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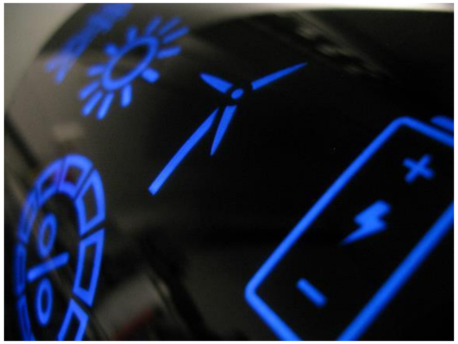
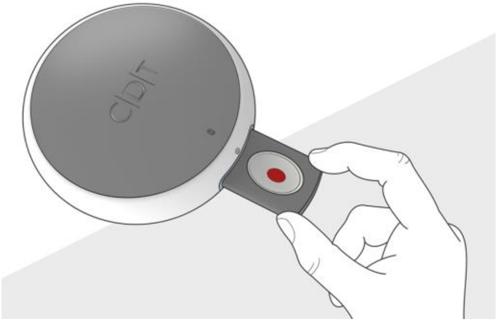
Printable Thermoelectrics to Enable the Self Powered IoT Revolution

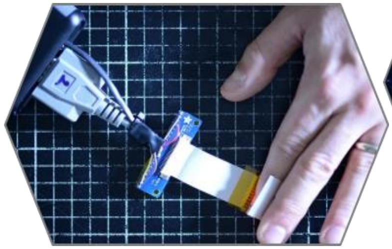
Thomas Fletcher

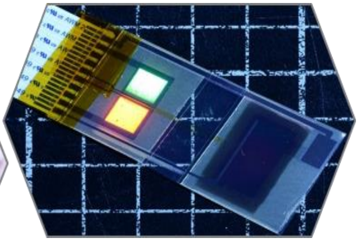
Introduction to CDT

- Spin-out from Cavendish Laboratory, University of Cambridge (1992) → POLEDs
- Part of Sumitomo Chemical Group since 2007
- Today, broader scope to research beyond OLED
  - Interdisciplinary team with strong expertise in physics, chemistry, materials and life sciences.
  - State-of-the-art chemistry & analytical labs, cleanrooms, device prototyping and testing.









Current Research Areas

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Biosensors and FlexOLED

- Bio-sensor Platform - new systems powered by printed semiconductors
- FlexOLED - low information content display

Lighting and Energy Applications

- Materials for large area OLED lighting
- Flexible Hybrid Battery/Supercapacitors
- Printed Thermoelectric Generators

Image and Gas sensors

- Printable Organic Photo Detector Arrays (OPD)
- Near infra-red photodiodes for medical and imaging applications
- Novel printable gas sensors

New Technologies

- Next generation of ideas that support SCC business themes.
- Feasibility projects to validate research proposals
- Build Open Innovation relationships

Outline

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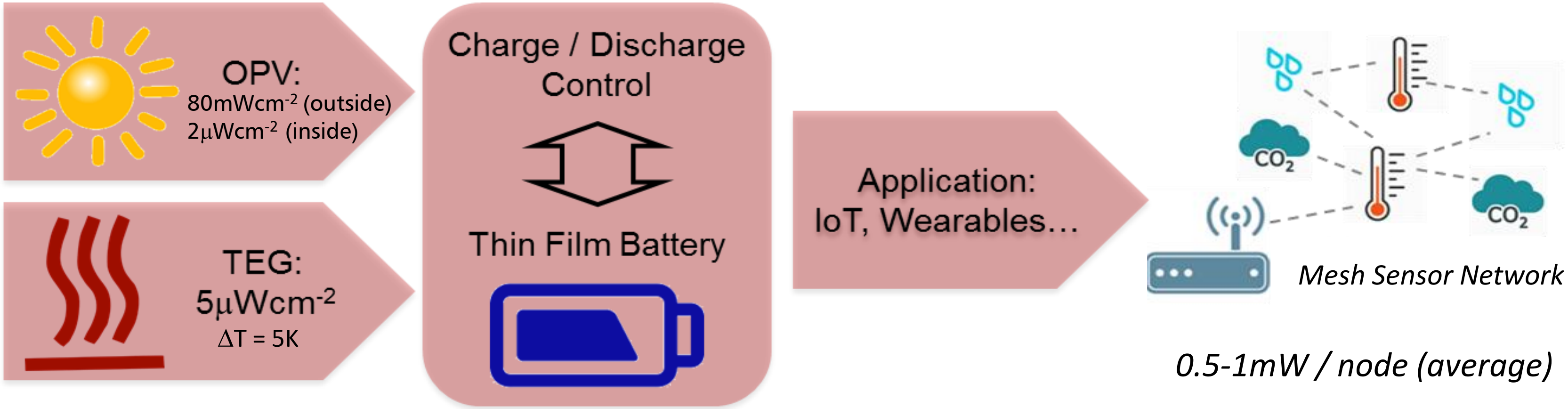
- Introduction to CDT
- **Energy Harvesting in IoT**
  - **Printable Thermoelectric Generators (P-TEGs)**
- Energy Storage requirements in IoT
  - Flexible hybrid supercapacitors/batteries

