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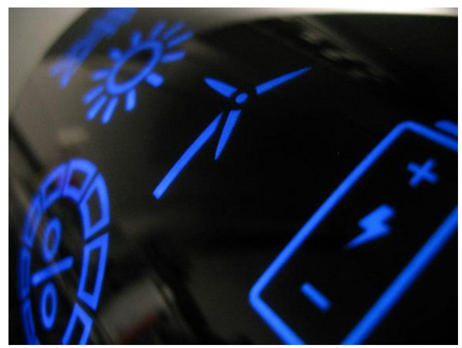
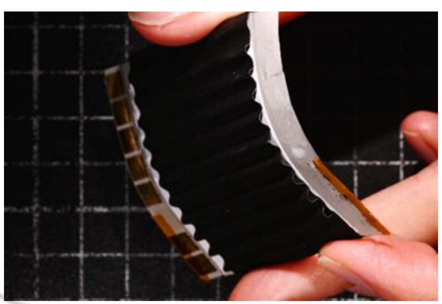
Printable Thermoelectrics to Enable the Self Powered IoT Revolution

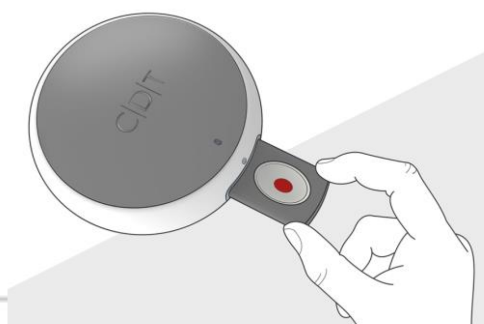
Simon King

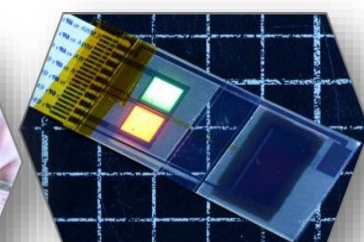
Introduction to CDT

- 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

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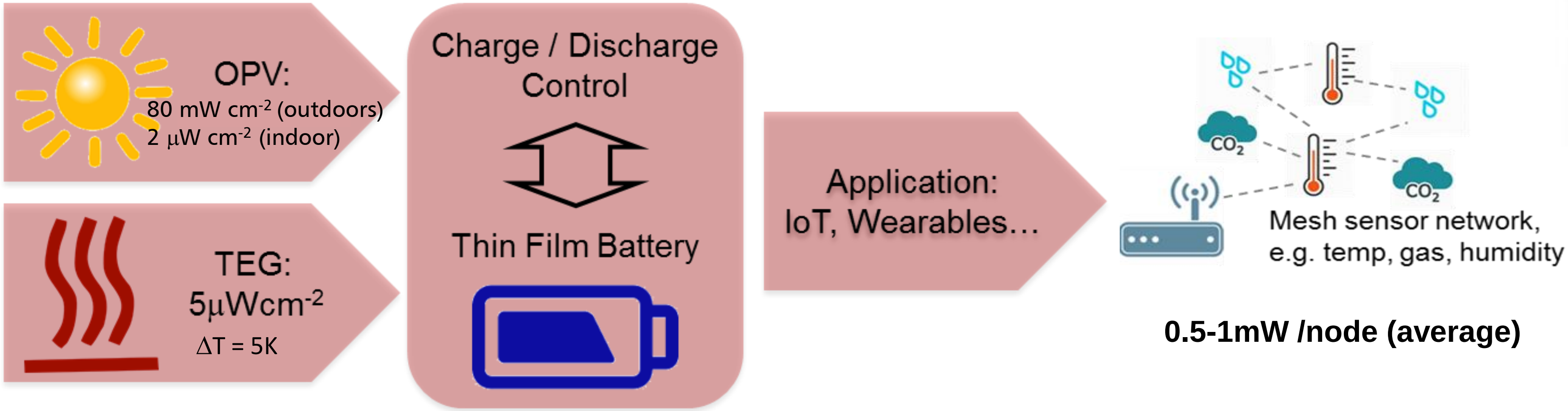
- Trend of increased monitoring of industrial processes, equipment and buildings has the power to reduce global energy consumption, improve safety and efficiency of production processes, and reduce equipment failures.
    - This will require billions of sensors all which will need power sources.
    - 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 and roadmap

