UiO : Centre for Materials Science and Nanotechnology
University of Oslo

Top-down to know thermoelectrics

Part 2

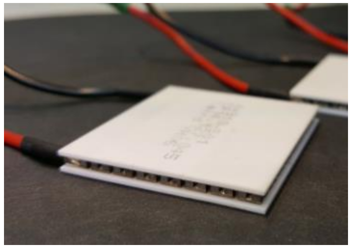
Fabrication of modules

Top-down to know thermoelectrics (TE)

-- From TE applications to Materials

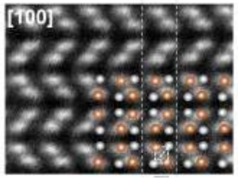
TE industrial applications

TE modules



TE Pairs

TE Materials



Availability and Installation

- ☐ Zinc Antimonides

Fabrication

- ☐ Conducting Oxide

Legs matching

- ☐ Oxide

Material properties

- ☐ Silicide

Novel approaches and interface engineering for the fabrication of oxide thermoelectric modules

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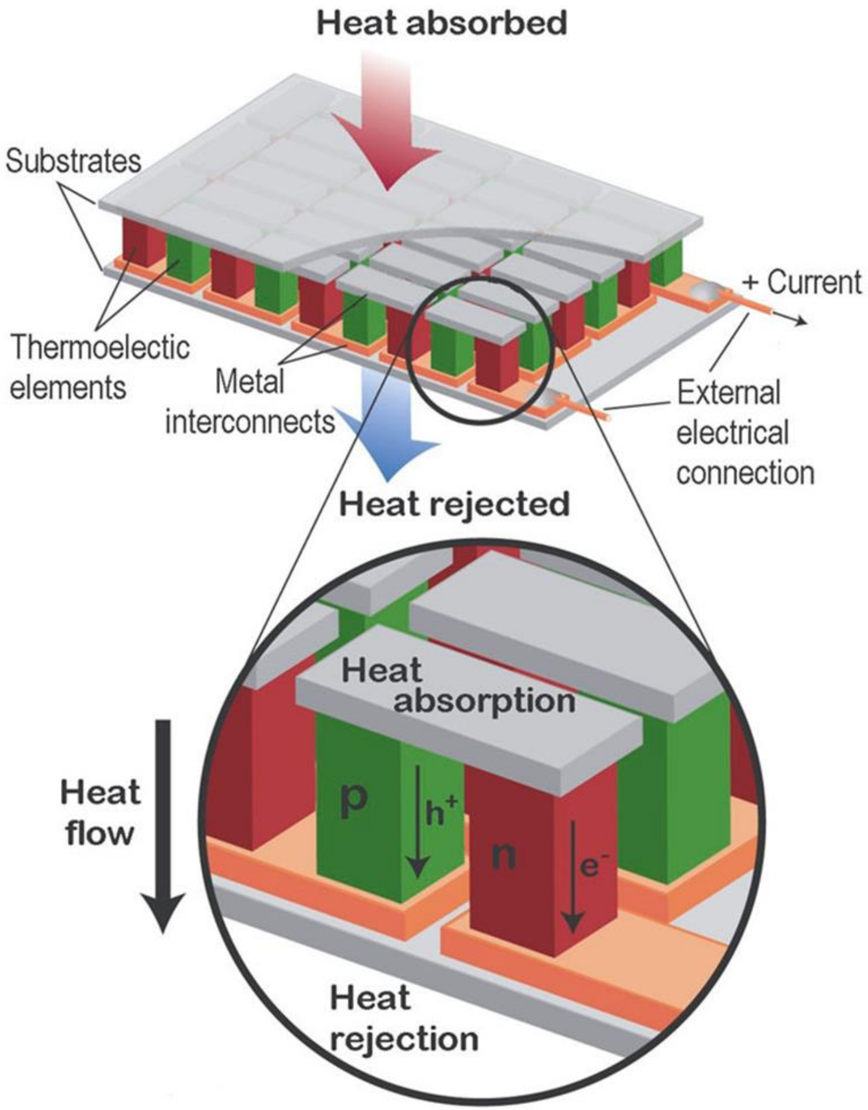
Plan of talk