Energy Harvesting & Storage

– an alternative to primary batteries

Trend of increased monitoring of industrial processes, equipment and buildings has the power to reduce global energy consumption, improve safety and efficiency of production processes, and reduce equipment failures.

- This will require billions of sensors all which will need power sources.
- Battery replacement will not be feasible on this scale – energy harvesting must be used to create autonomous self powered systems.
- Thermoelectric Generators (TEGs) harvest waste heat from hot surfaces (pipe, boiler, motor..) and generate electricity to provide a power source for such sensors.



Applications, Market, Roadmap

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Application: Wireless Sensor Networks; Autonomous Systems

- *Single node low power wireless sensor*; power requirement 20µW; material and module already available.
- *Mesh networks of multiple sensors*; power requirement 500µW; under development - prototype March 2019.

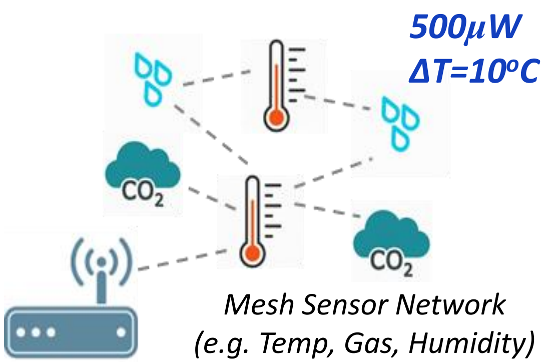
Market: TEG as energy harvesting for WSN predicted to reach $400M* by 2026. Total market for temperature and humidity sensors in the region of $2Bn.

*IDTechEx 2026

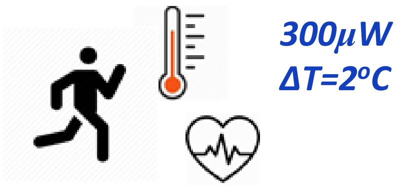
Future Applications: Wearable Electronics - wireless health & activity monitoring

- Key advantages: Conformability and freedom of design
- Increased output power enables additional applications/functionality and relaxes the ΔT requirements → Material development.