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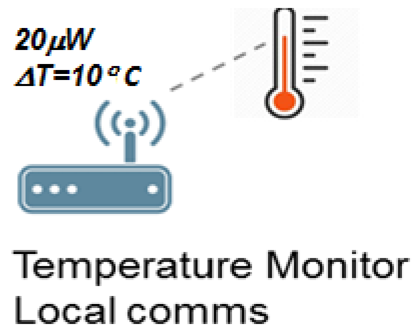
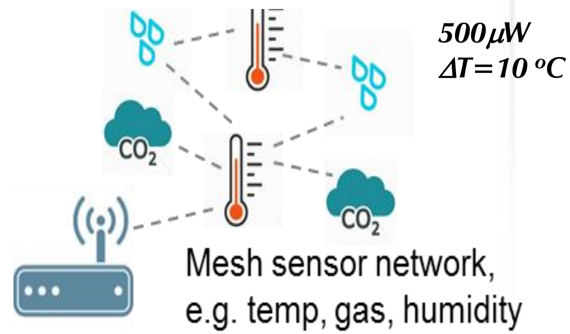
- **Application: Wireless Sensor Networks; autonomous systems**

  (1) *Single node low power wireless sensor*; power requirement 10 μW cm^{-2}. Material and module already available. Prototype by March 2018.

  (2) *Mesh networks of multiple sensors*; power requirement 100 μW cm^{-2}. Material and module under development. Prototype March 2019.
- Market for TEG as energy harvesting for WSN, is predicted to reach \$400M* by 2026. Total market for Temp and Humidity sensors in the region of \$2Bn.





- **Future applications: Wearable Electronics -** wireless health & activity monitoring
- Key advantages: Conformability and freedom of design
- Increases in output power will enable additional applications, added functionalities, or relax the ΔT requirements → Material development.

* (IDTechEx 2026)

What is a Thermoelectric Generator?

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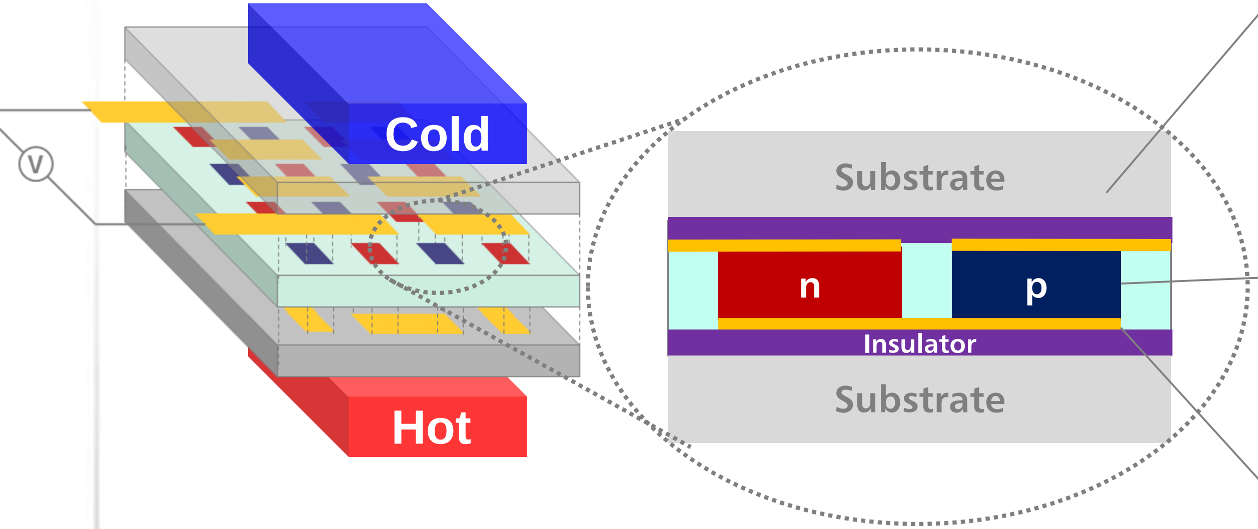
- Thermoelectric generators are semiconductor devices which generate a current from a temperature difference, usually between a hot surface and the ambient temperature.



