THERMOELECTRIC DEVELOPMENTS FOR VEHICULAR APPLICATIONS

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FreedomCAR and Vehicle Technologies
Energy Efficiency and Renewable Energy
US Department of Energy
Washington, D.C.

Diesel Engine-Efficiency and Emissions Research (DEER) Conference
Detroit, MI
August 24, 2006
One Level Above the Bridge
- Enhanced View of the Horizon
- See “Perhapsatron” Mirage or an Widely Encompassing Range of High Efficiency Thermoelectric Energy Saving Applications?

Here is the Presentation......You be the Judge
Thermoelectric Applications - Now to Near Term

- Historical
- Analytical
- Seebeck Effect Thermoelectric Generators
- Peltier Effect Thermoelectric Cooling/Heating

DOE/NETL Vehicular Thermoelectric Generators

- 2 Teams SI Gasoline Engine Powertrains
- 2 Teams Heavy Duty Truck Diesel Engines

Emerging High Efficiency Thermoelectrics

- Recent Quantum Well Results at Hi-Z Technologies
- Potential Scale up Nanoscale Thermoelectrics
- High Rate Sputtering Equipment and scale-up challenges
Nondimensional Figure of Merit

\[ ZT = \frac{\sigma S^2 T}{k} \]

- Joule Heating
- Seebeck Coeff.
- Electron Cooling
- Reverse Heat Leakage
- Through Heat Conduction

GPHS Radioisotope Thermoelectric Generator
To increase $Z$, we want

$$ S \uparrow, \quad \sigma \uparrow, \quad \kappa \downarrow $$

but

$$ S \uparrow \Leftrightarrow \sigma \downarrow $$

$$ \sigma \uparrow \Leftrightarrow \kappa \uparrow $$

With known conventional solids, a limit to $Z$ is rapidly obtained.

Best alloy: Bi$_{0.5}$Sb$_{1.5}$Te$_3$

$ZT \sim 1$ @ 300 K
Nanoscale Effects for Thermoelectrics

Interfaces that Scatter Phonons but not Electrons

Electrons

Mean Free Path
\( \Lambda = 10-100 \text{ nm} \)
Wavelength
\( \lambda = 10-50 \text{ nm} \)

Phonons

\( \Lambda = 10-100 \text{ nm} \)
\( \lambda = 1 \text{ nm} \)
Phonon in solid-state physics is a quantum of lattice vibrational energy. In analogy to a phonon (a quantum of light), a phonon is viewed as a wave packet with particle like properties.

The way phonons behave determines or affects various properties of solids.

Thermal conductivity, for instance, is explained by phonon interactions.
State-of-the-Art in Thermoelectrics

<table>
<thead>
<tr>
<th>Material Combination</th>
<th>Nano</th>
<th>Bulk</th>
</tr>
</thead>
<tbody>
<tr>
<td>PbTe/PbSeTe</td>
<td>32</td>
<td>28</td>
</tr>
<tr>
<td>Bi$_2$Te$_3$/Sb$_2$Te$_3$</td>
<td>40</td>
<td>50.9</td>
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</table>

Harman et al., Science, 2003

<table>
<thead>
<tr>
<th>Material Combination</th>
<th>Nano</th>
<th>Bulk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi$_2$Te$_3$ alloy</td>
<td>0.6</td>
<td>1.45</td>
</tr>
<tr>
<td>Si$<em>{0.8}$Ge$</em>{0.2}$ alloy</td>
<td>2.4</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Thermoelectric Wristwatch

> Converts temperature difference between body and surrounding air into electrical energy

> No battery change needed

> When not being worn, second hand moves in 10-second increments (non power generation mode)

> Number of semiconductors in thermocouple array: 1,242 pairs

> Operating time from a full charge: Approx. 6 months (approx. 16 months in power saving mode)
Spacecraft using Radioisotope Thermoelectric Generators

U.S. Radioisotope Missions

Used safely in 28 missions since 1961

9 Earth orbit (Transit, Nimbus, LES)
7 on lunar surface (Apollo ALSEP)
7 Planetary (Pioneer, Voyager, Galileo, Ulysses, Cassini)
5 on Mars surface (Viking, Pathfinder, Spirit, Opportunity)

Distances and Planets Are Not to Scale
TE Energy Recovery Benefit

- Use of aluminum results in a 500 lb weight reduction, with consequent fuel saving.
- Currently, only luxury cars use Aluminum frame and body, due to high cost.
- If we can recover sufficient energy from the Aluminum manufacture process, it may become feasible to use it for mass-produced cars, due to reduced cost.