Temperature Monitor, Local Communication



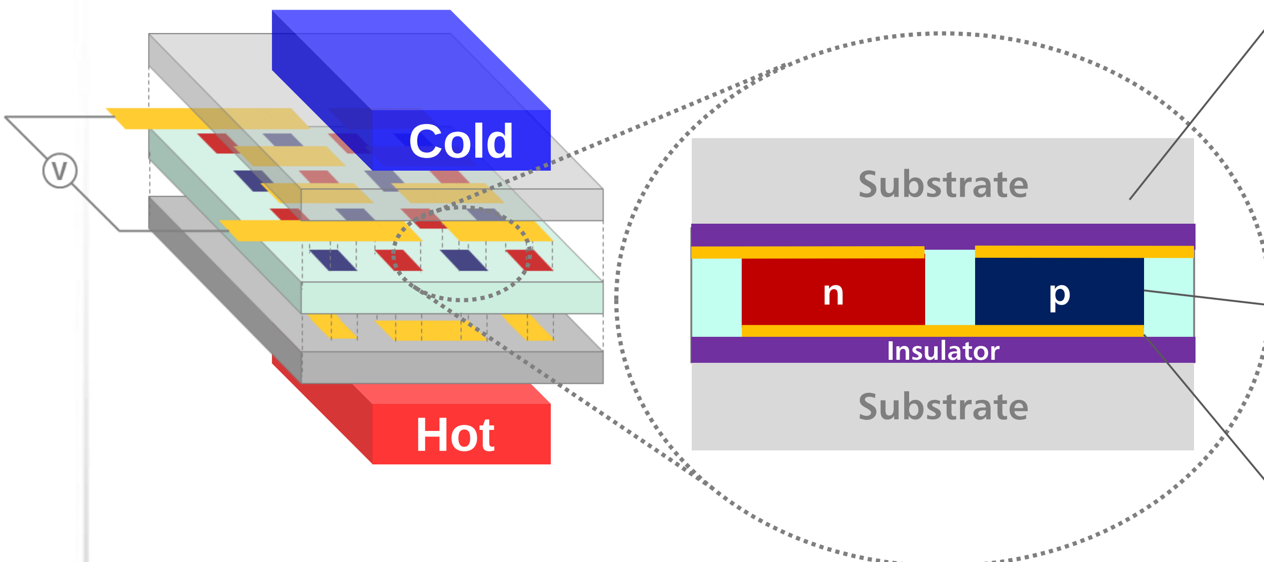
Mesh Sensor Network (e.g. Temp, Gas, Humidity)



Wearable Health/Activity Monitor

What is a Thermoelectric Generator?

Thermoelectric generators (TEGs) are semiconductor devices which generate a current from a temperature difference, usually between a hot surface and the ambient temperature.



1. Substrates:

- Transfer heat to active materials efficiently
- Electrically insulate active materials

2. Active Materials:

- Generate voltage from applied temperature difference
- High conductivity required

3. Contact resistance:

- Low resistance required to keep overall module resistance low

$$P_{max} = \frac{U^2}{4R_I} \qquad U \propto \Delta T$$

Benefits of Printed TEG

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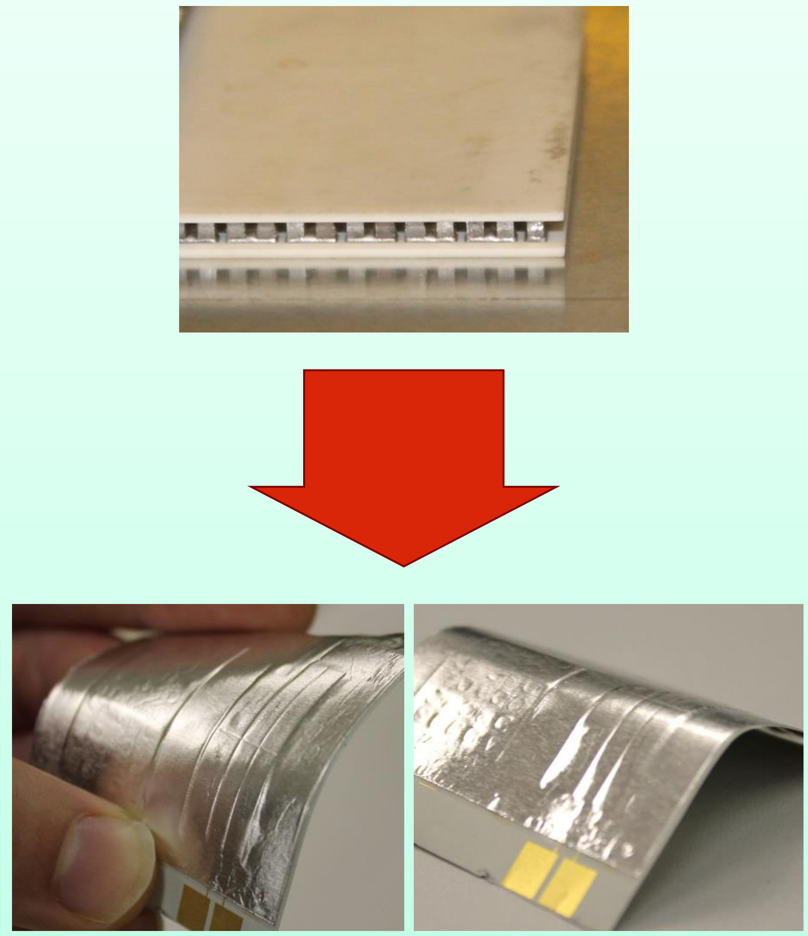
- Thin, low profile
- Flexible/Conformable
- Large area, customised shapes
- Low temperature processing
- Scalable production
- Integrates with other components