i. Traditional manufacturing techniques

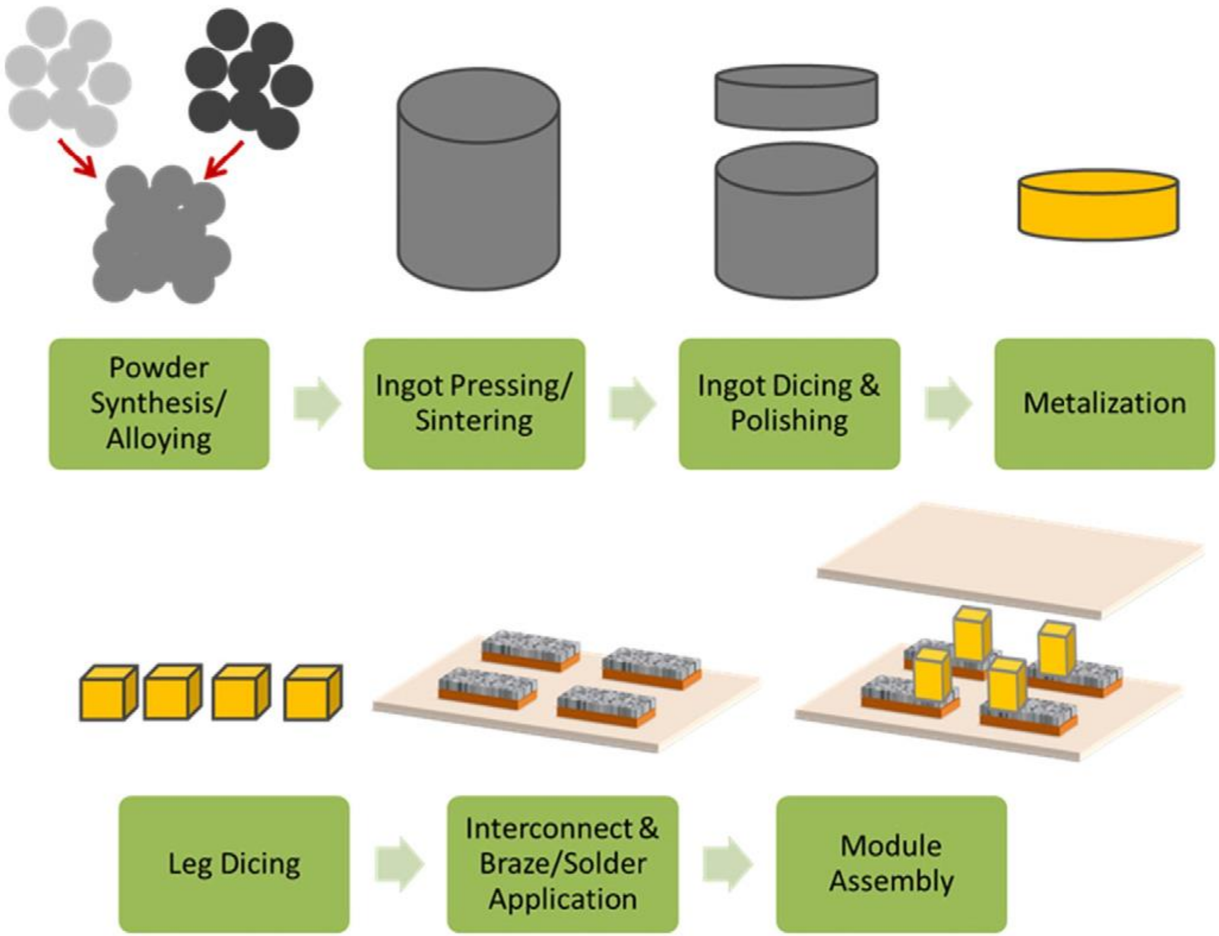
ii. Ohmic contact with conducting oxides