2004 Jaguar XJ
BMW’s Magnesium Engine Block

Quantum Well TE Module

Small size (1 in³) requirement satisfied using QW TEG

Provides power for wireless sensors:

- 5 mW at 3 V using 41°C ΔT from ship interior thermal environment

Generator dimensions:

- 1 in² footprint
- ½ inch height
15% Efficiency Predicted with two 5 kW$_e$ QW TE Generators Driven by Vehicle Exhaust

When Parked APU Burner to Provide Power Using Same Thermoelectric Generator
Five $kW_e$ Quantum Well Thermoelectric Generator

- Contains 64 QW Modules in Octagonal Arrangement
- Integrated Coolant & QW Module Unit
  - Each QW Module in Compression
- QW Generator provides 5x power of current $Bi_2Te_3$ module in same space
  - Fits in 27 inch length and 10 inch diameter with cover plate
**ZT ~ 2 to 3 would warrant TE technology development for large scale applications**

-ZT = 2 to 3 would warrant TE technology development for large scale applications.

- $T_H = 27 \, ^\circ C$
- $\Delta T = 20 \, ^\circ C$
- $\Delta T = 30 \, ^\circ C$
- $\Delta T = 40 \, ^\circ C$

- For $T_C = 30 \, ^\circ C$ and $T_H = 500 \, ^\circ C$, $\epsilon / \epsilon_{\text{carnot}} = 0.6$.

- $\Delta T = 20 \, ^\circ C$
- $\Delta T = 30 \, ^\circ C$
- $\Delta T = 40 \, ^\circ C$

- COP = 6

- $ZT \approx 2$ to $3$
today...

POWER SOURCE
- Batteries

CLIMATE CONTROL
- None

...tomorrow

POWER SOURCE
- Logistic fuel based system

CLIMATE CONTROL
- Thermoelectric based cooling/heating
  - On-demand

IMPACT
- >30% weight savings over existing systems

Enabled by Thermoelectrics (TE)

Assumptions
12 hour mission @ 110°F ambient temperature

DARPA TTO Program Manager: Ed van Reuth
- Heat-exchanger design optimization for 200 $W_e$ TE-based lightweight power generator
- Developed mass-optimized designs for air recuperator and cold-side TEG heat sink
- Design total system mass at 3 kg

Diagram:
- JP-8 FUEL
- 80% of heat to TEG
- 20% of heat to exhaust
- Power to soldier electrical needs or TE cooling
- Combustion air
- Cooling Air Flow
- Recuperator
- Combustor
R-134a refrigerant gas is the most common working fluid in vehicular air conditioners (A/C) since 11/15/95.
- Replaced Freon gas which was detrimental to Ozone layer

- R-134a has 1,300 times greater greenhouse gas impact than CO₂
- Car air conditioners (A/C) leak 10 to 70 g/year
  - 90 % personal vehicles in North America & Asia
    and 87 % European cars have A/C
- Peltier thermoelectric HVAC systems significantly reduce Man’s contribution to Greenhouse Gases
- While improving fuel economy
7-8 Billion Gallons/Yr of Fuel Use for Automotive A/C (NREL)

~6% of our National Light-Duty Fuel Use

Centralized Automotive A/C Systems Require ~ 4-5kW of Power Use

Smaller De-Centralized A/C Systems Could Require ~2-3 kW of Power
  > ZT > 2.0 Competitive with Refrigerant Gas Systems
- ZT ~ 1; COP ~ 0.9-1.0; Distributed HVAC System; P ~ 2 kW; Power Off Alternator
  - Decrease ~ 0.8 mpg/vehicle (0.8/27.5 ~ 0.029)
  - Increase ~ 1.9 Billion Gallons of Gasoline/Year Because of Low Alternator Efficiency
- ZT ~ 2; COP ~ 2; Distributed HVAC System; P ~ 1 kW; Power Off Alternator
  - Increase ~ 1.1 mpg/vehicle (1.1/27.5 ~ 0.04)
  - Save 2.6 Billion Gallons of Gasoline/ Yr
- Either ZT Case; Power From Thermoelectric Generator Converting Engine Exhaust Heat to Electricity
  - Increase ~ 3 mpg/vehicle (3/27.5 ~ 0.11)
  - Save ~ 7.1 Billion Gallons of Gasoline / Year

(Assumes: 3 kW for AC, 3 kW = 3 mpg, 130 M Gallons / Yr for Passenger Cars)
Thermoelectrics Replacing Gas Compressor Refrigeration?