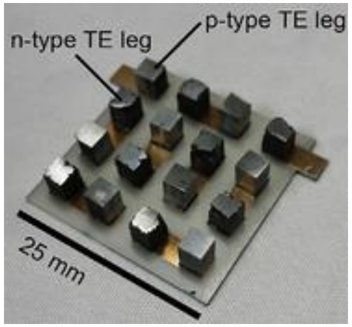


Printed TEG Fabrication

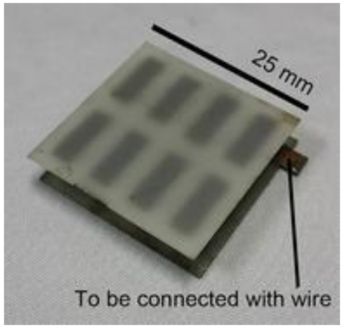
Conventional TEG Fabrication

1. Semiconductor ingot cast in furnace

2. Ingot cut into individual legs



3. Legs soldered onto ceramic substrate



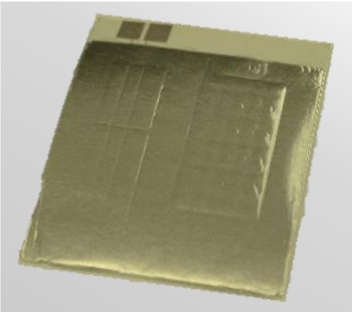
4. 2nd ceramic substrate soldered on top

CDT ***Printed*** *TEG Process*

1. Active material inks produced in ball mill

2. Foil Substrate with metal track and photoresist bank

3. Print active materials from ink



4. Encapsulate and cure ~250°c

Printed Module Performance

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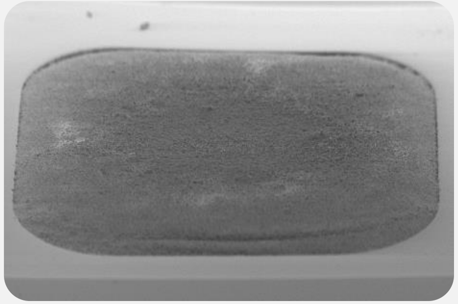
Printing process optimisation is key to obtain good module performance.

Dispense printing is used in R&D phase.
Screen printing will be used for larger module sizes and production volumes.

Summary of increases in power density

- 17x from PEN to foil
- 12x increase from material formulation
- 8x from lower contact resistance

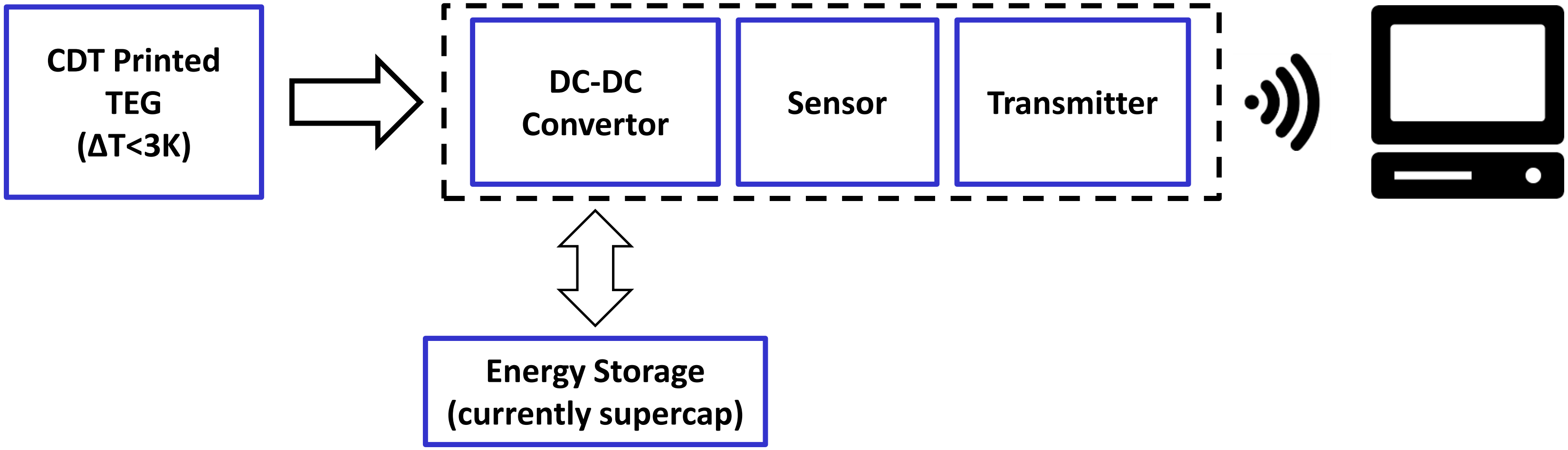
- ✓ Uniform print
- ✓ Filled wells
- ✓ Good contact