1. Substrates:
Efficient Transfer of applied heat to active materials.
Electrical insulated from active materials.

2. Active Materials:
Generate voltage from applied temperature difference. (high Seebeck)
High conductivity required

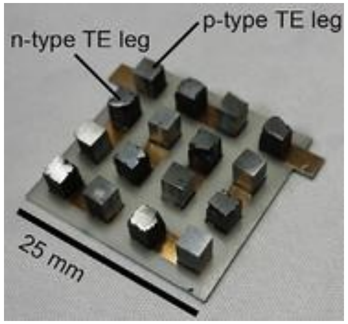
3. Contact resistance:
Low resistance required to keep overall module resistance low

Printed TEG Fabrication

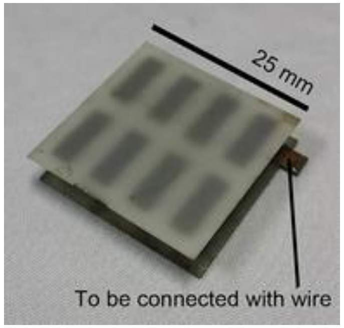
Conventional TEG Fabrication

1. Semiconductor ingot cast in furnace

2. Ingot cut into individual legs



3. Legs soldered onto ceramic substrate

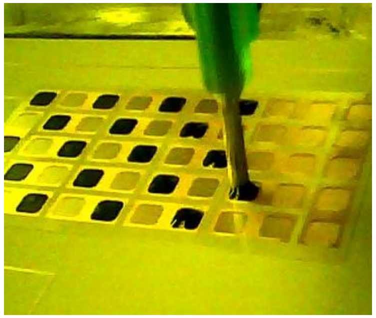


4. 2nd ceramic substrate soldered on top

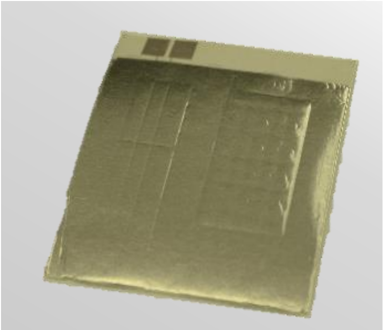
CDT Printed TEG Process

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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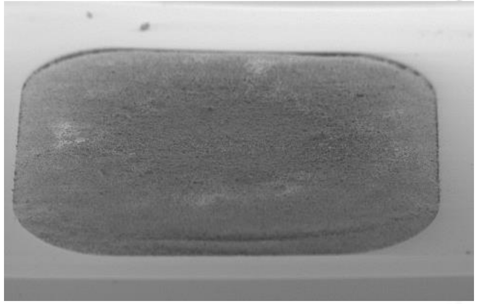
Printing process optimisation is key to obtain good module performance.