TODAY

Thermoelectric Hot & Cold Mini Fridge (1.5 ft³)

FUTURE?

Side-by-side Refrigerator/Freezer (27.5 ft³)
Temperature affects battery operation

> Round trip efficiency and charge acceptance
> Power and energy
> Safety and reliability
> Life and life cycle cost

Battery temperature impacts vehicle performance, reliability, safety, and life cycle cost
Embedded Semiconductor Cooling
Removes Heat From Die to Heat Sink

**Nextreme’s solution**

- **Hotspots effect**
  - Reliability
  - Performance
  - Package cost

- **Embedded Thermoelectric in IC**
  - Active micro-cooling of hotspot
  - Reduces total power cooled
  - Simplifies package

- **Resolve Critical Path**

- **100 μm thickness**
The selected vehicle is a state-of-the-art BMW sedan with a 3 liter displacement engine (BMW 530i, MY 2006, automatic transmission).

The engine is the newest generation of highly efficient, in-line, 6-cylinder engines with characteristics representative of engines in the 2010 to 2015 timeframe.
Where will Vehicular Thermoelectric Generator Electricity Directly Converted from Engine Waste Heat be Used?
Increasing electrical power needs are being driven by advanced IC Engines for enhanced performance, emission controls, and creature comforts.

- Stability controls
- Telematics
- Collision avoidance systems
- Onstar Communication systems
- Navigation systems
- Steer by-wire
- Electronic braking
- Powertrain/body controllers & Sensors

These requirements are beyond the capabilities of the current generators and require supplemental electrical generation, such as from a TE waste heat recovery unit.

Juhui Yang GM
Beltless or More Electric Engine

**Modular HVAC**
Variable speed compressor more efficient and serviceable
3X more reliable compressor no belts, no valves, no hoses leak-proof refrigerant lines instant electric heat

**Shore Power and Inverter**
Supplies DC Bus Voltage from 120/240 Vac 50/60 Hz Input Supplies 120 Vac outlets from battery or generator power

**Down Converter**
Supplies 12 V Battery from DC Bus

**Compressed Air Module**
Supplies compressed air for brakes and ride control

**Electric Water Pump**
Higher reliability variable speed faster warm-up less white smoke lower cold weather emissions

**Electric Oil Pump**
Variable speed Higher efficiency

**Starter Generator Motor**
Beltless engine product differentiation improve systems design flexibility more efficient & reliable accessories

**Auxiliary Power Unit**
Supplies DC Bus Voltage when engine is not running - fulfills hotel loads without idling main engine overnight

**Truck Electrification**
Electrify accessories decouple them from engine
Match power demand to real time need
Enable use of alternative power sources

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable
BMW’s Electric Water Pump Improves Fuel Economy 1.5 to 2.0 %
BMW Series 5 Engine with Electric Water pump

- BMW Valvetronic
- BMW VANOS
- Oil/coolant Heat exchanger
- One belt engine

Weight: 161 kg
Power: 190 kW
Max engine speed: 7000 rpm

Electric Water Pump (200 W)
**Project Objective:** Improve fuel efficiency of a heavy-duty, on-highway truck by 10%

**Phase I Results:**
- 18 kW TE generator designed
- Full system projects 8 – 8.5% improvement in fuel economy
- Critical customers demand, to buy, 2 – 9% improvement in fuel economy
Thermoelectric Recovery of Engine Waste Heat
at United Technologies

Diesel Engine

Caterpillar

Aircraft Engine

Pratt & Whitney

Waste Heat Recovery

Thermoelectric Solid State Technology

Energy
## High Efficiency Thermoelectric Teams

<table>
<thead>
<tr>
<th>General Motor Corporation and General Electric</th>
<th>University of Michigan, University of South Florida, Oak Ridge National Laboratory, and RTI International</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSST, LLC.</td>
<td>Visteon, BMW-NA, and Marlow, Purdue, UC Santa Cruz, NREL, Teledyne, JPL</td>
</tr>
<tr>
<td>United Technologies Corporation</td>
<td>Pratt &amp; Whitney, Hi-Z Technology, Pacific Northwest National Laboratory, and Caterpillar, Inc.</td>
</tr>
<tr>
<td>Michigan State University</td>
<td>Jet Propulsion Laboratory, Tellurex and Cummins Engine Company</td>
</tr>
</tbody>
</table>
Available Energy in Engine Exhaust
Primary contributors:
Visteon, BMW and Teledyne