Recent increase in module size to give >100µW ΔT = 5K, over 1mW ΔT = 20K

Module (at ΔT = 5K)	Ink-1 PEN	Ink-1 Foil	Ink-2 Foil	Ink-2 Low R	Ink-2 Area Doubled
Voc / mV	3.25	11	31	25	66
Resistance / Ω	108	75	50	5	10
Total Power / µW	0.02	0.4	4.9	35	105
Power Density / µW cm^{-2}	0.004	0.08	1.0	7.4	8.8

Wireless Sensor Integration



Successful proof of concept that TEG can power EnOcean wireless temperature sensor.

- Continuous operation, with data transmission every 15 mins.
- TEG is actively cooled with $\Delta T<3K$

Next step is to integrate CDT energy storage to allow operation with fluctuating heat source.

TEG Status and Applications

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	Power Density (ΔT=5K)	Area	Cooling	Fabrication
April 2018	>6 $\mu W\ cm^{-2}$	12 cm^2	Active	Dispense
April 2019	>6 $\mu W\ cm^{-2}$	100 cm^2	Passive	Screen Print

Single Wireless Sensors

20 – 100 μW
ΔT = 5K

Integrated Multi-sensor Networks

500 – 1000 μW
ΔT = 5K

Valves & Actuators

Conformable Cooling

5 – 15mW
ΔT = 10K

Wearable & Medical

500 μW
ΔT = 1.5K

Increased TEG Performance

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  - **Flexible hybrid supercapacitors/batteries**

