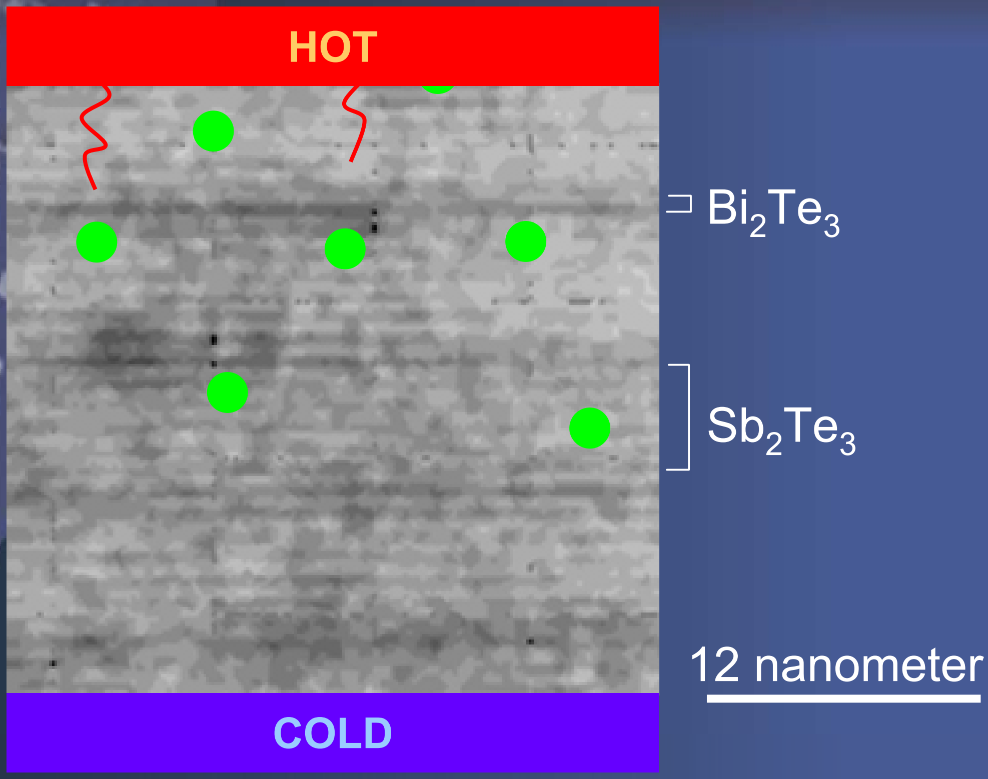
The RTI breakthrough arises from reducing heat transmission without disrupting electron flow

RTI's Superlattice Material



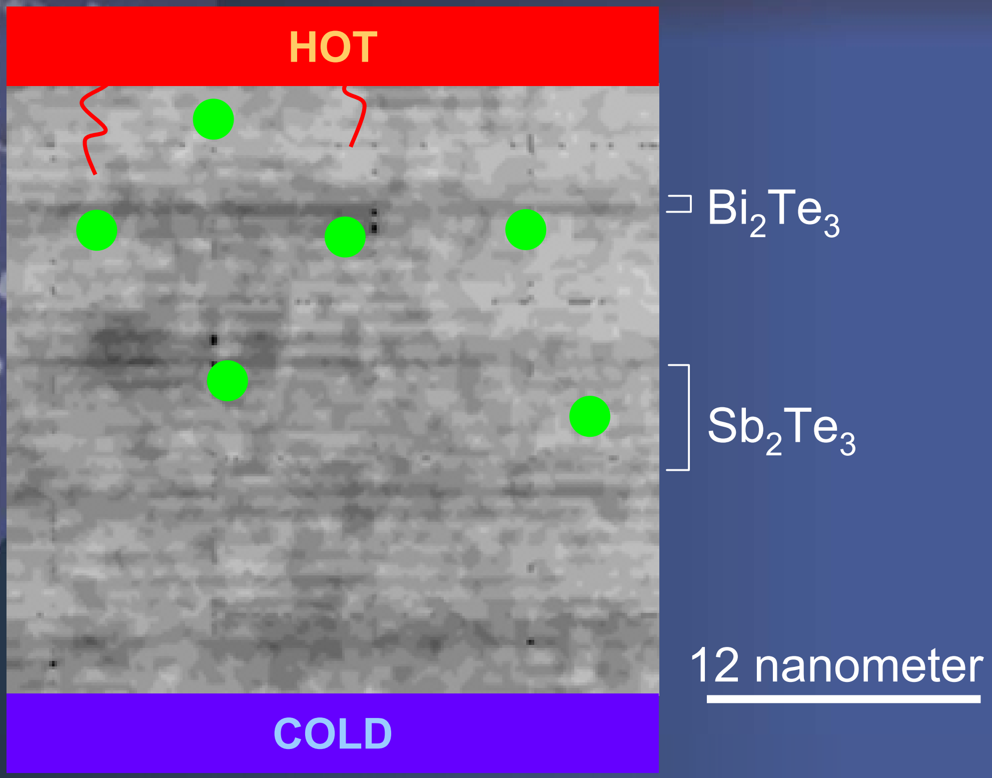
The RTI breakthrough arises from reducing heat transmission without disrupting electron flow

RTI's Superlattice Material



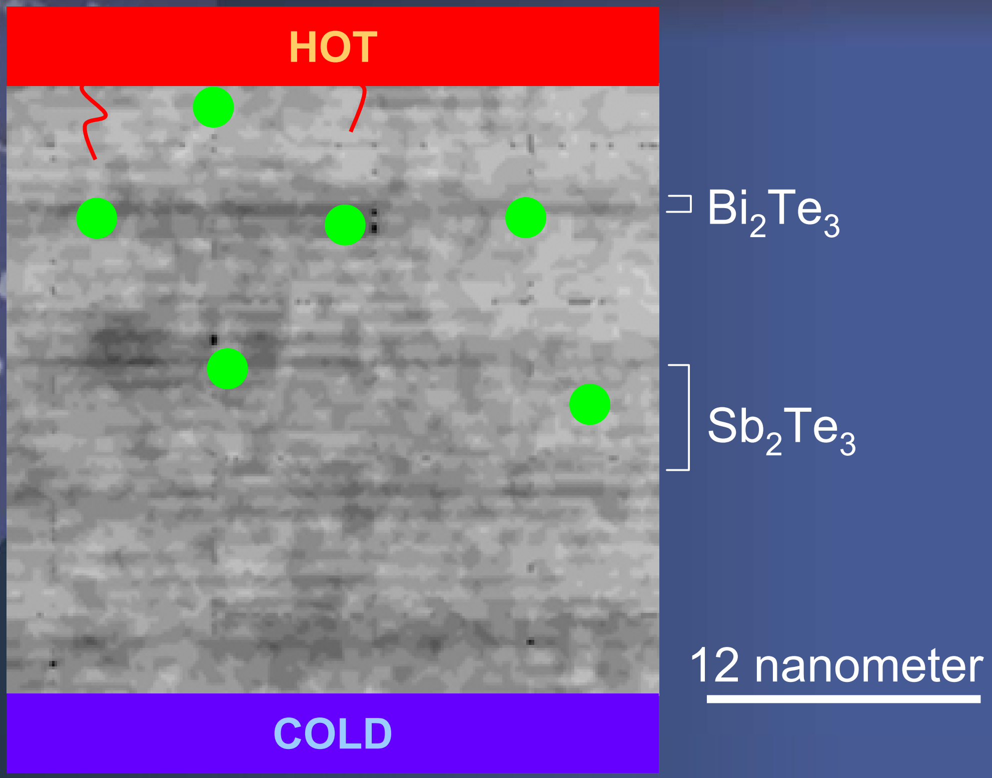
The RTI breakthrough arises from reducing heat transmission without disrupting electron flow

RTI's Superlattice Material



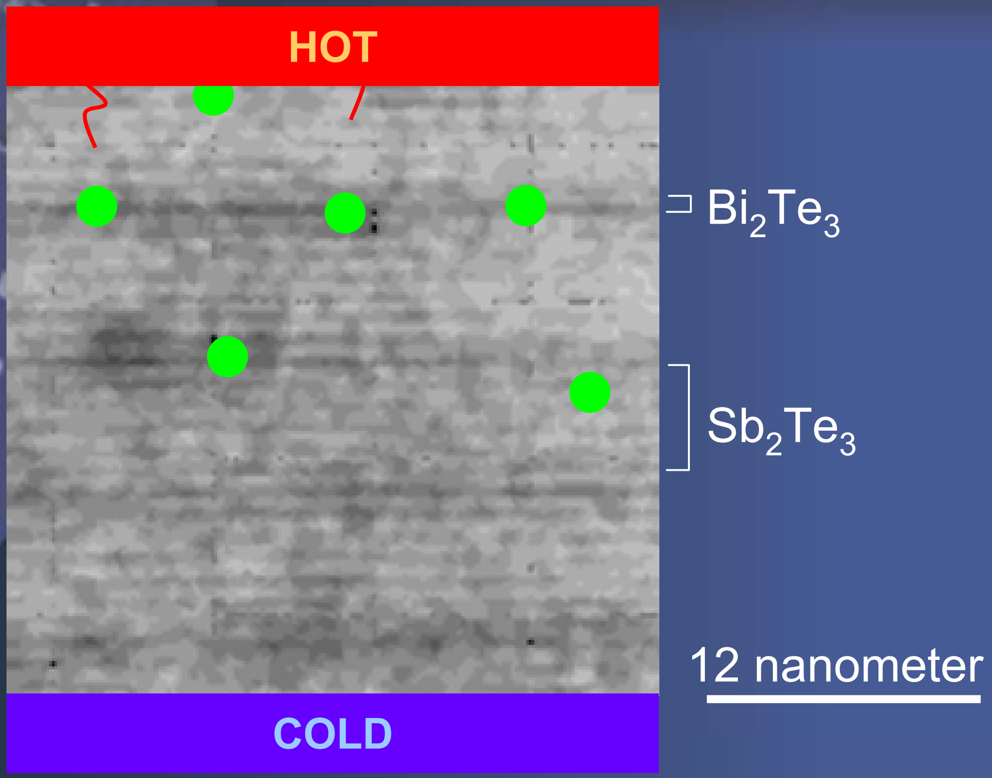
The RTI breakthrough arises from reducing heat transmission without disrupting electron flow