iii. Additive fabrication/ 3D printing of oxide modules



Snyder et al.,*Nature Materials* (2008) 105-114

1. Traditional manufacturing techniques

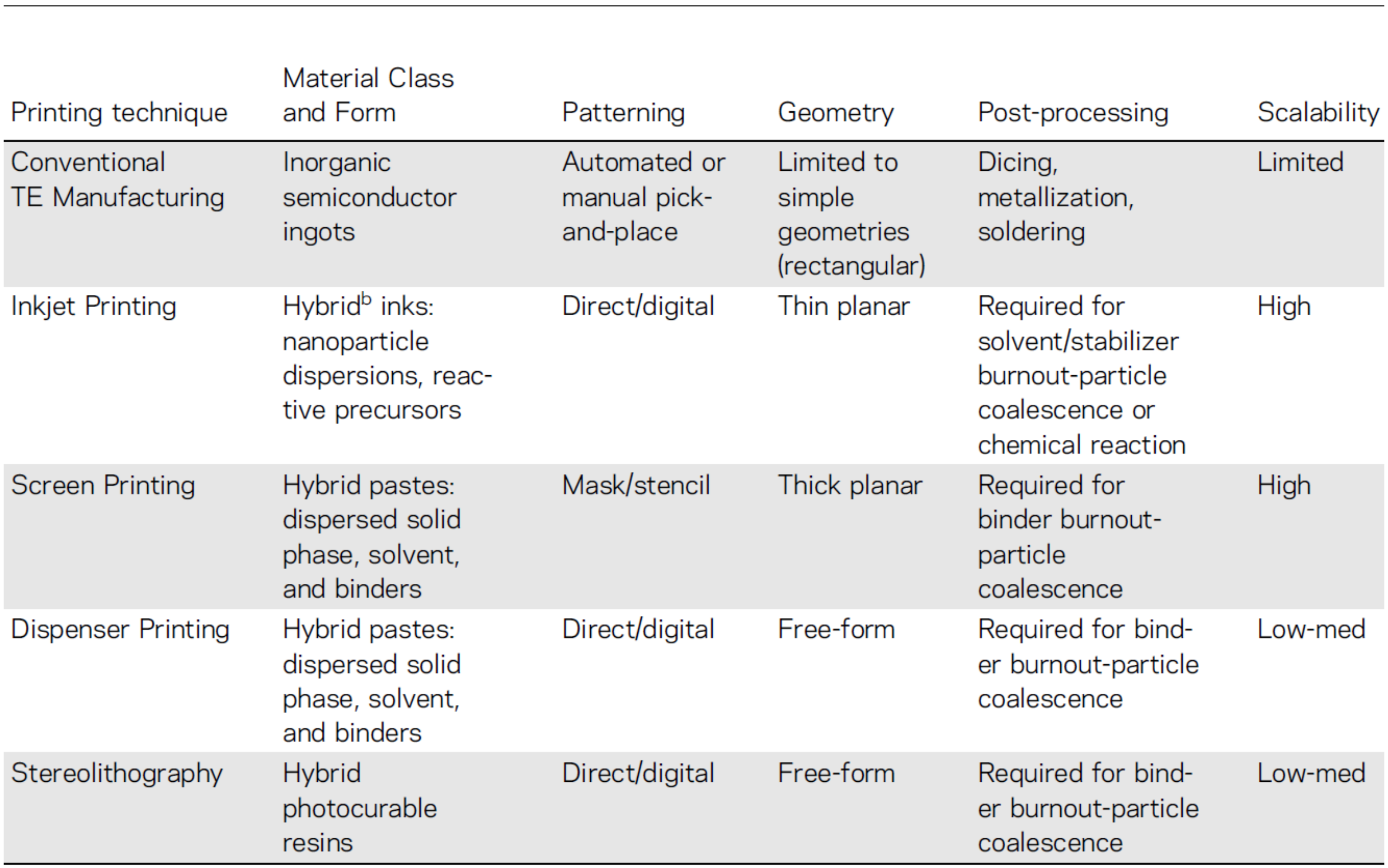


- Constrains the size and shape
- Leads to microcracks
- Limited scalability

Schematic of a traditional TE device manufacturing process

S. LeBlanc., *Sustainable Materials and Technologies*, (2014) 26–35

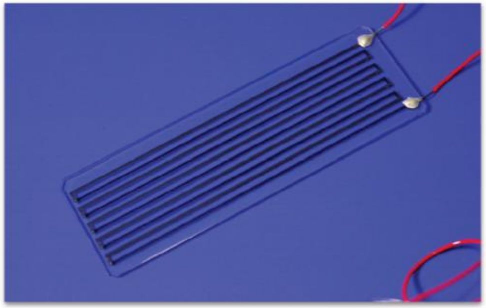
Summary of TE device manufacturing methods comparing the traditional manufacturing approach to printing techniques