Supporting this technology development:
NREL, University of California at Santa Cruz, Purdue University and JPL
BSST’s Vehicular Thermoelectric Generator Project

OBJECTIVE: WASTE HEAT RECOVERY AND CONVERSION TO ELECTRIC ENERGY

10% Fuel economy improvement by offloading the alternator
Shell & tube heat exchanger for exhaust gas heat transfer

He/Xe working fluid transports thermal energy to TEG

Cat converter

Exhaust gas bypass flow

Muffler
High power density liquid to liquid heat exchanger
Modeled performance validated through testing
The selected vehicle is a state-of-the-art BMW sedan with a 3 liter displacement engine (BMW 530i, MY 2006, automatic transmission).

The engine is the newest generation of highly efficient, in-line, 6-cylinder engines with characteristics representative of engines in the 2010 to 2015 timeframe.
BMW Series 5, Model Year 2010, 3.0 Liter Gasoline Engine w/ Thermoelectric Generator
- High performance $\text{Bi}_2\text{Te}_3$-based superlattice for radiator-based applications
- High performance bulk Silicon/Germanium, PbTe, and TAGS for exhaust-based applications
- Advanced materials based on nano-structured bulk (NSB) composites
Joule heating from all electrical contacts are accounted for.

Contact Resistances

- Thermal
- Electrical & thermal
- Joule & Peltier terms

Subpart Modeling

- Hot side heat exchanger
- Insulator
- Conductor
- Metal
- Volume resistivity
- Cold side heat exchanger
- Insulator
Temperature Profile Through TEG

Results indicate hot gas heat transfer is a primary bottleneck
Grow Si/Ge-based SL materials with enhanced ZT
Remove film while preserving the nanostructure within the particles
Combine SL film particles to form bulk pellet of enhanced ZT material
Larger ΔT for NSB potential higher efficiency and more power output.
- Films sent to Ames for conglomeration via hot pressing
- A more aggressive cleaning etch composed of HF and HNO$_3$ was used
- Conglomeration is improving
RTI SL materials out-perform bulk equivalent with higher ZT and efficiency at ΔT available in automotive applications

- Bulk segmented couples producing >300mW with >8% efficiency (ΔTₑ~ 600°C)
- Bulk couple arrays producing >1 Watt (ΔTₑ~ 600°C)

- Nano-structured bulk material work started with encouraging results – team with GM to enhance conglomeration

Enabled by DARPA/ONR support
High Temperature Material Testing: RT- 500C
1. N-type, P-type and undoped Marlow Elements (15)
2. Skutterudites: GM (4 misch-metal compositions)
3. Clathrates: USF (5 compositions)
4. NIST: Half-heusler (HoNiSb)

Other materials being tested:
- Oxides: Bulk ORNL, thin film PSU
- LAST (similar to MSU by GM)
Japanese Vehicular Thermoelectric Generator Program

Thermoelectric Power Generation for Diesel Engine Co-Generation System

KOMATSU Ltd.

Cooling Water

High Efficiency Condenser

TE Element

Cooling Plate

Exhaust Gas

Tubes

High Efficiency Evaporator

Diesel Engine

Schematic of Thermo-Siphon Type Heat Recovery TE System

Courtesy of Dr. Takanobu Kajikawa, Project Leader,

Japanese National Project on Development for Advanced Thermoelectrics
Nanostructured QDSL materials greatly improves ZT
Impact of ZT on Efficiency

Medium-Grade Heat Sources

- ΔT = 50
- ΔT = 100
- ΔT = 150
- ΔT = 250

Low-Grade Heat Sources

- ΔT = 5
- ΔT = 10
- ΔT = 15
- ΔT = 20

Exciting for many applications
Comparison of P-type B$_4$C/B$_9$C & N-type Si/SiGe Quantum Well materials using measured $\alpha$ & $\rho$, & published bulk $\kappa$ versus current Bi$_2$Te$_3$, PbTe & SiGe materials