RTI's Superlattice Material



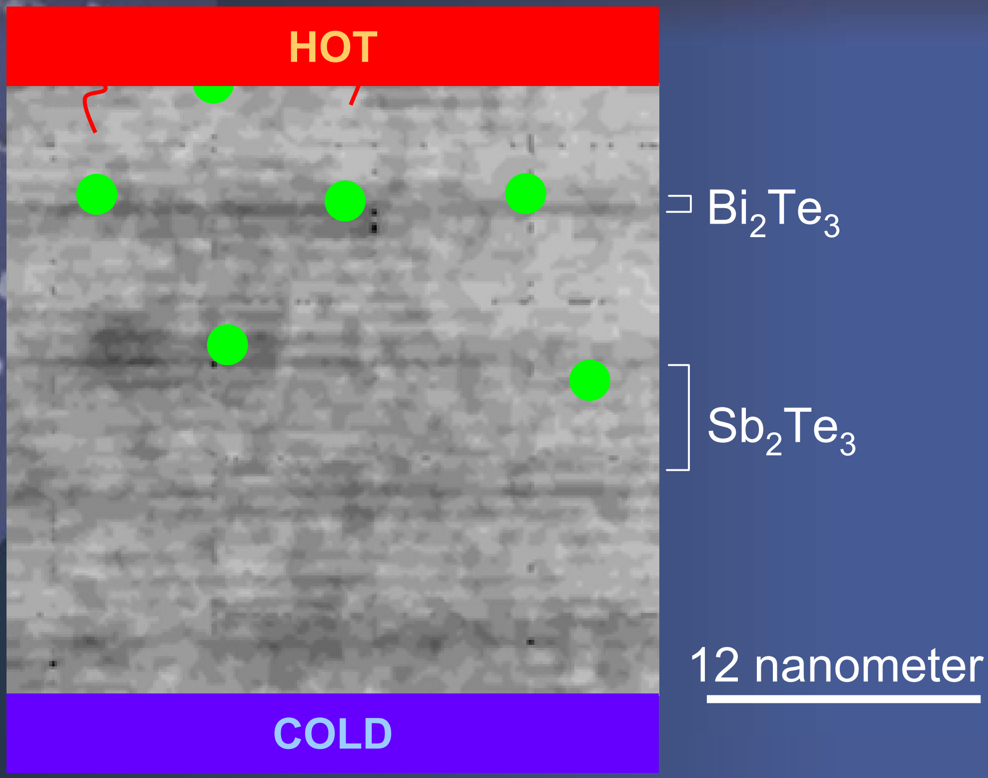
The RTI breakthrough arises from reducing heat transmission without disrupting electron flow

RTI's Superlattice Material



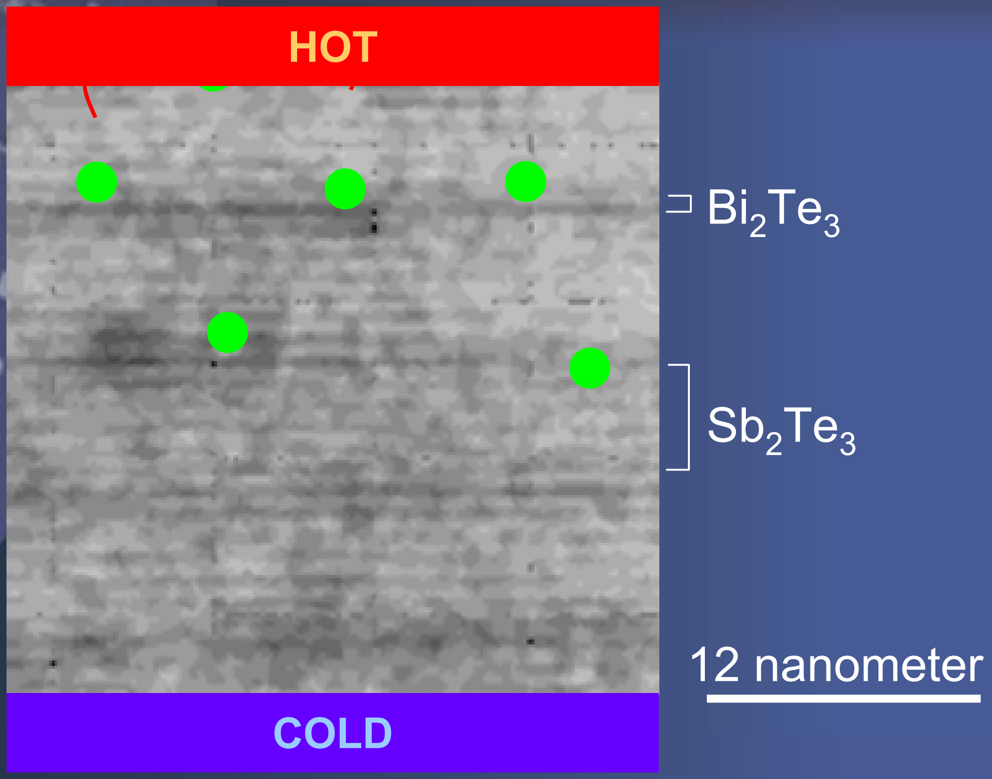
The RTI breakthrough arises from reducing heat transmission without disrupting electron flow

RTI's Superlattice Material



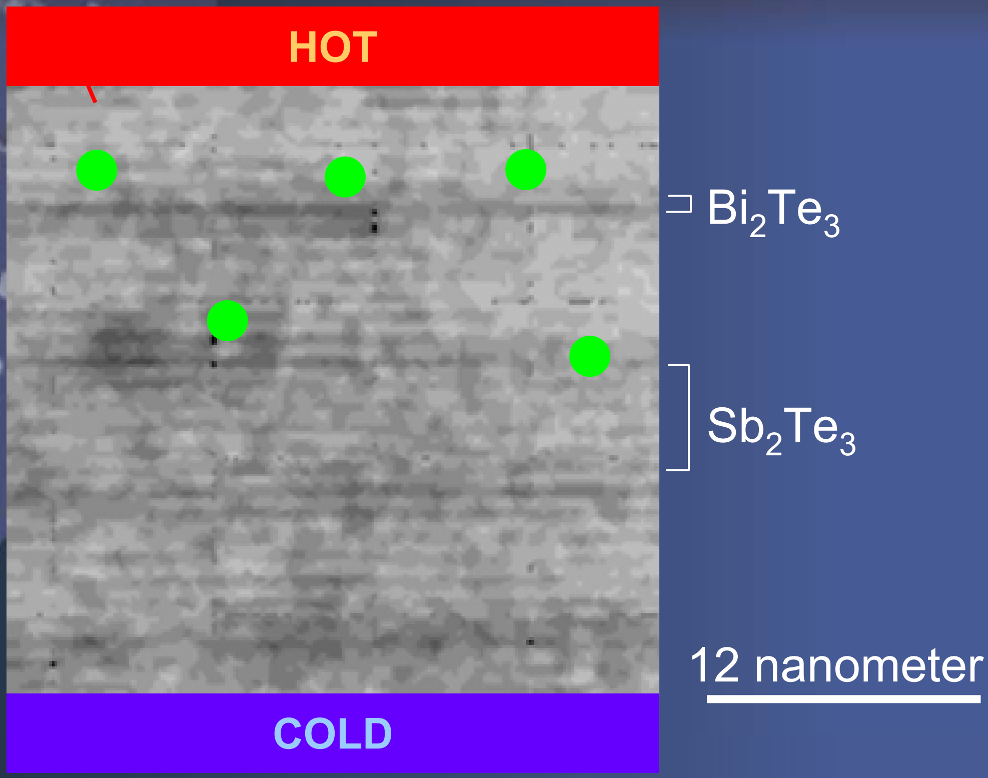
The RTI breakthrough arises from reducing heat transmission without disrupting electron flow

RTI's Superlattice Material



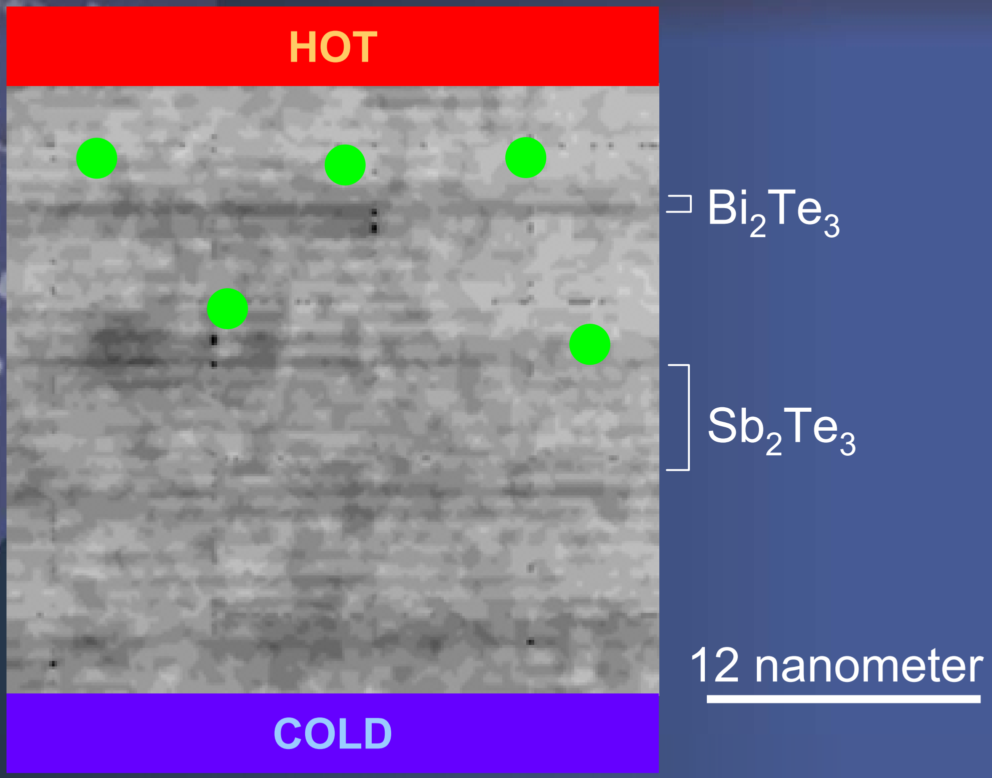
The RTI breakthrough arises from reducing heat transmission without disrupting electron flow