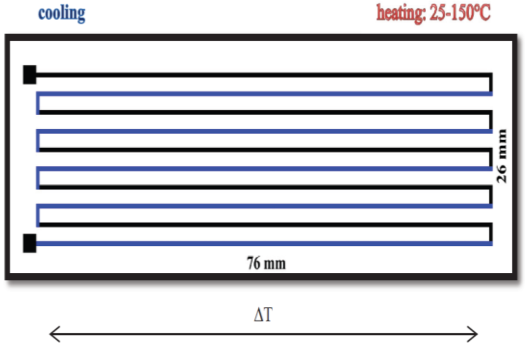


Printing technique	Material Class and Form	Patterning	Geometry	Post-processing	Scalability
Conventional TE Manufacturing	Inorganic semiconductor ingots	Automated or manual pick-and-place	Limited to simple geometries (rectangular)	Dicing, metallization, soldering	Limited
Inkjet Printing	Hybrid[b] inks: nanoparticle dispersions, reactive precursors	Direct/digital	Thin planar	Required for solvent/stabilizer burnout-particle coalescence or chemical reaction	High
Screen Printing	Hybrid pastes: dispersed solid phase, solvent, and binders	Mask/stencil	Thick planar	Required for binder burnout-particle coalescence	High
Dispenser Printing	Hybrid pastes: dispersed solid phase, solvent, and binders	Direct/digital	Free-form	Required for binder burnout-particle coalescence	Low-med
Stereolithography	Hybrid photocurable resins	Direct/digital	Free-form	Required for binder burnout-particle coalescence	Low-med

Michael Orrill and Saniya LeBlanc., *J. APPL. POLYM. SCI* (2016) 44256

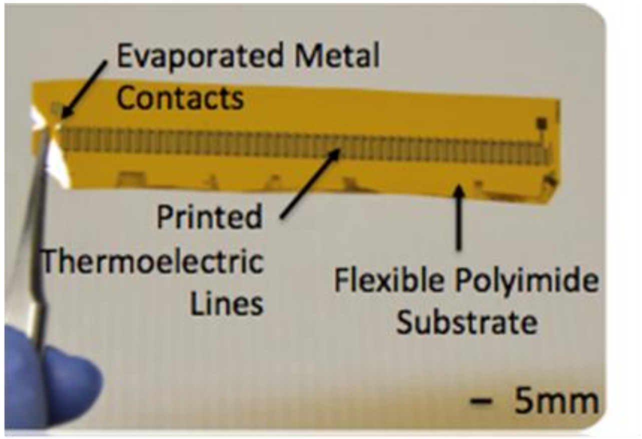
Inkjet-printed ZnO/PEDOT:PSS composite TEGs





black: metal electrodes and interconnects
blue: TE-material/composite

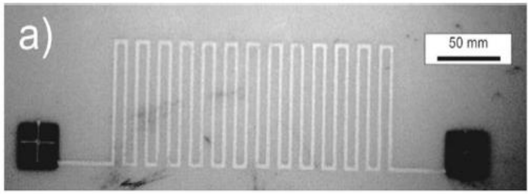
Angelina Besganz et al., *Procedia Technology 15* (2014) 99 – 106



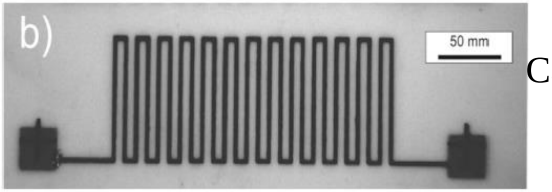
Dispenser printed TE device

UC@Berkeley

Screen-printed oxide-based TE made from p-type $Ca_3Co_4O_9$ and n-type $(ZnO)_5In_2O_3$ legs

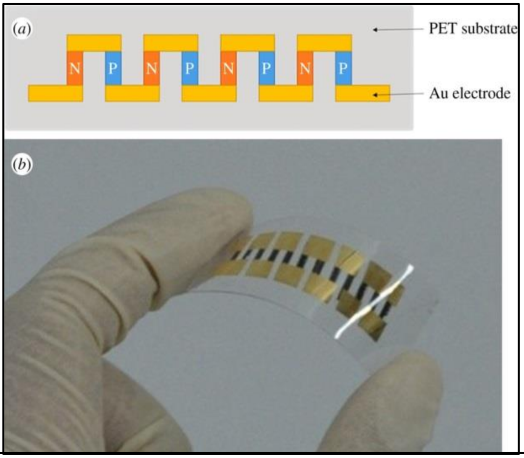


$(ZnO)_5In_2O_3$ legs



$Ca_3Co_4O_9$ legs

R. Rudež et al. *Ceramics International* 41 (2015) 13201–13209



Schematic and (b) image of a inkjet-printed composite TE device on a flexible PET substrate.