Dispense printing is used in R&D phase, next step is to scale to screen printing for larger module sizes and production volumes

Summary of increases in power density
- 17x from PEN to foil;
- 12 x 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 Increased Area
Voc / mV	3.25	11	31.25	25	66
Resistance / Ω	108	75	50	5	10
Total Power / μW	0.02	0.40	4.88	35	105
Power Density / μW cm^{-2}	0.004	0.083	1.02	7.4	8.75

Demonstration of Integration of TEG into Wireless Sensor

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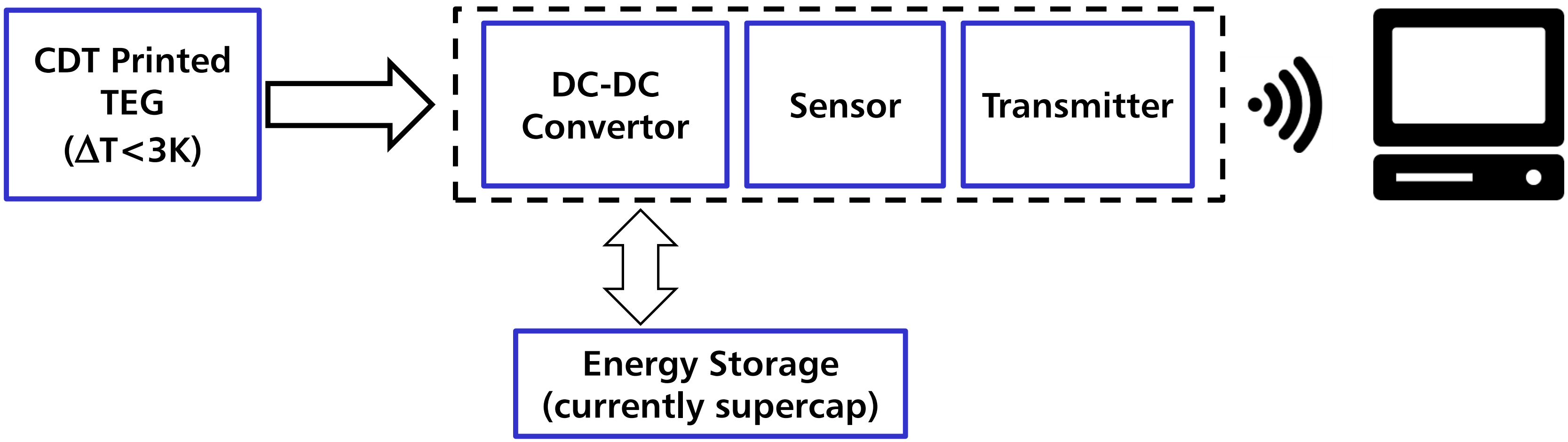

- Successful proof of concept that TEG can power EnOcean wireless temperature sensor.
  - ✓ Continuous operation, with data transmission every 15 mins.
  - ✓ TEG is actively cooled with $\Delta T < 3K$

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

TEG Status and Roadmap

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

Key Next Steps: **Complete development of passive cooling**
Screen printing and increase of module size.

Single Wireless Sensors

Integrated Multi Sensor Networks

Valves and Actuators

Conformable Cooling

Wearable and medical

1μWcm^{-2} **5μWcm^{-2}** **20μWcm^{-2}** **100μWcm^{-2}**

Increased Power Requirement

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- **Energy Storage requirements in IoT**
  - **Flexible hybrid supercapacitors/batteries**