RTI's Superlattice Material



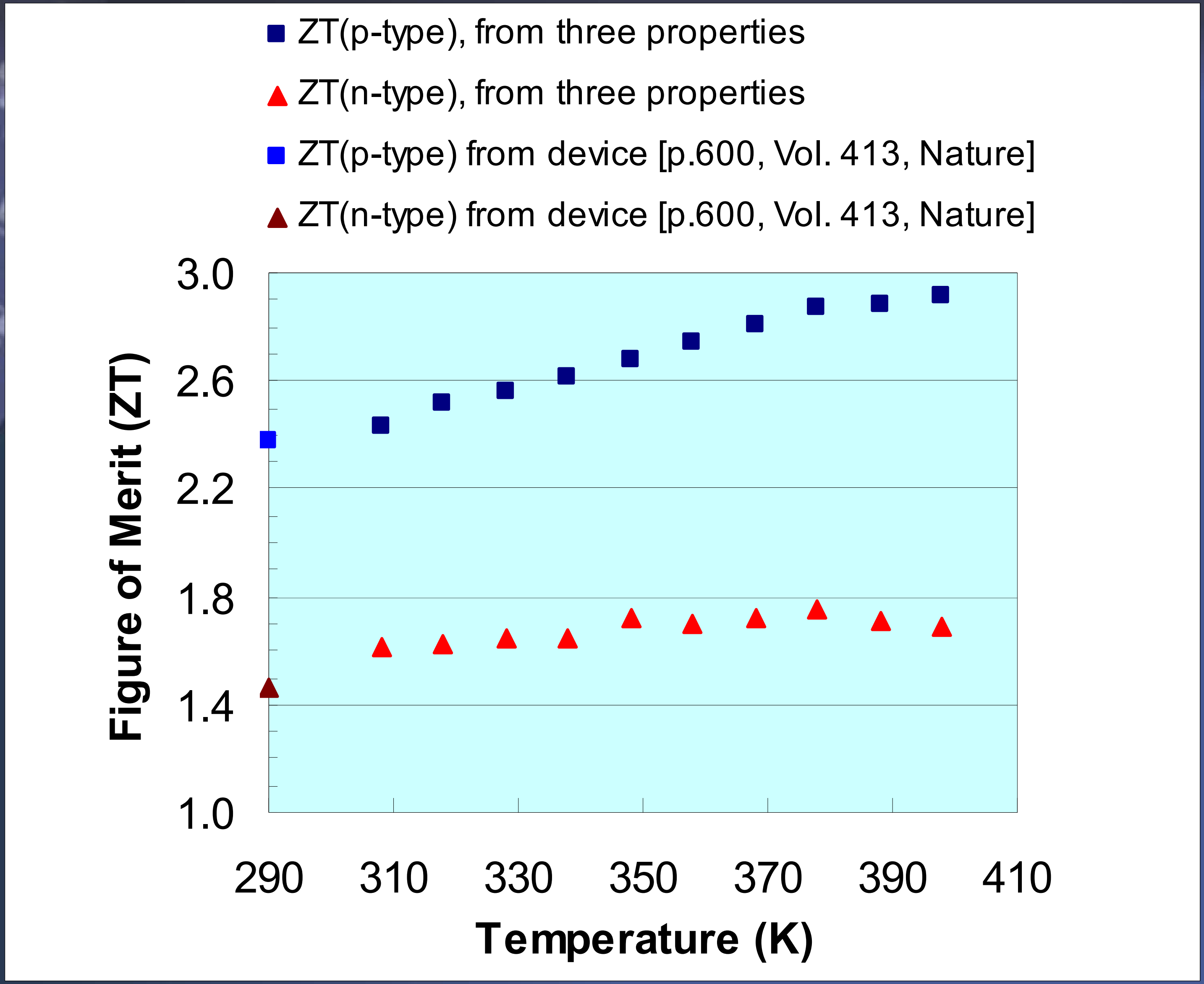
The RTI breakthrough arises from reducing heat transmission without disrupting electron flow

RTI's Superlattice Material

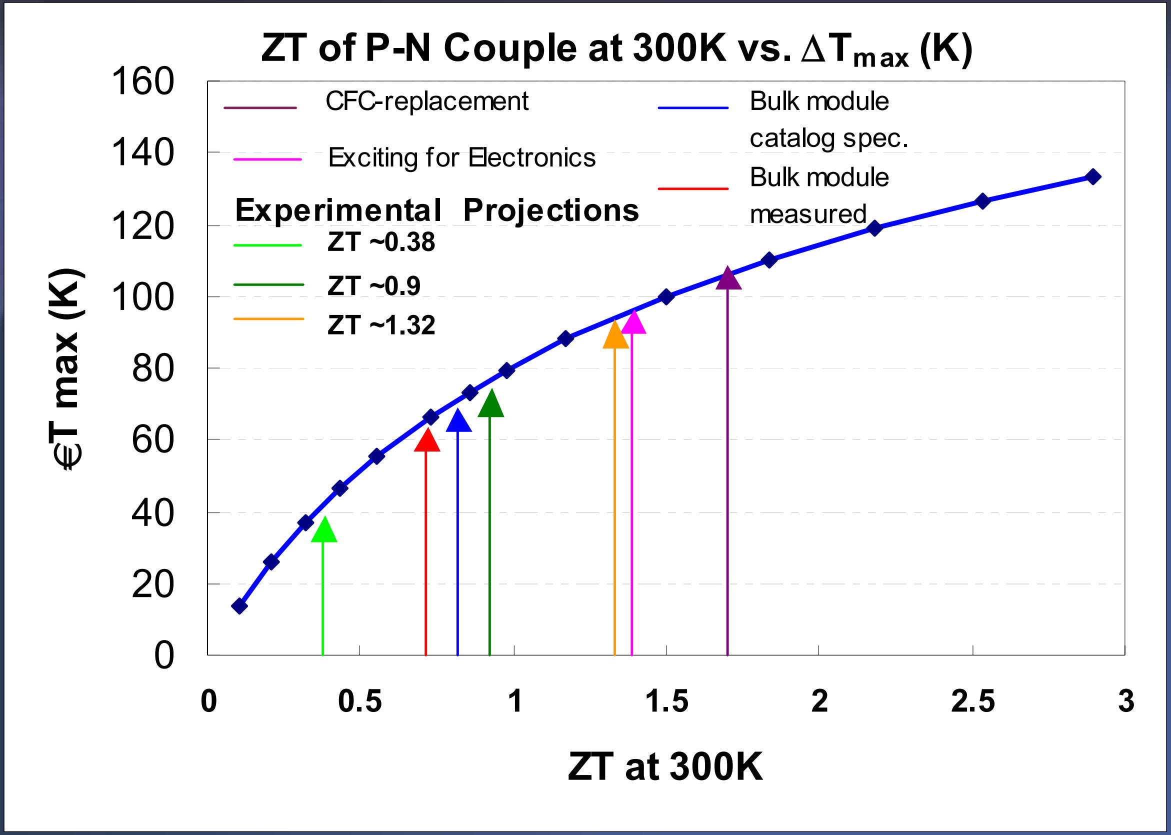


The RTI breakthrough arises from reducing heat transmission without disrupting electron flow

Best Intrinsic ZT Values in Bi_2Te_3-based P-type and N-type Superlattices for Power Conversion (300K- 420K)



Correlation Between ZT and ΔT_{max}

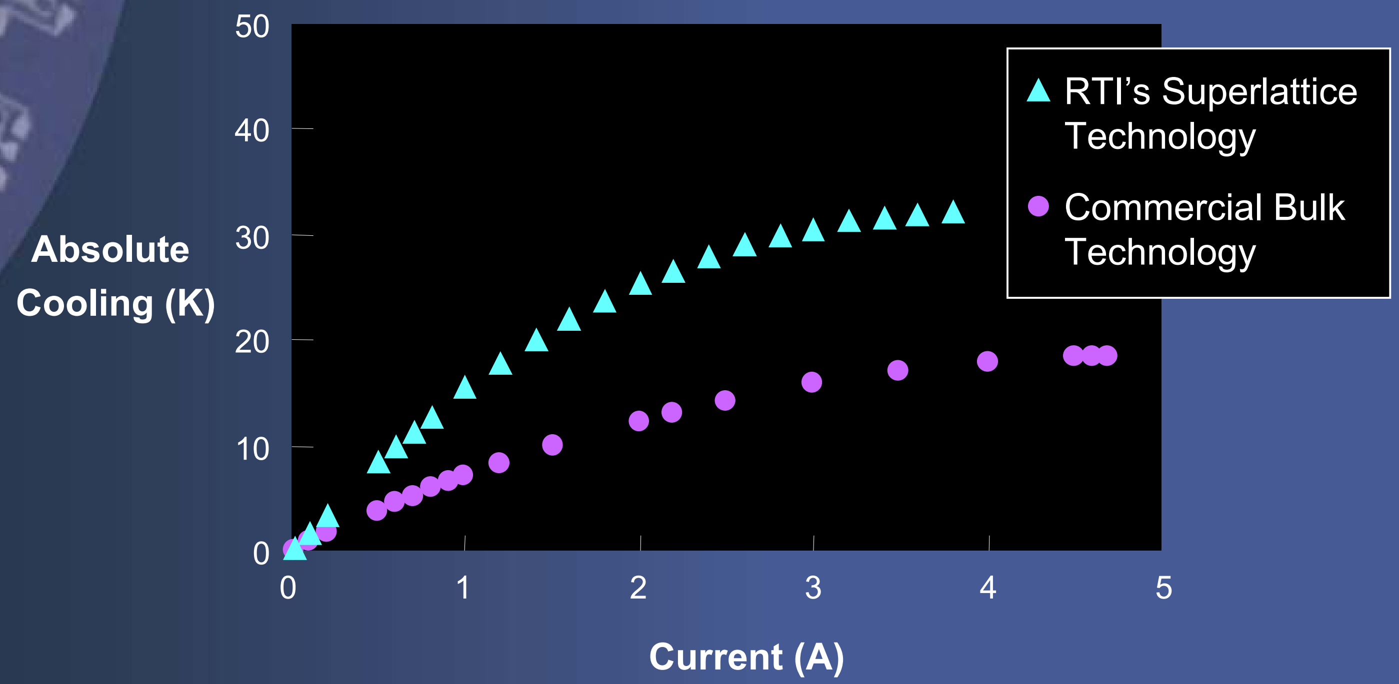


- **Current focus of program to translate ZT of material closer to system-level external cooling or efficiency**

Advantages and Thin-film Cooling Examples

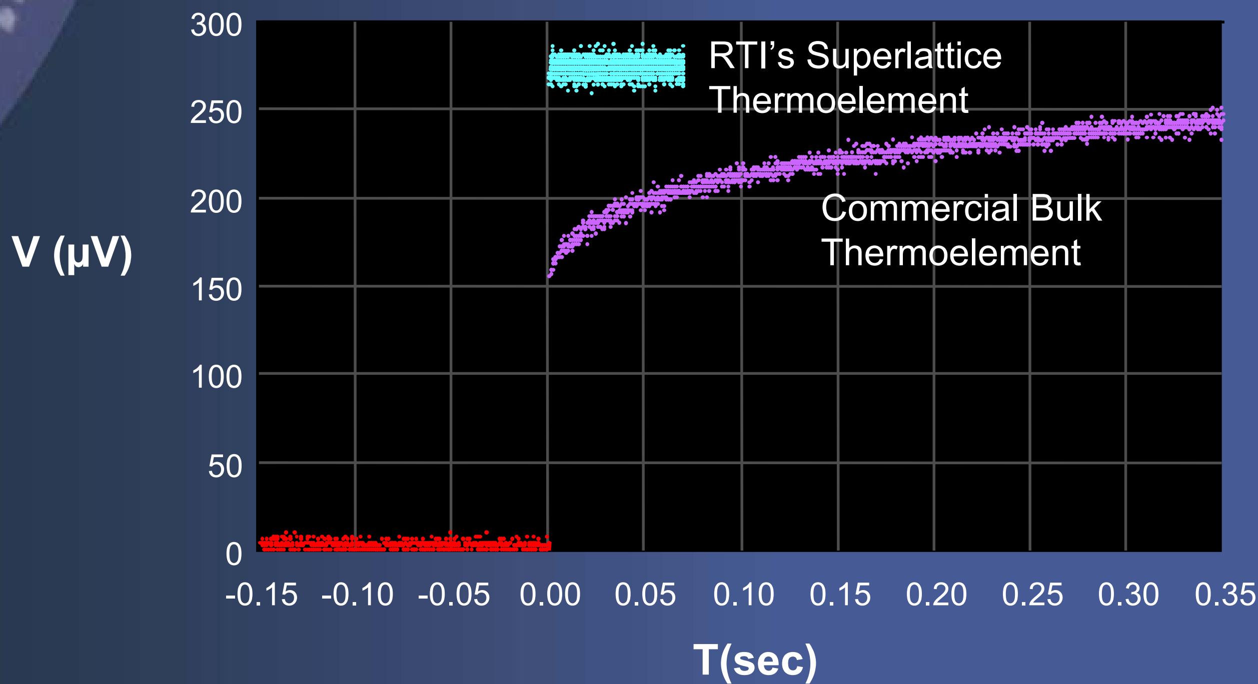
Advantages of RTI's Superlattice Thermoelectric Technology