Fei Jiao et al., *Phil. Trans. R* (2017) 1-10

Obstacles to commercialization of TE devices

- ❖ Scarcity
- ❖ Toxicity
- ❖ High costs of raw materials
- ❖ Stability and
- ❖ High processing cost

Oxides

- ✓ Low thermal conductivity
- ✓ High Seebeck coeficient
- ✓ High thermal and chemical stability
- ✓ Environment friendly
- ✓ Abundant

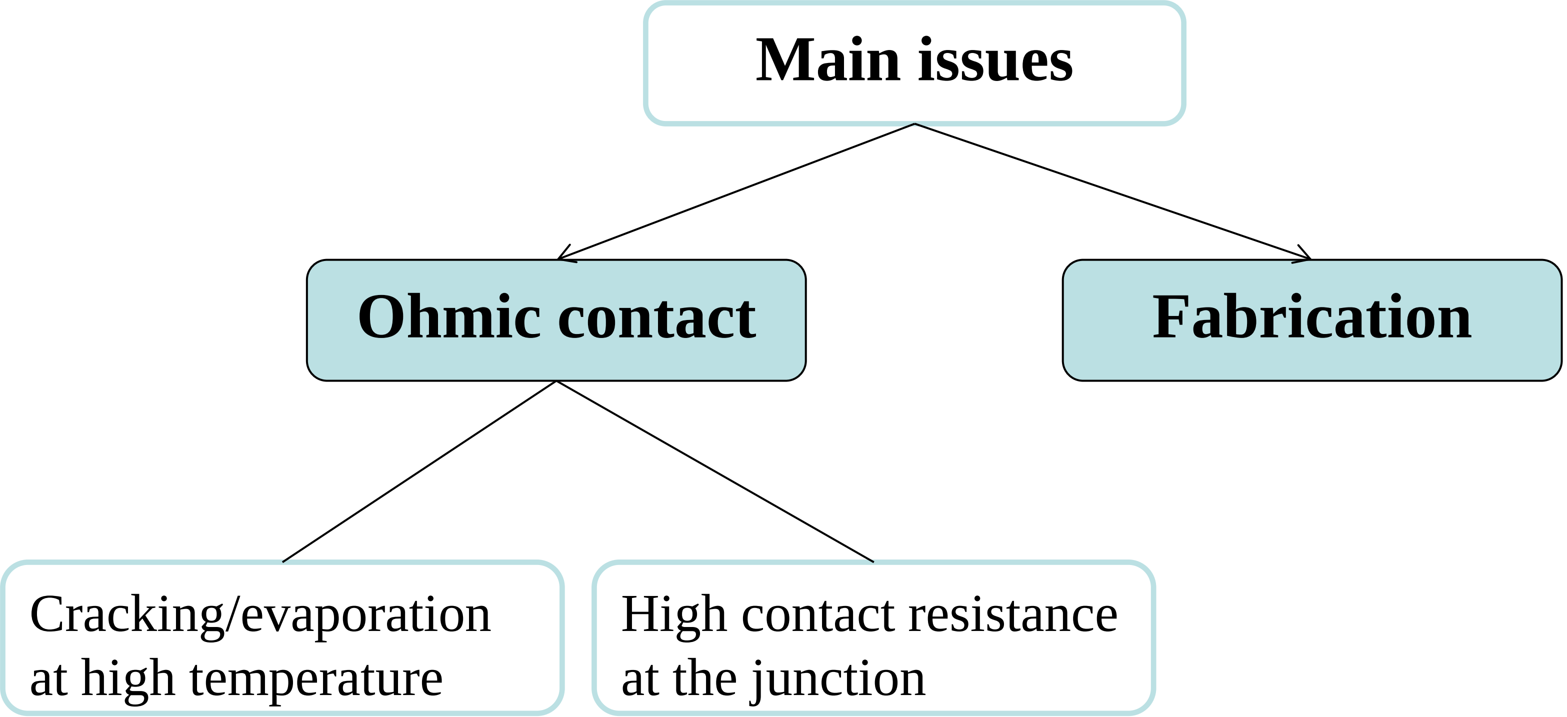
Oxides

👍

High stability
Environment friendly

👎

Low ZT



Main issues

Ohmic contact

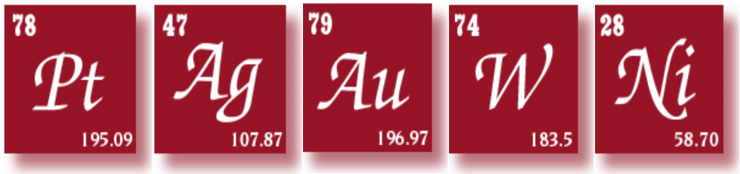
Fabrication

Cracking/evaporation at high temperature

High contact resistance at the junction

2. Conducting oxide interconnect

p-n oxide thermoelectric junctions still need an ohmic contact: Noble metal? Or metallic oxide?



- ❖ Metal diffuse at high temperature