IoT Energy Storage Requirement

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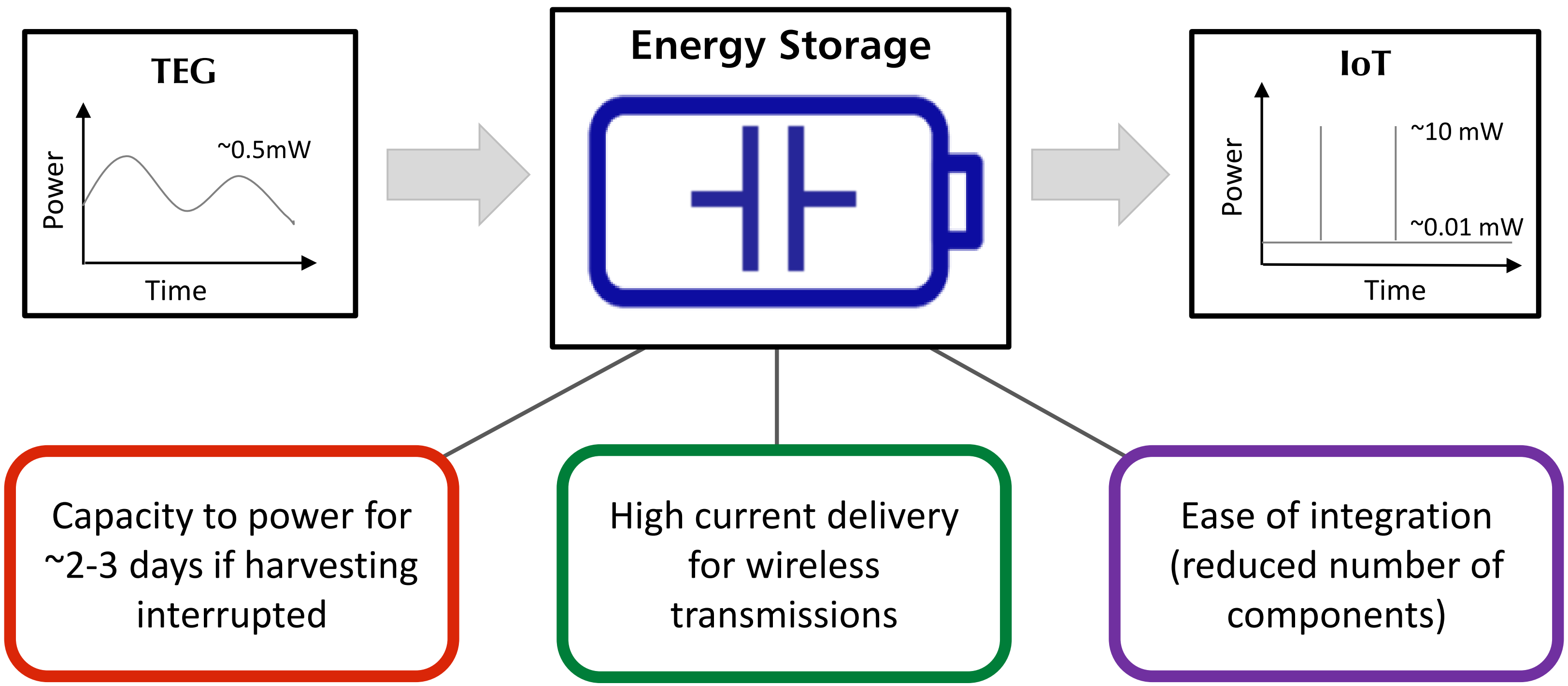
- Energy harvesters are intermittent and variable
- IoT devices have irregular power requirements
- A combination of energy harvester and energy storage is required



Our Value Proposition

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We are developing *Tuneable Hybrid* energy storage devices that combine properties of a supercapacitor (fast charge/discharge) and battery (high energy storage).

Conformable devices that can be easily integrated with energy harvesters.

High temperature stability (>100°C) that enables a variety of fabrication processes.

Autonomous Systems and WSN

- Mechanical flexibility and fast recharging.
- Secondary battery for increased product lifetime in combination with harvesters.

Wearables for Healthcare, Lifestyle, and Novel Applications

- Fast charging [<15 min]
- Safety
- Rechargeable & high current delivery (over Zn/MnO_2)