- Enhanced cooling



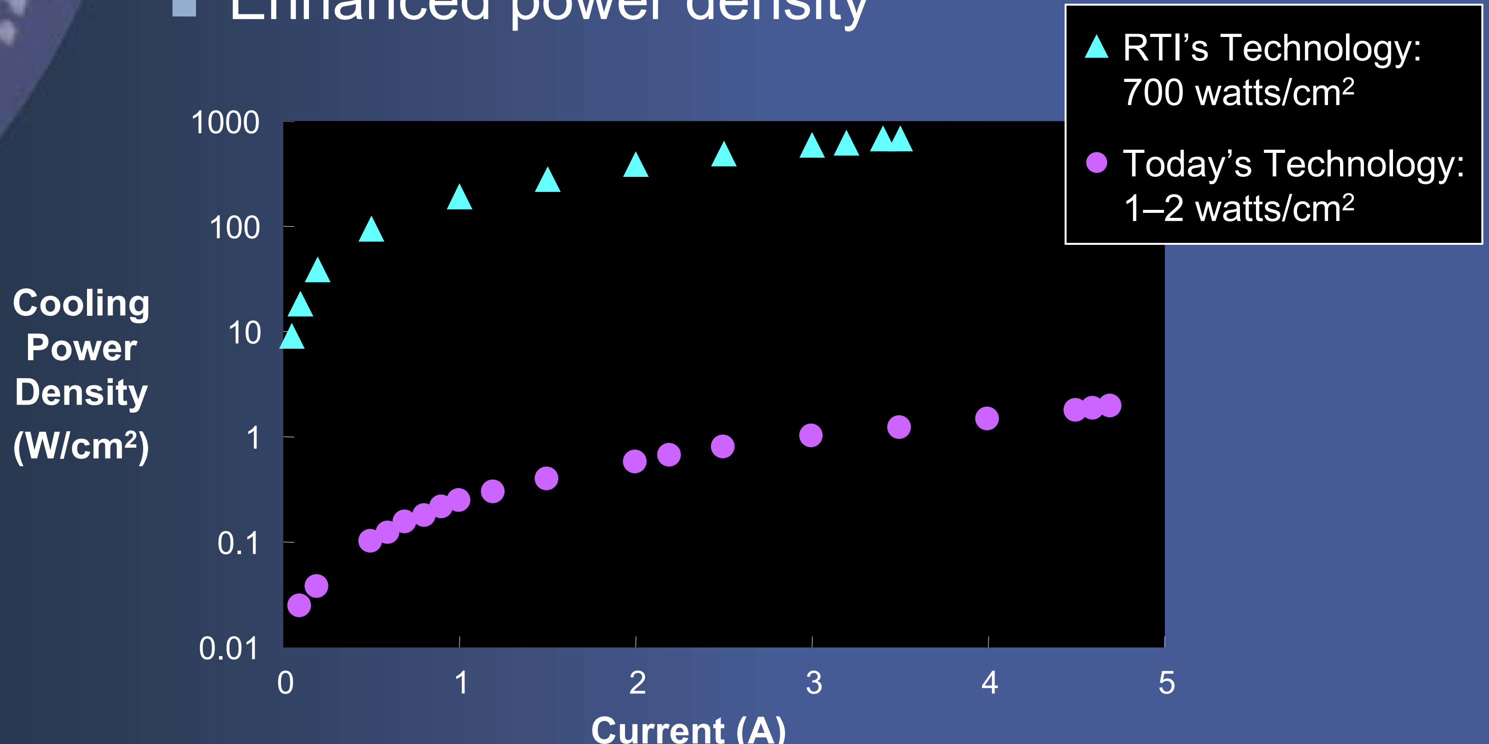
Advantages of RTI's Superlattice Thermoelectric Technology

- Enhanced cooling
- Super-fast cooling and heating



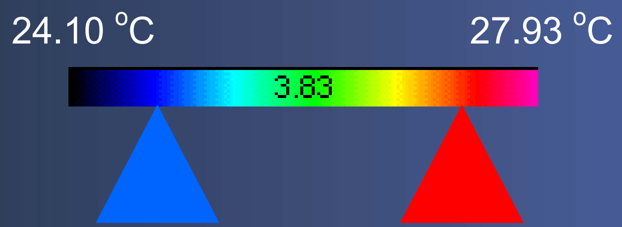
Advantages of RTI's Superlattice Thermoelectric Technology

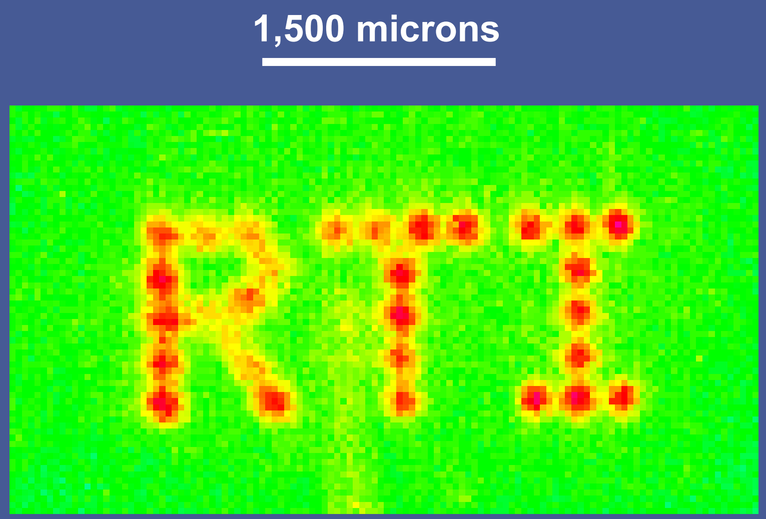
- Enhanced cooling
- Super-fast cooling and heating
- Enhanced power density



Advantages of RTI's Superlattice Thermoelectric Technology

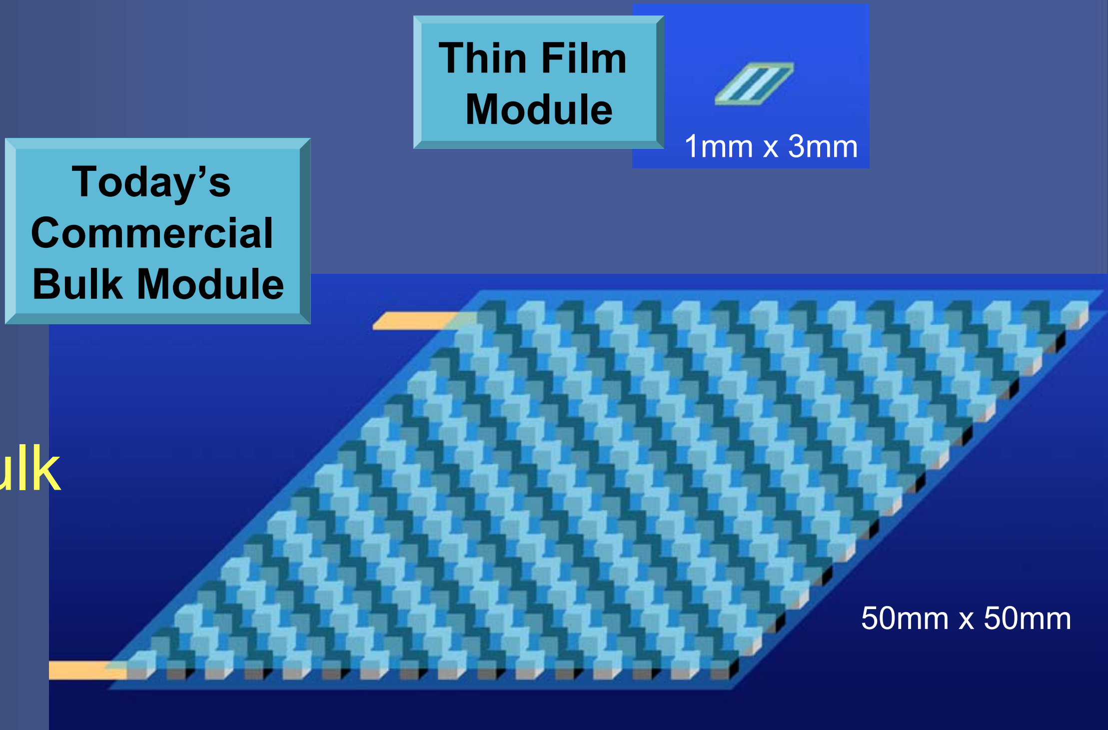
- Enhanced cooling
- Super-fast cooling and heating
- Enhanced power density
- Anywhere, any time cooling/ heating technology



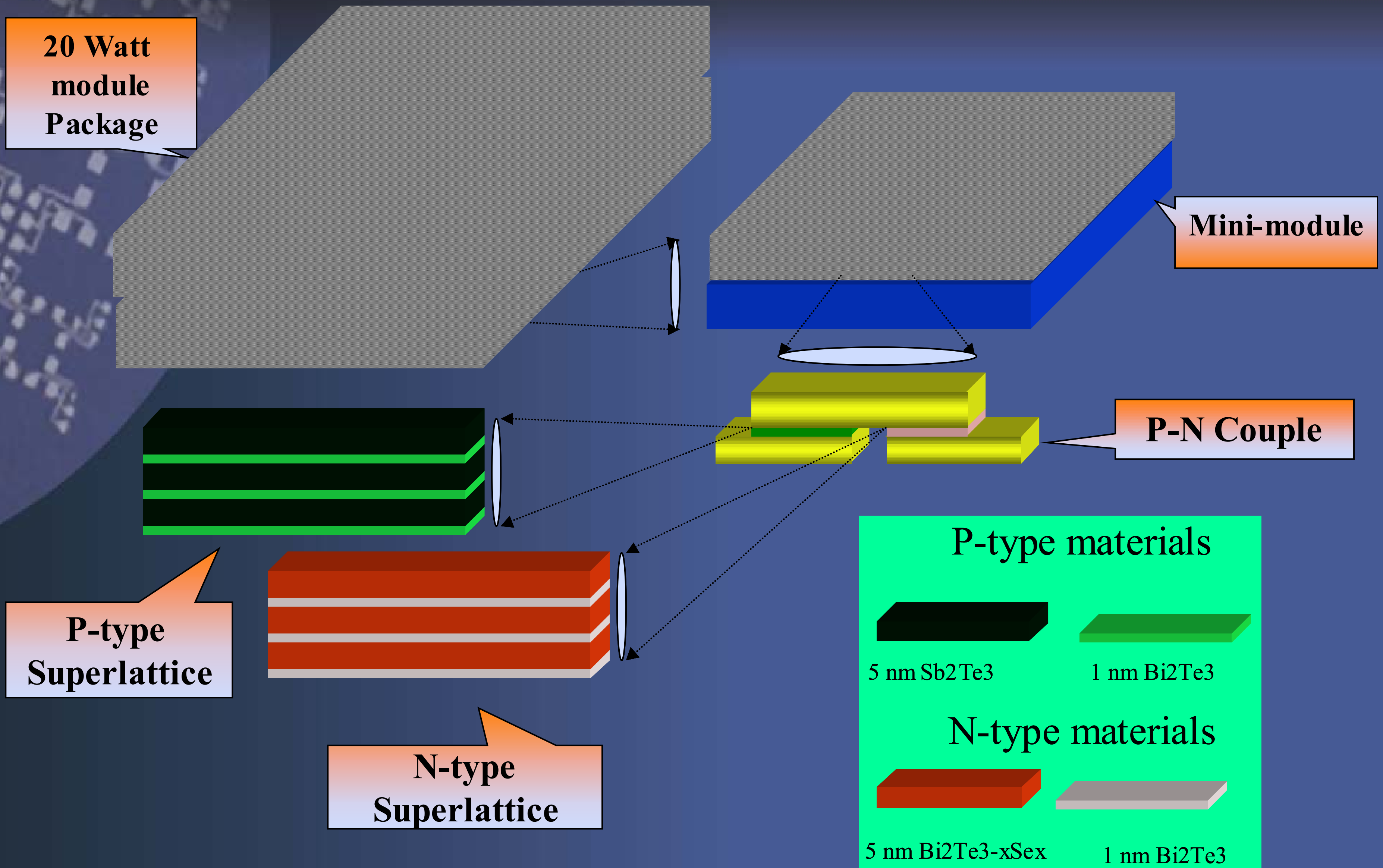


Advantages of RTI's Superlattice Thermoelectric Technology

- Enhanced cooling
- Super-fast cooling and heating
- Enhanced power density
- Anywhere, any time cooling/ heating technology
- 1/40,000th the actual TE material requirement of bulk technology – low recycle costs