- ❖ High contact resistance at the junction
- ❖ Cracking/ evaporation of metal contact
- ❖ High cost

metallic oxide

- High thermal stability
- High resistance to chemical corrosion
- Favorable integration with TE oxide

I. High electrical conductivity

II. High thermal conductivity

III. Matched CTE with the TE elements

IV. Low contact resistance at the interface

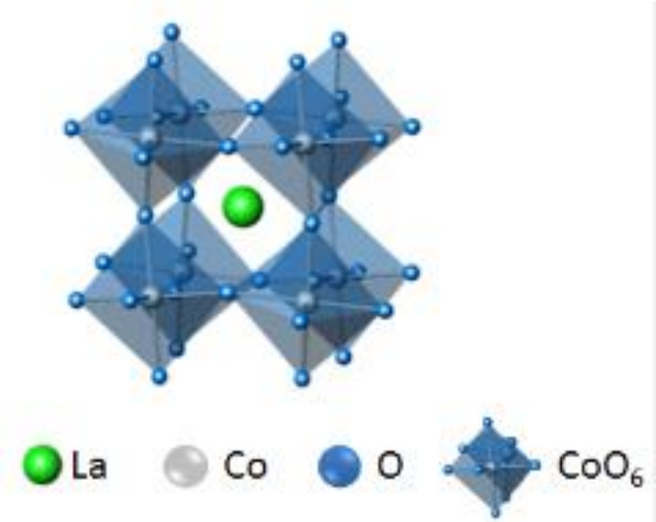
V. Stability at high temperature

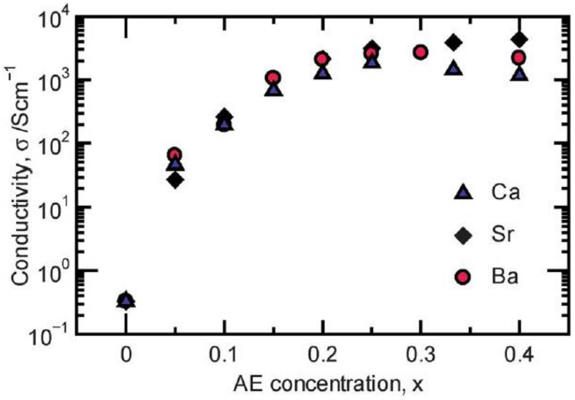
VI. Ability to form strong mechanical bonds with the TE layer

W. Liu et al., *Acta Materialia* 87 (2015) 357–376

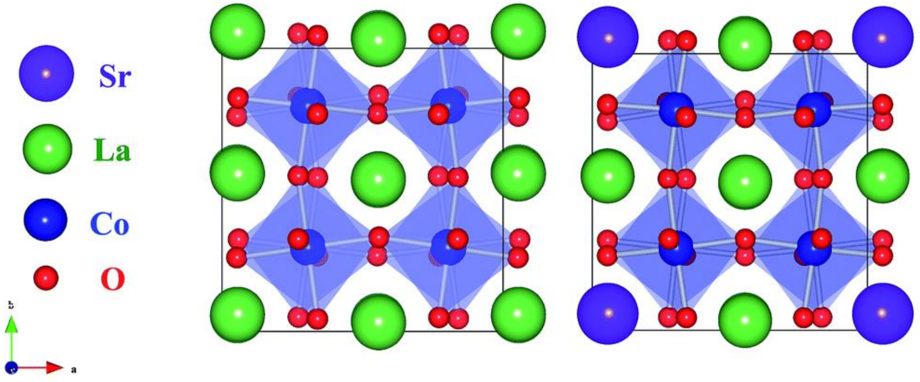
In this project, we will investigate alkaline earth doped $LaCoO_3$ as metallic oxide interconnect.