Data: QW & Bi$_2$Te$_3$ Hi-Z; PbTe & SiGe JPL Properties Manual
General Atomics Sputtering Capabilities

New coatings developed on R&D coater

New products developed on R&D Web Coaters

12” Coater (LESKER)

36” Web Coater (ISM)

40” Web Coater (8-Ball)

Material production on 80” Web Coater

80” Web Coater (ALOC)
Large Scale Sputter Coating System

Production Roll Coater can Provide Precision Polymer Coatings on up to 80-inch Wide Materials

Mayer Rod Coating & Micro-gravure
Solid State All-Electric Thermoelectric Hybrid Vehicular Powertrain
Thermoelectric Technology Possibilities for Vehicular Powertrains

Near Term (3-5 yrs)

- Thermoelectric Generator providing 10% fuel economy gain (MPG)
- "Beltless" or more electric engine
  Thermoelectric HVAC (air conditioner/heater) for vehicles

Mid Term (8-12 yrs)

- 2nd Generation Thermoelectric Generators
  - 20% fuel economy gain auto, light truck (SUV’s, Pick-ups and Mini-vans) gasoline engines
  - 16% fuel economy gain heavy duty trucks

Long Term (12-25 yrs)

- 35% efficient Thermoelectrics with 500 °C ΔT
  - Replace Internal Combustion Engine
  - Combustor burns any fuel

Very Long Term (60+ yrs)

- Radioisotope replaces combustor for vehicle propulsion
  - 30+ years life powertrain
  - Replace vehicle body periodically
Find thermoelectric materials and system designs that can replace the internal combustion engine

A system that can convert 25% of its input fuel energy to electric power can potentially replace some internal combustion engines

A system that can convert 50% of its input fuel energy to electric power could potentially replace most gasoline and diesel engines and would even challenge fuel cells.

Francis Stabler, GM, MRS 11/28/05
“If capacity to generate power from heat can be enhanced significantly …………..

No effort should be spared if there is the remotest prospect of realizing such high efficiency devices”

» Harold Wickes letter 12/05/05 to MIT Technical Review in response to article “Free Power for Cars”
Key: Scale is important
Technical Challenges for Nanoscale Thermoelectrics

- Scale Up to Commercially Viable Thermoelectric Modules
  - Reproduce Lab Scale Microstructure
  - Minimize Contact Resistance
  - Interlayer Diffusion
  - Substrate
    - Provide Structural Support
    - Minimal Thermal Shunt

Measurements
Power Conditioning
Vehicle Integration
Further Fundamental Investigation

NO SHOW STOPPERS AT THIS TIME
Quantum Well Film Comparisons to Current Bi$_2$Te$_3$

- Quantum well module with N- and P-type Si/SiGe on Kapton Substrate vs
- Current Bi$_2$Te$_3$ module at the same geometry and operating conditions ($\Delta T = 200 ^\circ C$, heat flux $= 10$ W/cm$^2$)
  - 3x power
    - 50 W for QW vs 14 W for Bi$_2$Te$_3$
  - 7x voltage
    - 12 Volts for QW vs 1.7 Volts for Bi$_2$Te$_3$
  - 10x higher specific power
    - 2.5 W/gm for QW vs 0.2 W/gm for Bi$_2$Te$_3$
  - 10x lower raw materials cost
    - $0.10$/Watt for QW vs $1.00$/Watt for Bi$_2$Te$_3
From Quantum Well Films to Thermoelectric Power Module

Alternating 10 nanometer Thick Si/SiGe Films Up to 11 µm Thick

Kapton Substrate ~ 50 µm Thick

100 films form one TE couple
N element
P element

49 TE couples give 50 Watts in 6x6x1 cm TE module at ΔT=200°C
Two Couple Power Producing Device with Si/SiGe Quantum Wells and Mo Contacts on Kapton Substrate Yields Expected Power