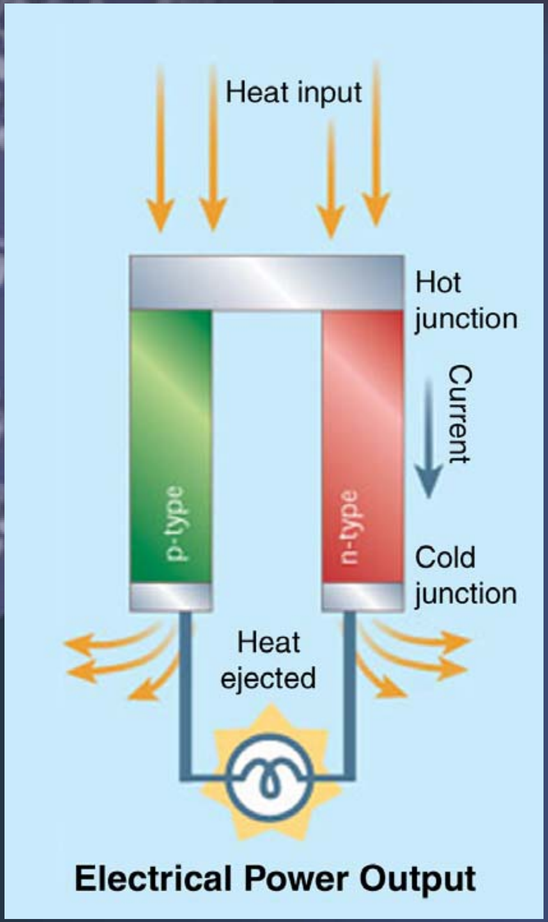


Thin-film Thermoelectric Module Fabrication



Thin-film Power Conversion Examples

Thermoelectric Power Conversion

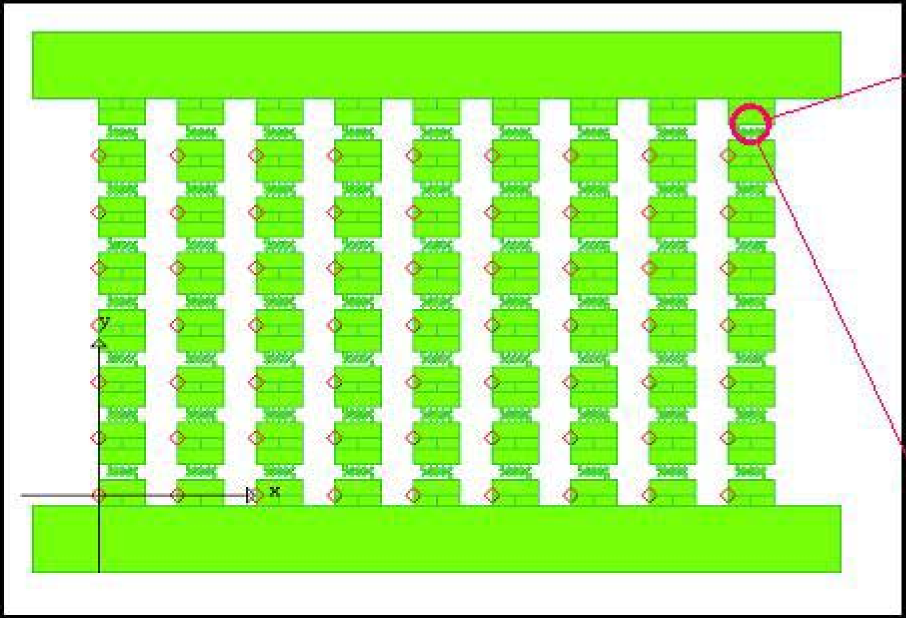


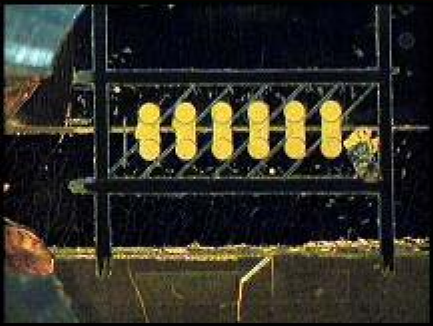
$$\psi = \frac{(T_h - T_c)}{T_h} \; \frac{\{(1+ZT)^{1/2} - 1\}}{\{(1+ZT)^{1/2} - 1\} + T_c/T_h}$$

- Power Conversion Efficiency critically dependent on the material Figure of Merit (ZT)

- Maximize ΔT
  - ➢ Thermal management (getting the heat out from the heat-sink) is important to generating the maximum ΔT

RTI's Gen-1 Power Module Design Using 63 Mini-modules (Area ~ 3.5 cm x 2.4 cm)

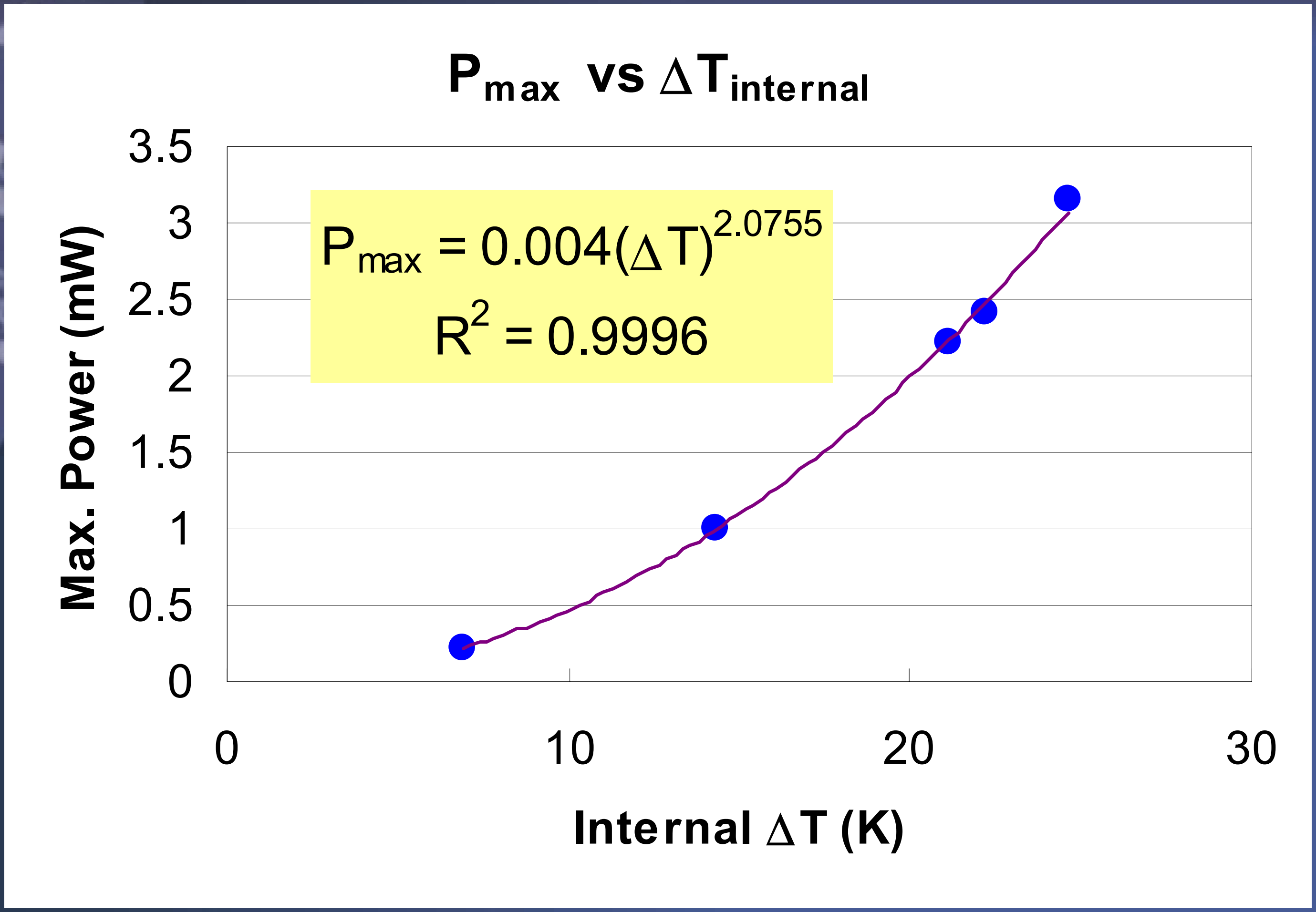




- **6x2 300-µm Series mini-module**
- **V_{oc} ~ 76 mV**
- **P_{max} = 3.160 mW**
- **ΔT ~ 25°C**