- High, metallic conductivity
- Low cost
- High thermal stability





Electrical conductivity of $La_{1-x}AE_xCoO_3$ at room temperature.



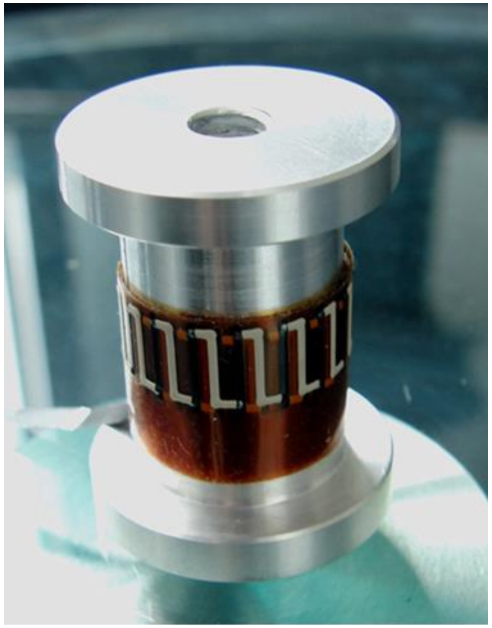
(*a*) undoped (*b*) Sr-doped

Electrical conductivity has a maximum, $\sigma = 4.4 \times 10^3$ S cm^{-1} In $La_{0.6}Sr_{0.4}CoO_3$

Shuguang Zhang,Ning Han and Xiaoyao Tan., *RSC Adv.* 5 (2015) 760–769

3. Additive fabrication/ 3D printing

- Simplicity
- Affordability
- Material compatibility
- Less energy input
- Reduced material waste
- Scalability
  - Ability to produce many devices rapidly
  - The ease of altering design



3D printing makes it possible: A demonstrator of a printed TEG wriggles flexibly around a sample component

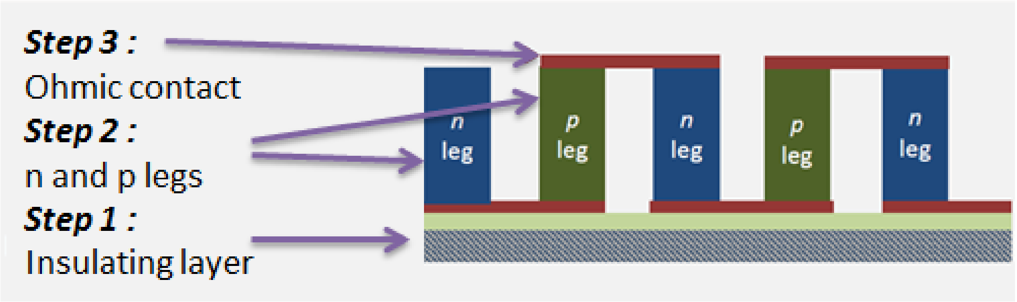
Fraunhofer IWS Dresden

Types of 3D printing technologies

Additive manufacturing processes	Processes	Technologies/ Methods
Vat photopolymerization	Exposure to light and undergoes photopolymerization and become solid	a. Stereolithography (SLA) b. Direct light processing (DLP) c. Continuous direct light processing (CDLP)
Powder bed fusion	Thermal source to induce fusion between powder particles	a. Selective Laser Sintering (SLS) b. Selective laser melting (SLM) c. Direct metal laser sintering (DMLS) d. Electron beam melting (EBM) e. Multi jet fusion (MJF)
Material extrusion	Extrude a material through a nozzle onto a build plate	a. Fused Deposition Modeling (FDM)
Material jetting	Materials cure or harden when exposed to light or elevated temperatures and printed	a. Material jetting b. Nano particle jetting (NPJ) c. Drop on demand (DOD) material jetting
Binder jetting	Printing a binding agent onto a powder bed to form part cross sections	a. Binder jetting
Direct energy deposition	Creates parts by melting material as it is deposited	a. Laser engineered net shape (LENS) b. Electron beam additive manufacture (EBAM)