Energy Storage Requirement for IoT

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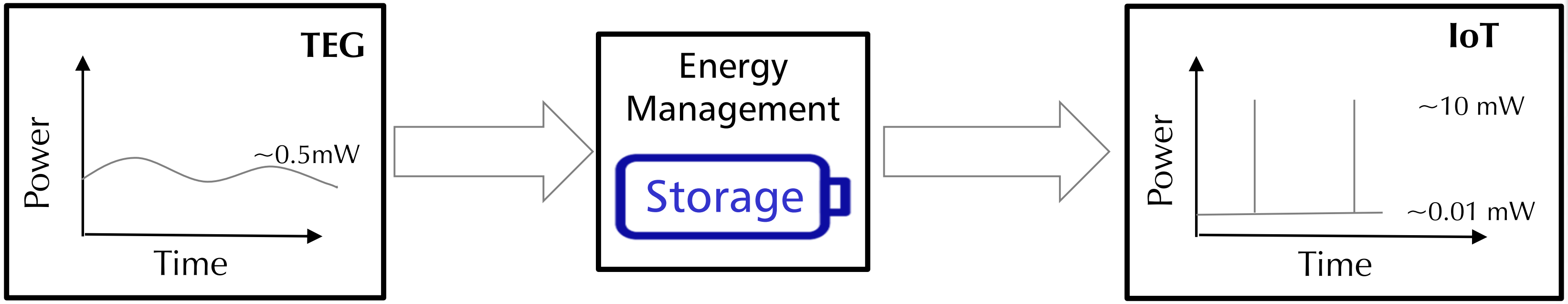
- Intermittent nature of energy harvesting and irregular power requirements from WSN and autonomous systems makes the combination of energy harvesting and storage an interesting approach:



- Energy storage requirements for integration into a flexible energy harvesting system:
  - Sufficient capacity to power system if energy harvesting is interrupted for short periods of time e.g. 2-3 days.
  - High current delivery to power wireless transmission of data – energy harvesting devices are typically continuous low power sources.
  - Ease of integration into energy harvesting or power management system – reduced number of individual components.

Our value proposition

CDT

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

Conformable devices that can be easily integrated with energy harvesters.

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

Autonomous systems and WSN

- Key advantages:
  - Mechanical flexibility and fast recharging.
  - Secondary battery for increased product LT in combination with harvesters.

Wearables for healthcare, lifestyle, and novel applications

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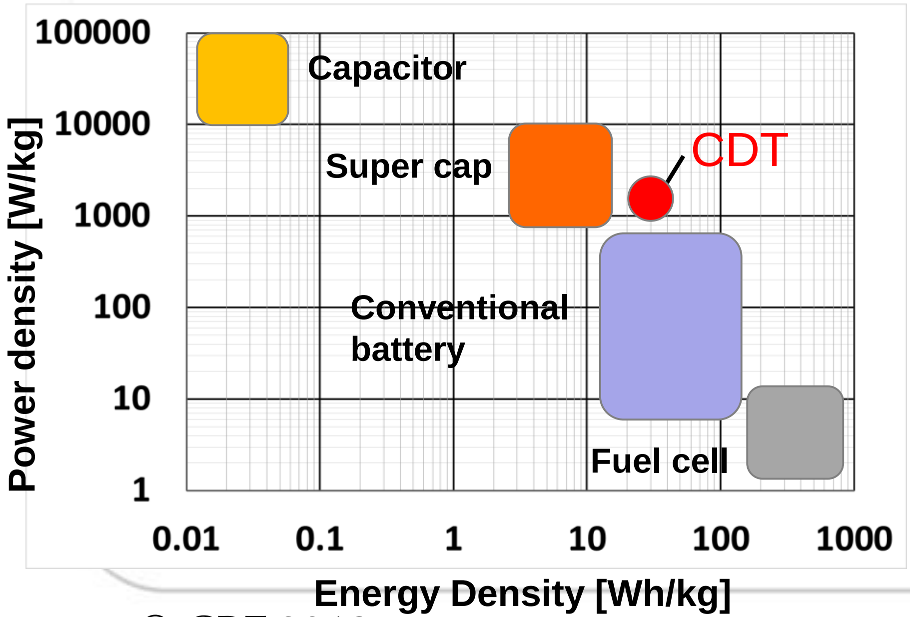
- **Key Features of**
  - ✓ No toxic polymer active materials and Ionic Liquid Electrolyte
  - ✓ High power density* up to 25mWcm^{-2}– required for Bluetooth protocols
  - ✓ Printable, conformable form factor – potential for monolithic integration with TEG
  - ✓ Stable voltage during discharge – simple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