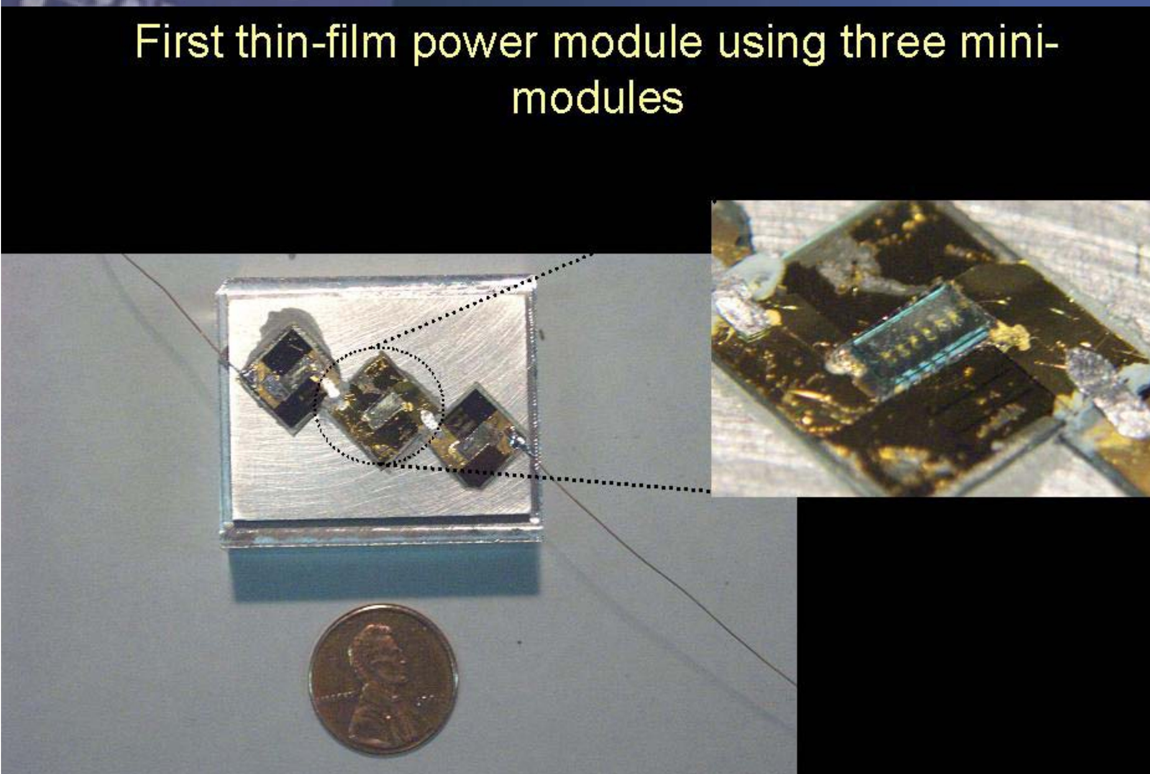
- One year target of 5 Watts Module based on power from all 63 mini-modules, ΔT of 75°C, factor of three improvement in reducing internal series resistance and translating <u>current</u> material ZT to external ZT
  - 3.16 mW x 63 x $(75/25)^2$ x 3 ~ 5 W
- **Larger Immediate Powers Possible with Larger Area Modules for Immediate Applications as in RTI Thermoelectric Power Shields™**
- Three-year target of 20 Watt Based on ΔT of 150°C

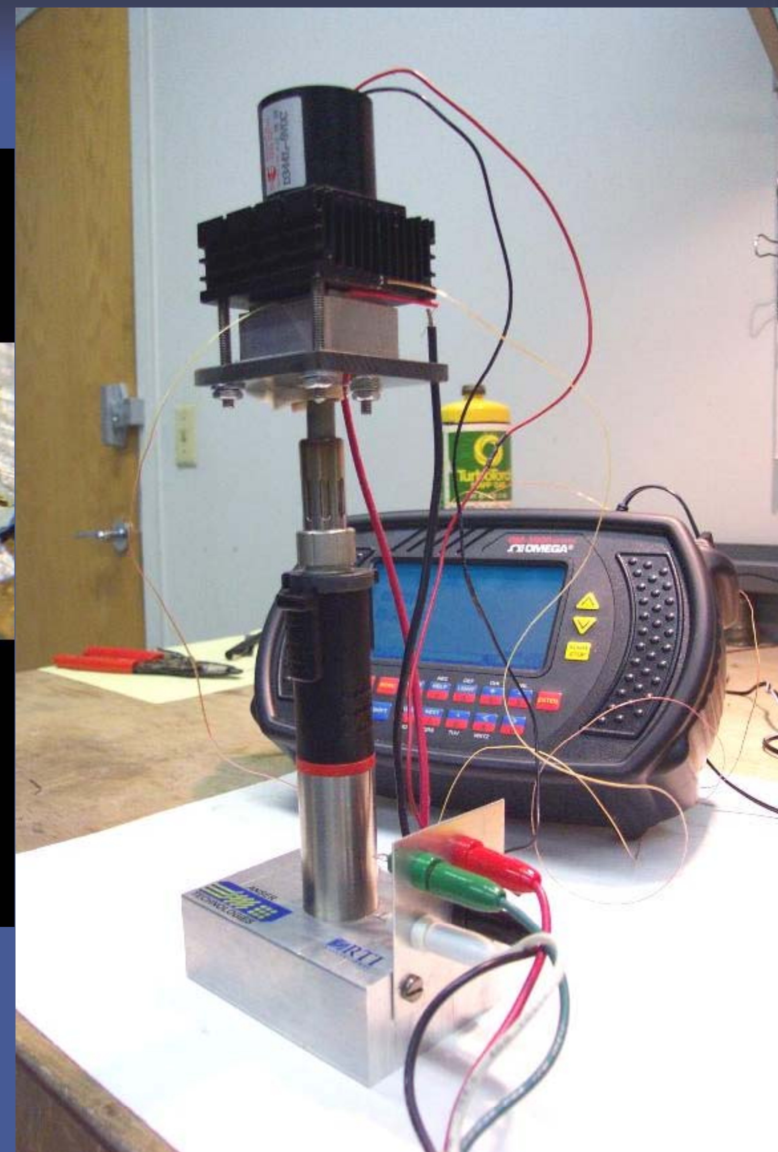
One of the next big focus areas - Reduce thermal interfaces to get more ΔT into the device



- Note square-dependence of P_{max} on ΔT across TE device

36–element, 0.025 cm^2-active area – enough power for a small fan





Long-term Potential Efficiencies for Heat Sources at 660K and 750K

$T_{heat-sink}$ = 300K			$T_{heat-source}$ = 660K	$T_{heat-source}$ = 750K
			∆T ~ 120K per stage	∆T ~ 150K per stage
Very Optimistic Projection		ZT_{ave}	Efficiency (%)	Efficiency (%)
300K < **T** < 420K to 450K	Stage 1	2.75	10.1%	12.0%
420K to 450K < **T** < 540K to 600K	Stage 2	2.25	6.9%	7.9%
540K to 600K < **T** < 660K to 750K	Stage 3	2.25	5.6%	6.1%
Total Efficiency for 3-stage Cascade			**22.6%**	**26.0%**
Moderately Optimistic Projection		ZT_{ave}	Efficiency (%)	Efficiency (%)
300K < **T** < 420K to 450K	Stage 1	2.5	9.6%	11.4%
420K to 450K < **T** < 540K to 600K	Stage 2	2	6.5%	7.4%
540K to 600 K < **T** < 660K to 750K	Stage 3	2	5.2%	5.8%
Total Efficiency for 3-stage Cascade			**21.3%**	**24.6%**
Conservatively Optimistic Projection		ZT_{ave}	Efficiency (%)	Efficiency (%)
300K < **T** < 420K to 450K	Stage 1	2.25	9.1%	10.8%
420K to 450K < **T** < 540K to 600K	Stage 2	1.75	6.0%	6.8%
540K to 600K < **T** < 660K to 750K	Stage 3	1.75	4.8%	5.4%
Total Efficiency for 3-stage Cascade			**19.9%**	**23.0%**

Major Issues in Application to Waste-Heat Recovery from Heat Sources Operating at Various Temperatures

- High ZT Materials for higher temperatures
- Thermal Management at significant flux levels
- Low electrical resistivity metal-semiconductor Ohmic Contacts in the range of 300K to 750K
- Low resistivity metal-metal current injection and thermal transfer contacts in the range of 300K to 750K
- Low resistivity metal-dielectric thermal transfer contacts in the range of of 300K to 750K

Bulk versus Thin-film TE Cooling/Heating

Performance Parameter	Bulk Technology (ZT ~ 1)	Thin-film Technology (ZT ~ 2.5)
COP (Heat Pumped/Electrical Power in) for a Δ**T of 25^{o}C**	1	2 to 2.5
Wight of TE module for pumping 50 Watts (without thermal management components)	~ 22 grams	< 3 grams
Cost of heat pumping	$ 0.5 to 1 per Watt as of today after 40 years of maturity	Long-term (three to five years) projected cost < $ 0.5 per Watt
Cooling Power Density Potential Maximum Cooling per stage	< 1 W/cm^2 ~ 60^{o}C	> 700 W/cm^2 ~ 120^{o}C

Bulk versus Thin-film TE Power

Performance Parameter	Bulk Technology (ZT ~ 1)	Thin-film Technology (ZT ~ 2.5)
Efficiency for a **ΔT of 150^{o}C**	3 to 4%	10 to 11%
Specific Power excluding thermal management components	1 Watt/gram of TE module weight	570 Watts/gram of TE module weight
Cost	$5 per Watt as of today after 40 years of maturity	Long-term (three to five years) projected cost < $1 per Watt
Current Density Voltage levels from <u>each</u> module Power Density	< 200 mA/cm^2 5 to 10 Volts < 1 W/cm^2	> 50 Amp/cm^2 possible 48 Volts achievable with microelectronically interconnected circuits > 20 W/cm^2

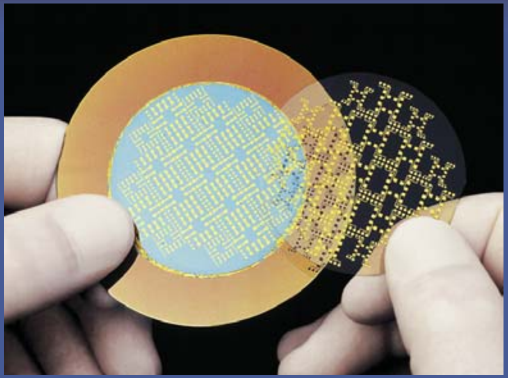
Low-cost, Efficient Fabrication of Large-Power Modules Using Standard Microelectronic Tools

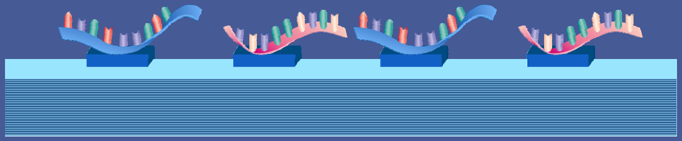
Standard Wafer Dicer and Pick-and-Place machines for Rapid Module Fabrication

Other Emerging Applications

Application in Genomics and Proteomics

- High-speed PCR for rapid DNA analysis
- Self-assembly of DNA and Protein molecules
- Today's analytical tools are inadequate
  to study proteins
  (2-D gel electrophoresis, liquid chromatography, and mass spectrometry)
- Wafer-scale thermoelectrics can enable "fingerprinting" of proteins and their interactions