Device Architectures

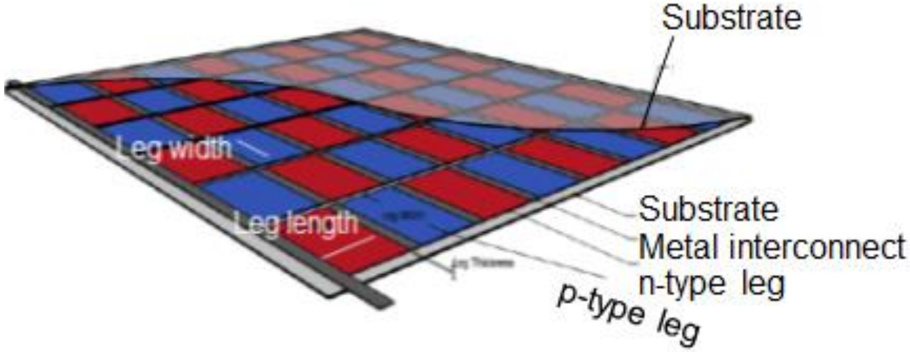
I. Printing Pattern of Material on Substrate



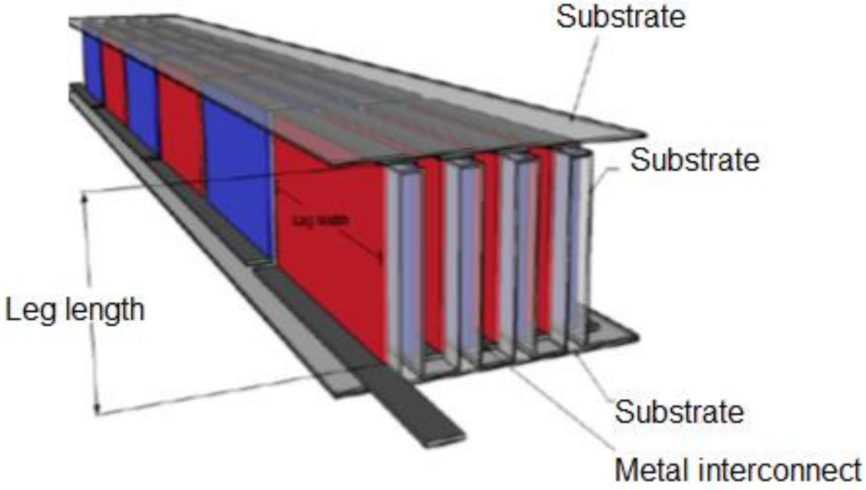
Step 3 :
Ohmic contact

Step 2 :
n and p legs

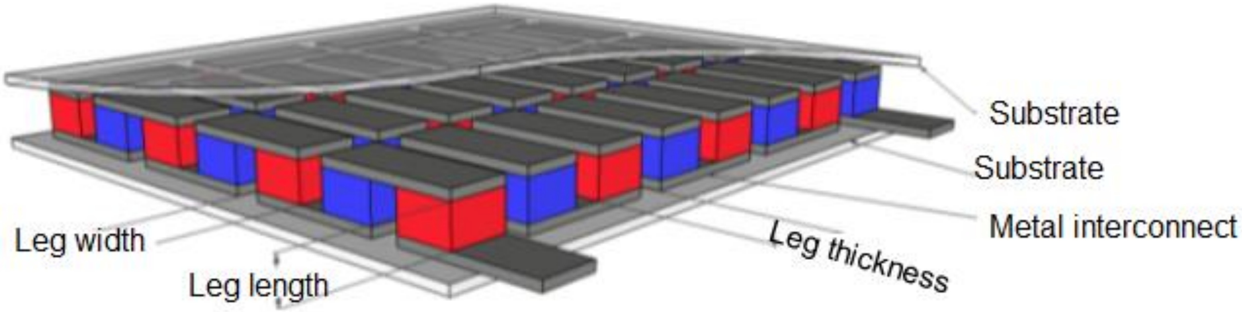
Step 1 :
Insulating layer



II. Processing



II. Final device



Antonik, Margaret., *j. Thermal Sci. Eng. Appl* 8 (2016) 1214

Conclusion

- Oxides are promising materials for TEGs at high temperatures
- A good metallic oxide interconnect is needed for better TE performance.
- 3D printing enable easier construction and various designs of TE modules.
- TE devices can be made in a reliable and cost-effective manner with effective techniques

Thank You