Supercapacitor-like Discharge Power & Battery-like Voltage Characteristics

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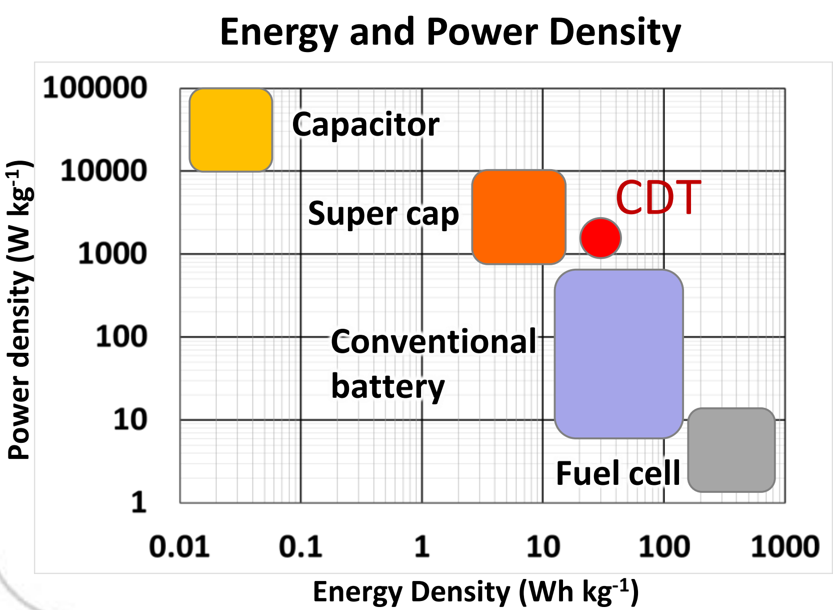
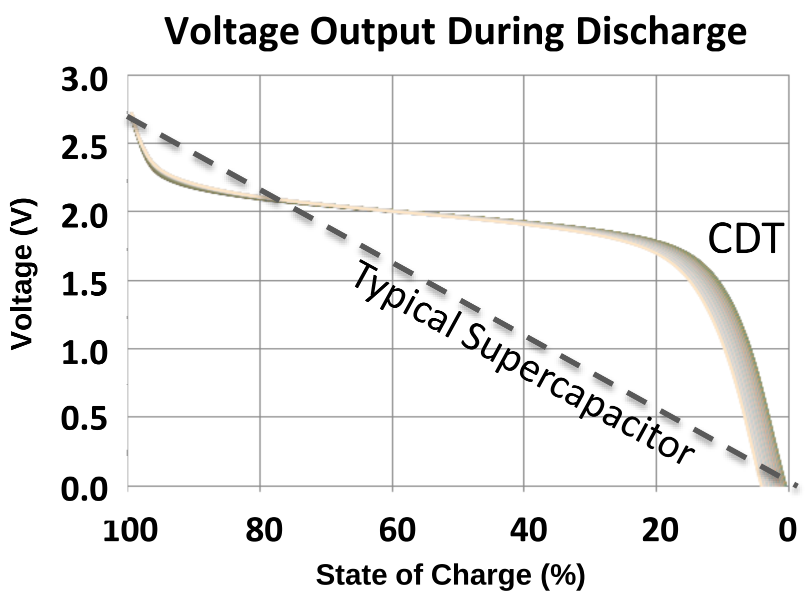
- ✓ No toxic polymer active materials and Ionic Liquid Electrolyte
- ✓ High power density* up to $25 mWcm^{-2}$ – required for Bluetooth protocols
- ✓ Printable, conformable form factor – potential for monolithic integration with TEG
- ✓ Stable voltage during discharge – simple to interface with electronics.
- ✓ Energy density of battery – sufficient to bridge variations in energy harvesting.

*(20ms pulse, 2V threshold)

Charge capacity > 1 $mAh\ cm^{-2}$ Lifetime > 400 cycles





Conclusion

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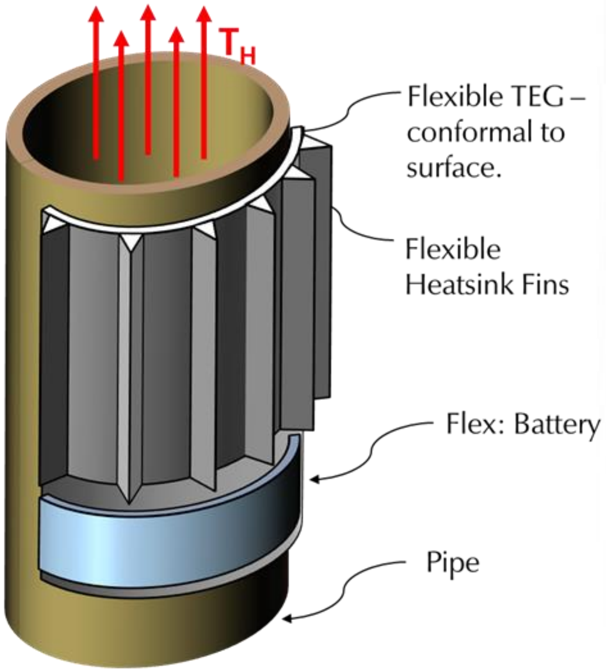
- Driven by application requirements, CDT is developing printable TEGs and conformable hybrid supercapacitors / batteries to enable self-sustaining low-power electronic devices.

- In addition to designing new materials, research into ink & paste formulations is critical for achieving high power output from printed TEGs and hybrid supercapacitors / batteries.

- We are looking for partners interested in the <u>development and commercialisation</u> of these technologies. Our offer includes providing limited numbers of prototypes for our partners.



Integration concept for flexible TEG and energy storage based energy harvester.

Acknowledgments

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- You – for your attention
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- Our collaborators
  - Sumitomo Chemical Corporation Ltd
  - Prof. J Evans' group at UC Berkeley
  - Prof. Yee, Reynolds and Marder groups at Georgia Tech.

If you are interested in working with us please contact us at:

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