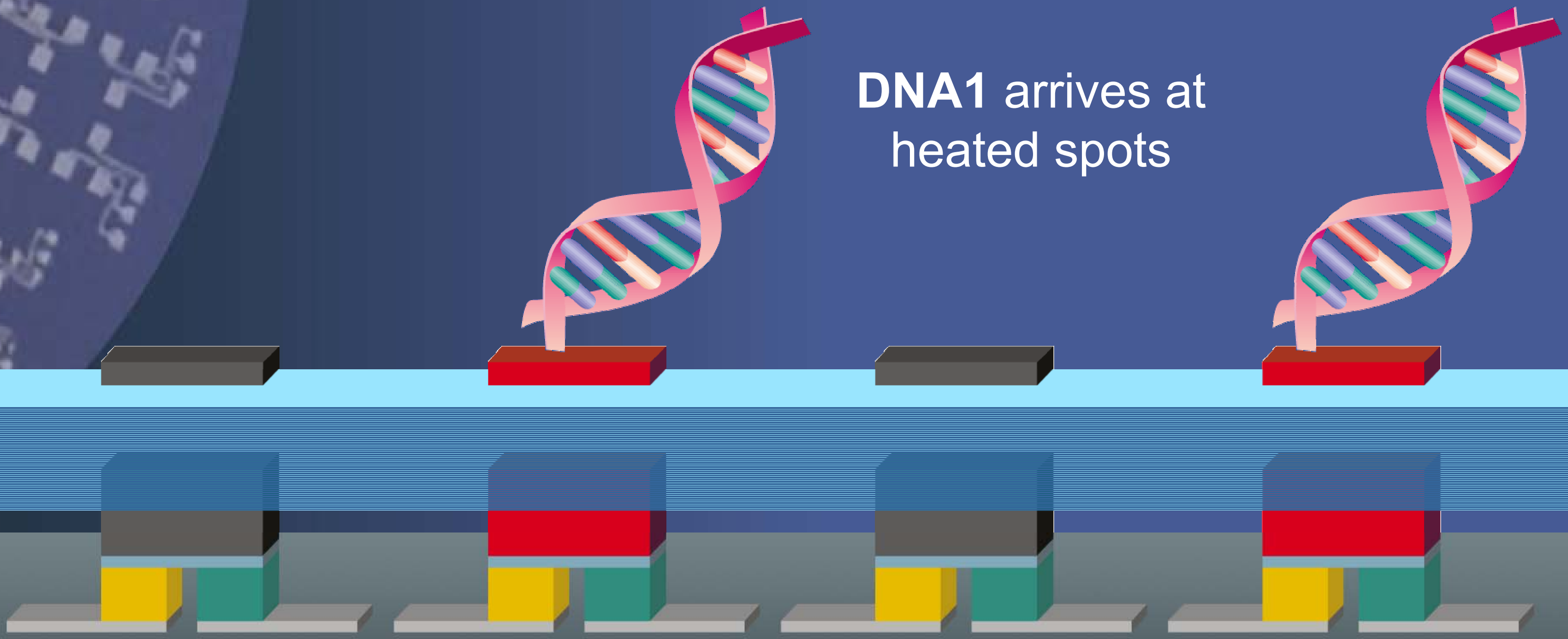


High-speed PCR

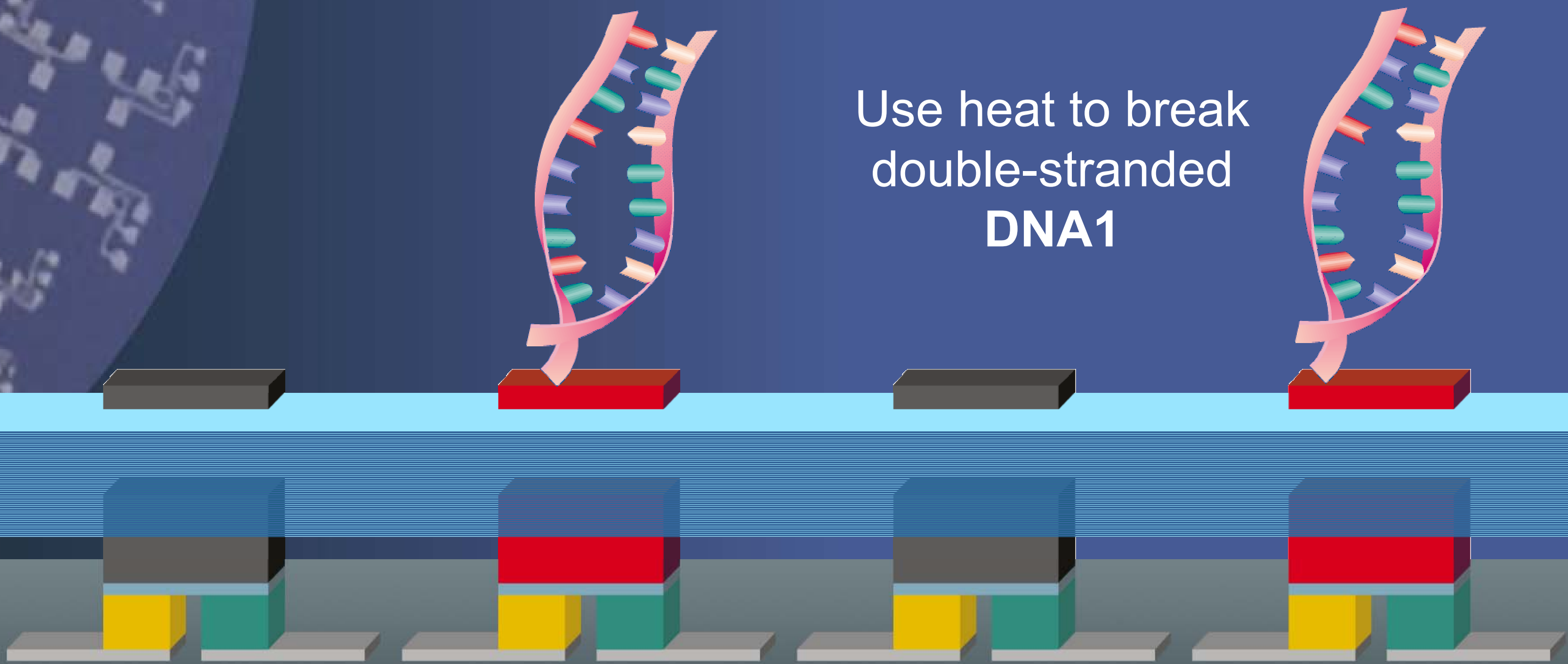
- Typical PCR- starts with double-strand DNA being split at 95°C, temperature lowered to where single strands can bind together with new strands
  - Two-step heating cycle is repeated n times, produces 2^n copies of target sequence
  - From a single starting molecule, 20 cycles yield over 1M, 30 cycles 1B, and 40 cycles 1T copies
  - Typically each cycle is 1 minute
- Reducing cycling time, efficient devices, and small-scale battery-operated systems can lead to field applications for DNA testing for pharmacology and bio-weapon detection