Fabrication Approach

Results

<table>
<thead>
<tr>
<th></th>
<th>Experimental</th>
<th>Calculated</th>
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<tbody>
<tr>
<td></td>
<td>2 Couples Measurements</td>
<td>26 Couples at ΔT = 40°C</td>
</tr>
<tr>
<td></td>
<td>at ΔT = 40°C</td>
<td></td>
</tr>
<tr>
<td>T_COLD = 26°C</td>
<td>225 milli Volt</td>
<td>2.93 V</td>
</tr>
<tr>
<td>T_HOT = 66°C</td>
<td>0.371 milli Watt</td>
<td>3V</td>
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<tr>
<td>Voltage (V_OC)</td>
<td></td>
<td>0.5V</td>
</tr>
<tr>
<td>Power</td>
<td>4.82 milli Watt</td>
<td>5 milli Watt</td>
</tr>
<tr>
<td></td>
<td>1.5 mili Watt</td>
<td></td>
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</table>

Quantum Wells
Si/SiGe
with ZT ~ 3.0

Bulk
(Bi,Sb)_2(Se,Te)_3
With ZT ~ 0.75
Quantum Well Film Materials Summary

Quantum well TE material for 50 Watt module

- 0.32 m² with 11 micron multilayer film thickness
- Volume 3.5 cm³
  - Based on $\Delta T = 200^\circ C$, heat flux = 10 W/cm² gives » 64 cm²/Watt
  - Area/volume reduced with higher $T\Delta$ and heat flux
- Raw materials
  - Si $37.20$/kg
  - Ge $956.30$/kg
  - B $94.15$/kg
  - C $16.10$/kg
- 5μ Si substrates: $15,128.25$/m²
- Sputtered 2 μ Si on 1 Mil Kapton: $21.14$/m²
- High volume cost for QW TE module: ~0.20/Watt
Large Area Sputtering Leads to Rapid TE Module Assembly

Process Change - Folded Quantum Well Module
Sputtering process forms module & eliminates eggcrate
Improves efficiency and reduces costs

Masked for N & P size
N on one side of ribbon
P on other side

Folded ribbon with N & P facing each other
Metallized module with contact materials

Heat Flow
Path to Commercialization for Quantum Well Thermoelectrics

Dr. Lawrence Woolf
General Atomics
San Diego, CA

Presented at the
2006 Diesel Engine-Efficiency and Emissions Research Conference
Detroit, Michigan
August 24, 2006
A path to commercialization currently exists

- High rate sputtering on plastic films
  - “Web coating”
- Large-area, high-rate sputtering systems exist and are currently in use
- Kilometer-length rolls of meter-wide plastic film are continuously sputter coated in large vacuum chambers
General Atomics 36” wide film coater

36” wide roll of film
General Atomics 40” wide film coater
General Atomics 2.2-meter (80”) wide film coater
## Si/Si-Ge QWTE: path to commercialization

<table>
<thead>
<tr>
<th>Issue</th>
<th>State of Art</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Si is commonly used</td>
</tr>
<tr>
<td>Coating rate</td>
<td>1 μm thick at 100 m²/hr</td>
</tr>
<tr>
<td></td>
<td>10 nm thick at 10,000 m²/hr</td>
</tr>
<tr>
<td>Coating cost for 200 10 nm layers (2 μm total)</td>
<td>~$15/m²</td>
</tr>
<tr>
<td>Reproducibility/uniformity</td>
<td>~1%</td>
</tr>
<tr>
<td>Film length</td>
<td>0.5-5 km</td>
</tr>
<tr>
<td>Film width</td>
<td>1-2.2 m</td>
</tr>
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</table>
## Scale-Up Challenges

<table>
<thead>
<tr>
<th>Issue</th>
<th>Problem</th>
<th>Solution</th>
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<tbody>
<tr>
<td>Thermal</td>
<td>Coatings require 300-900 °C</td>
<td>Heat treatment during or after deposition</td>
</tr>
<tr>
<td>treatment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Substrate</td>
<td>Width, cost, temperature</td>
<td>Kapton-1.2m, $6/m², 400°C Proprietary substrates</td>
</tr>
<tr>
<td>Stress</td>
<td>Coatings &gt; few microns can crack</td>
<td>Process optimization Need to validate</td>
</tr>
<tr>
<td>Processing</td>
<td>100-1000 layers</td>
<td>Requires high quality film handling (~50 layers done)</td>
</tr>
<tr>
<td>TE Properties</td>
<td>Achievable in large scale/high rate</td>
<td>Need to validate</td>
</tr>
<tr>
<td>B-C films</td>
<td>Large area sputtering uncommon</td>
<td>Need to validate</td>
</tr>
</tbody>
</table>
A path to commercialization currently exists:

High rate continuous sputtering onto plastic films