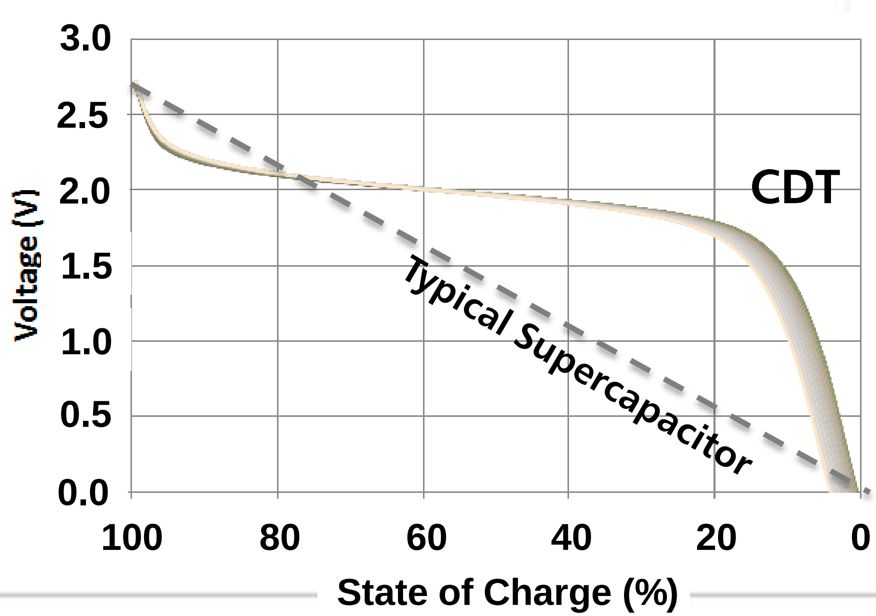
Charge cap. > 1 mAh cm^{-2}
LT > 400 cycles

*(20ms pulse, 2V threshold)

Energy and Power Density



Voltage Output During Discharge:



Conclusion

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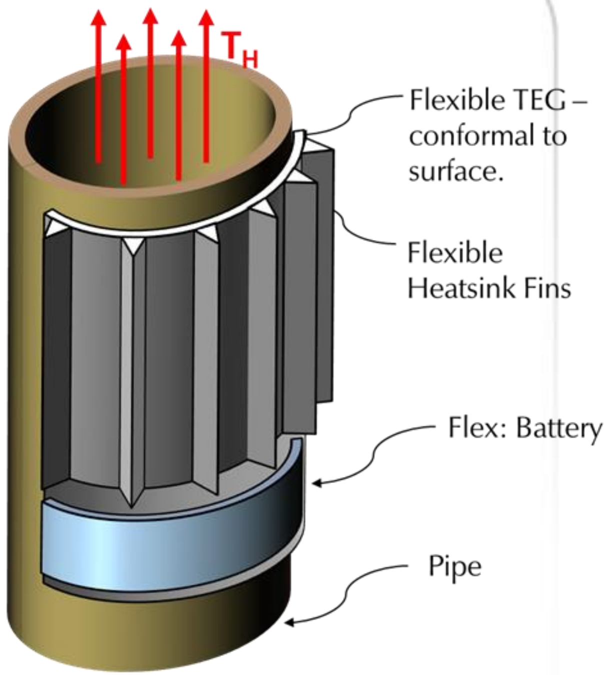
- Driven by application requirements, CDT is developing printable TEGs and conformable hybrid supercapacitors / batteries to enable self-sustaining low-power electronic devices.
- In addition to designing new materials, research into ink & paste formulations is critical for achieving high power output from printed TEGs and hybrid supercapacitors / batteries.

- We are looking for partners interested in the development and commercialisation 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
- The organisers – for the invitation
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- Our collaborators
  - Sumitomo Chemical Corporation Ltd
  - Prof. J Evans' group at UC Berkeley
  - Prof. Yee, Reynolds and Marder's groups at Georgia Tech.

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