Self-Assembly of DNA Microarrays

Self-Assembly of DNA Microarrays

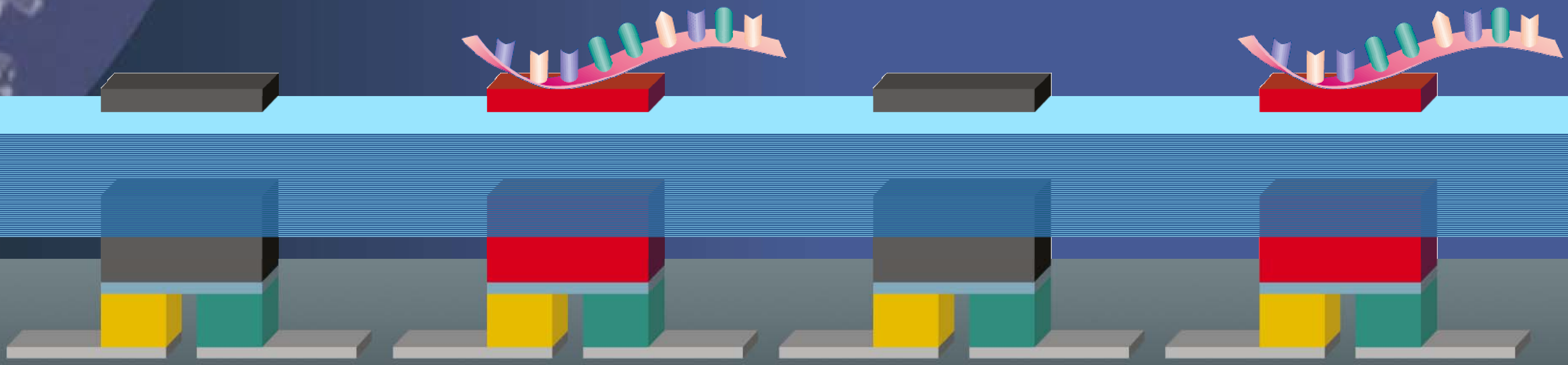


Self-Assembly of DNA Microarrays



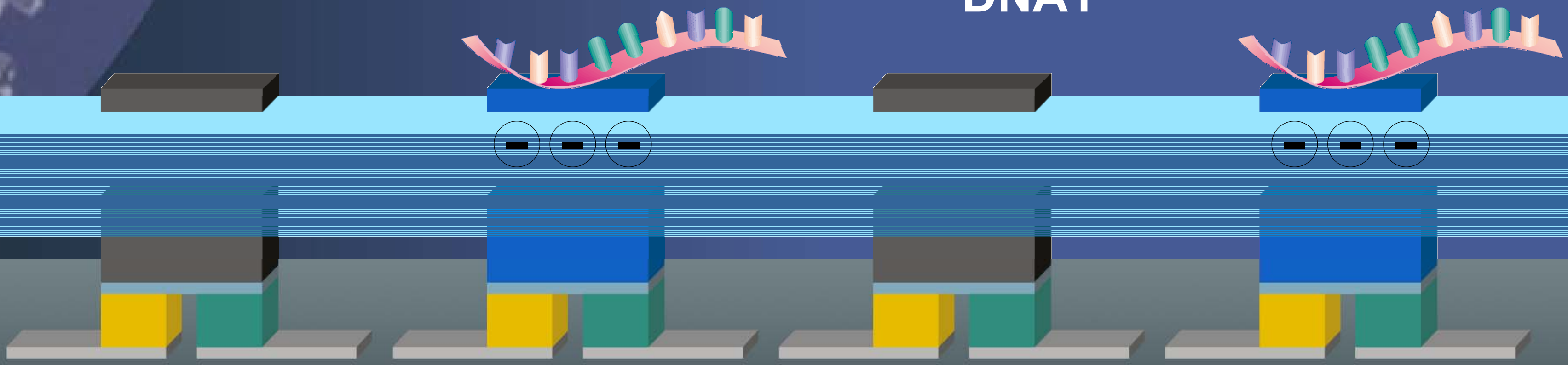
Self-Assembly of DNA Microarrays

A single-stranded
DNA1 is created

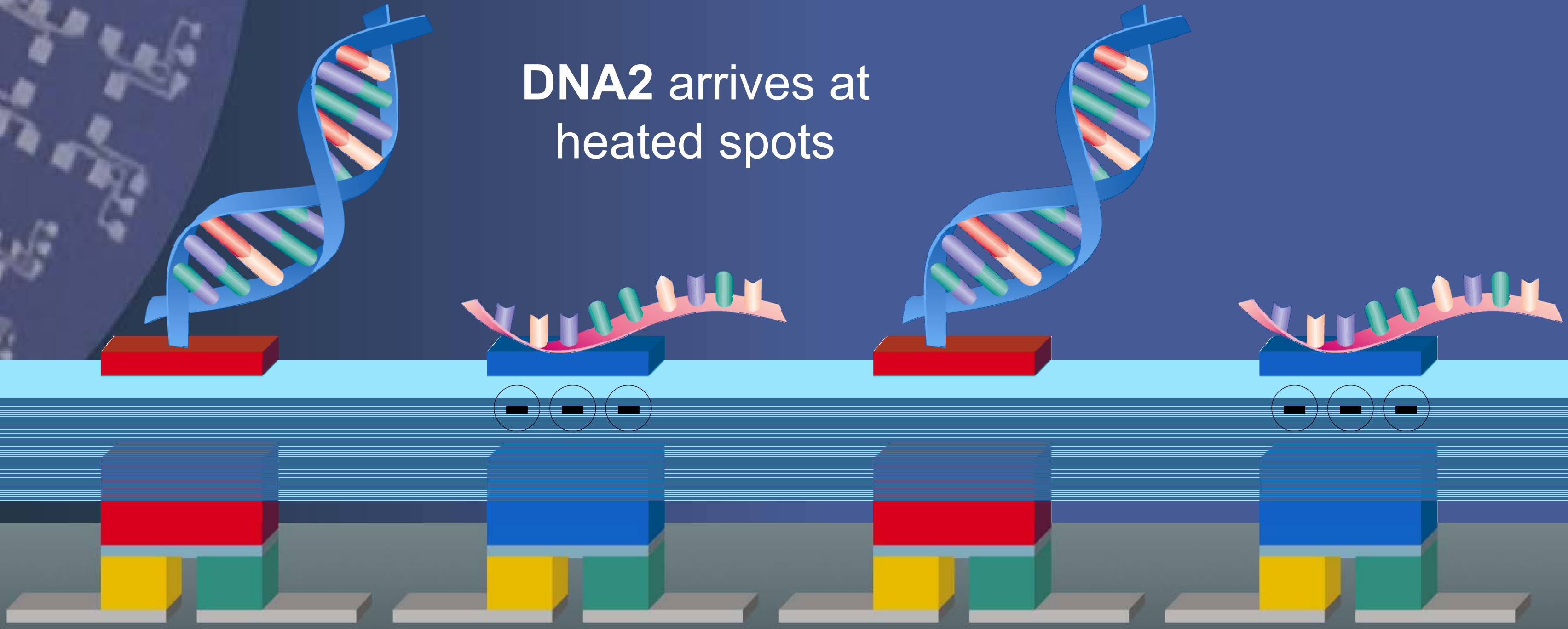


Self-Assembly of DNA Microarrays

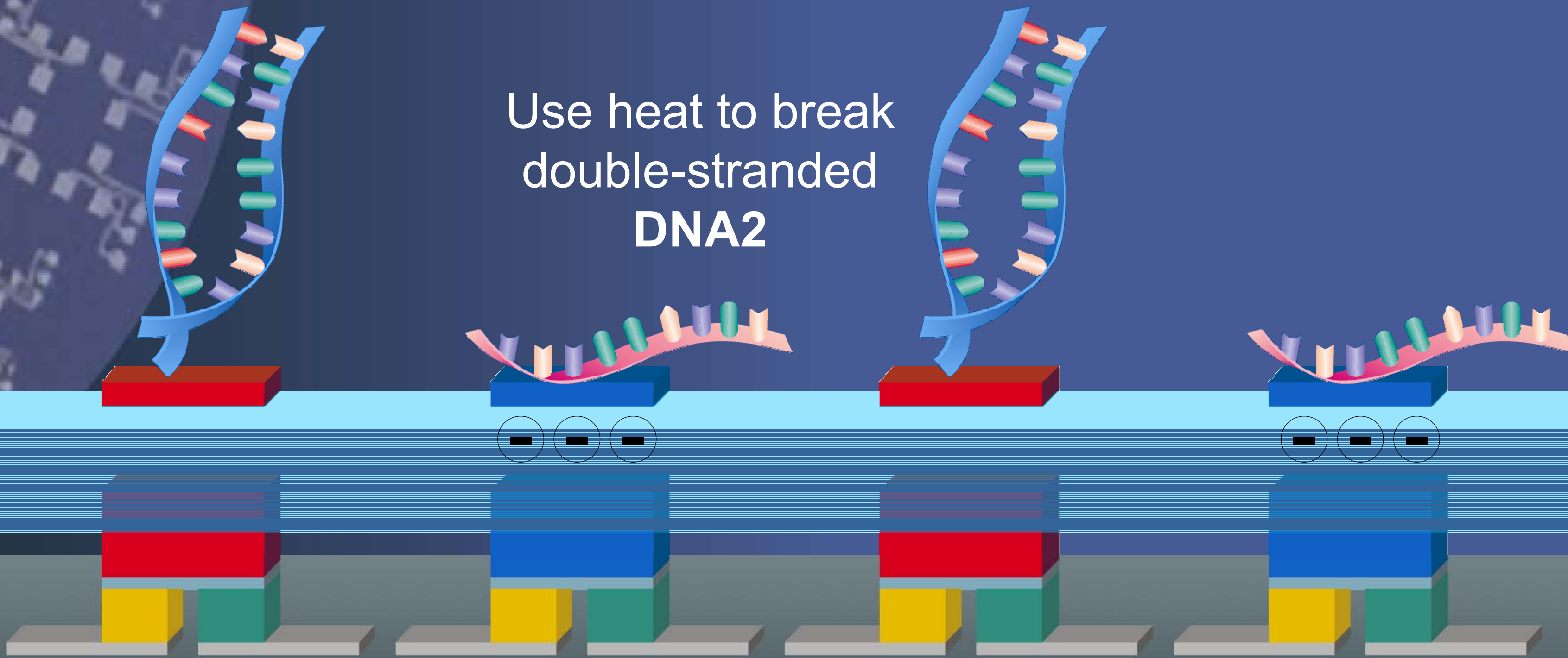
Use charge and
cooling to trap
single-stranded
DNA1



Self-Assembly of DNA Microarrays

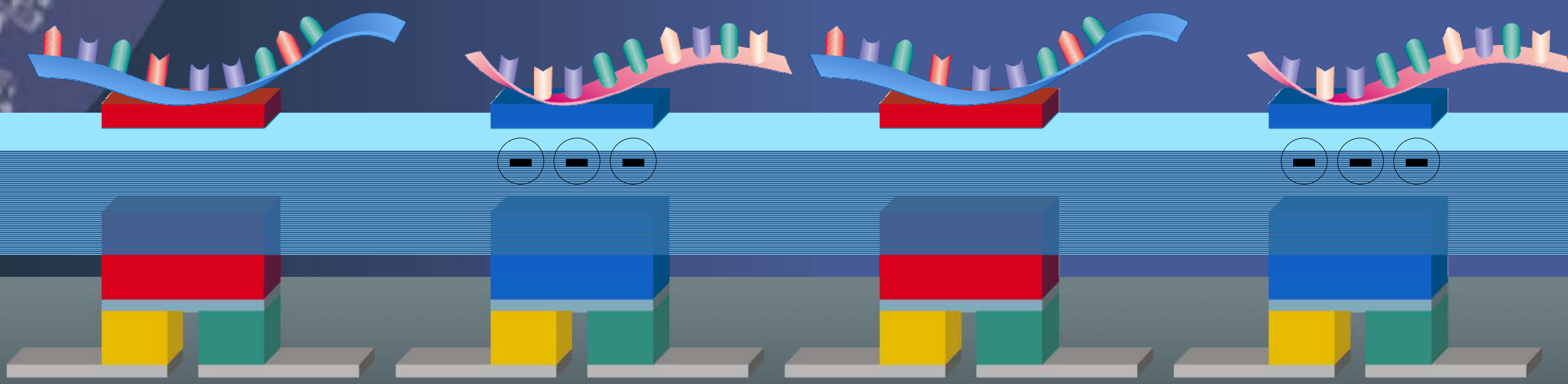


Self-Assembly of DNA Microarrays



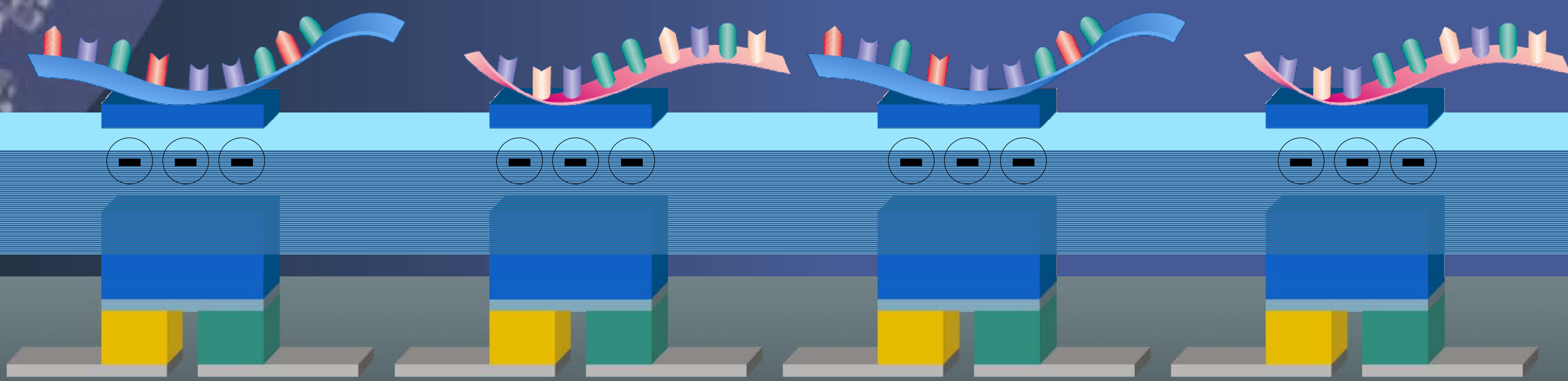
Self-Assembly of DNA Microarrays

A single-stranded
DNA2 is created



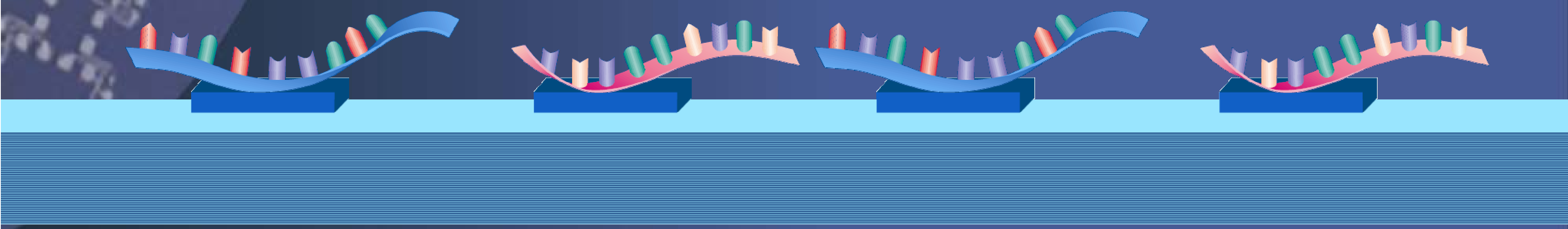
Self-Assembly of DNA Microarrays

Use charge and
cooling to trap
single-stranded
DNA2



Self-Assembly of DNA Microarrays

Self-assembled DNA-array ready
for experiments



40-Year Breakthrough — A Multitude of Opportunities