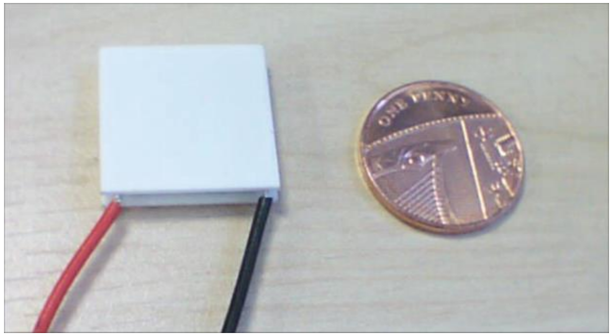
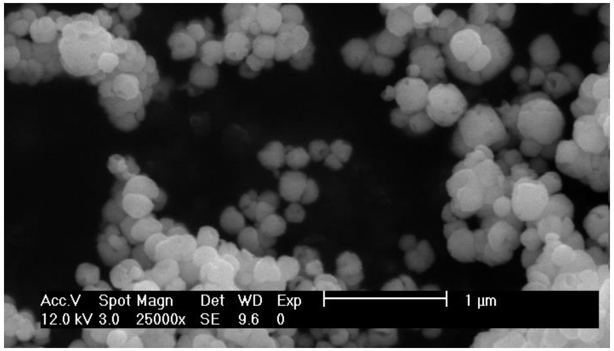
Printed Thermoelectric, Piezoelectric and Pyroelectric Energy Harvesters

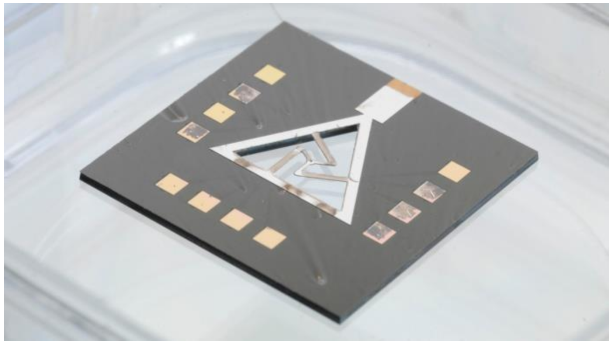
Professor Robert Dorey, Chair of Nanomaterials

Introduction

- Harvesting using films
- Creating film harvesters
- Performances





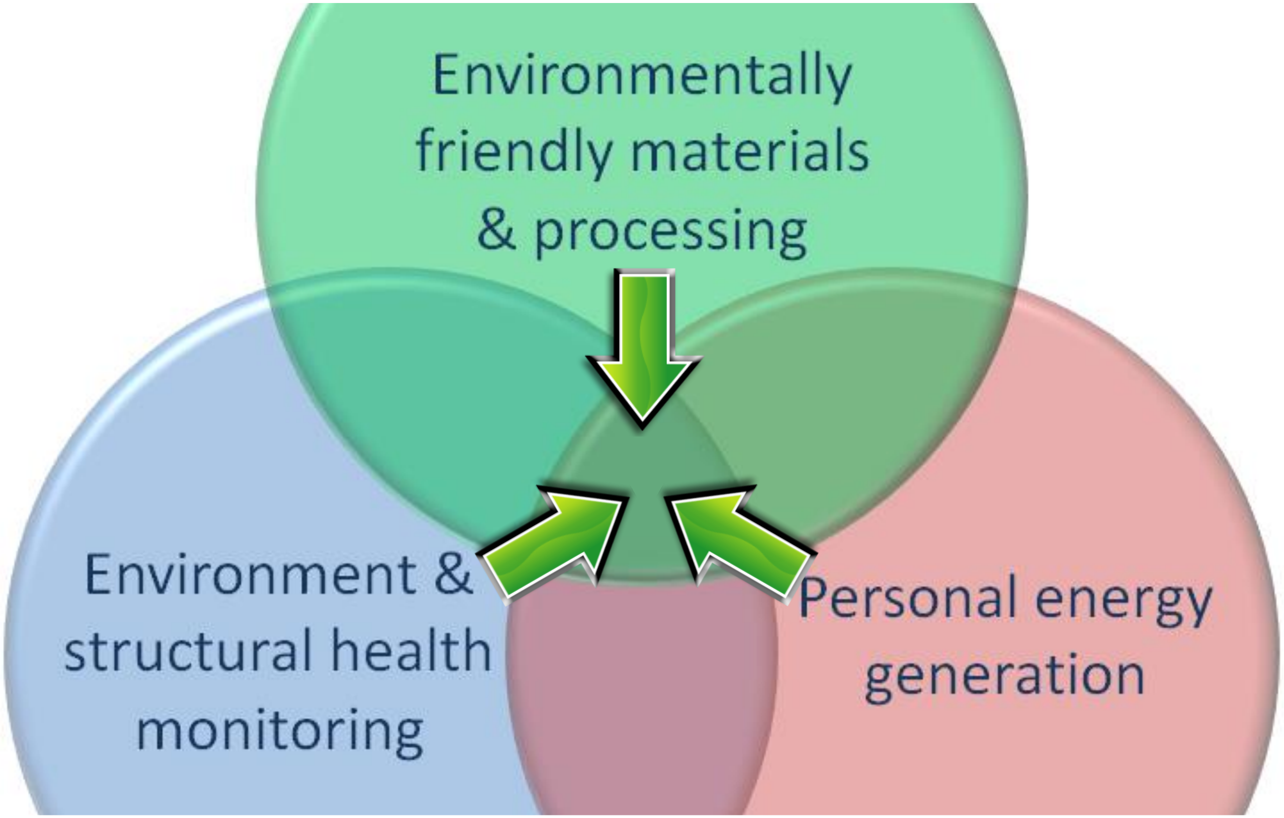


Based on:

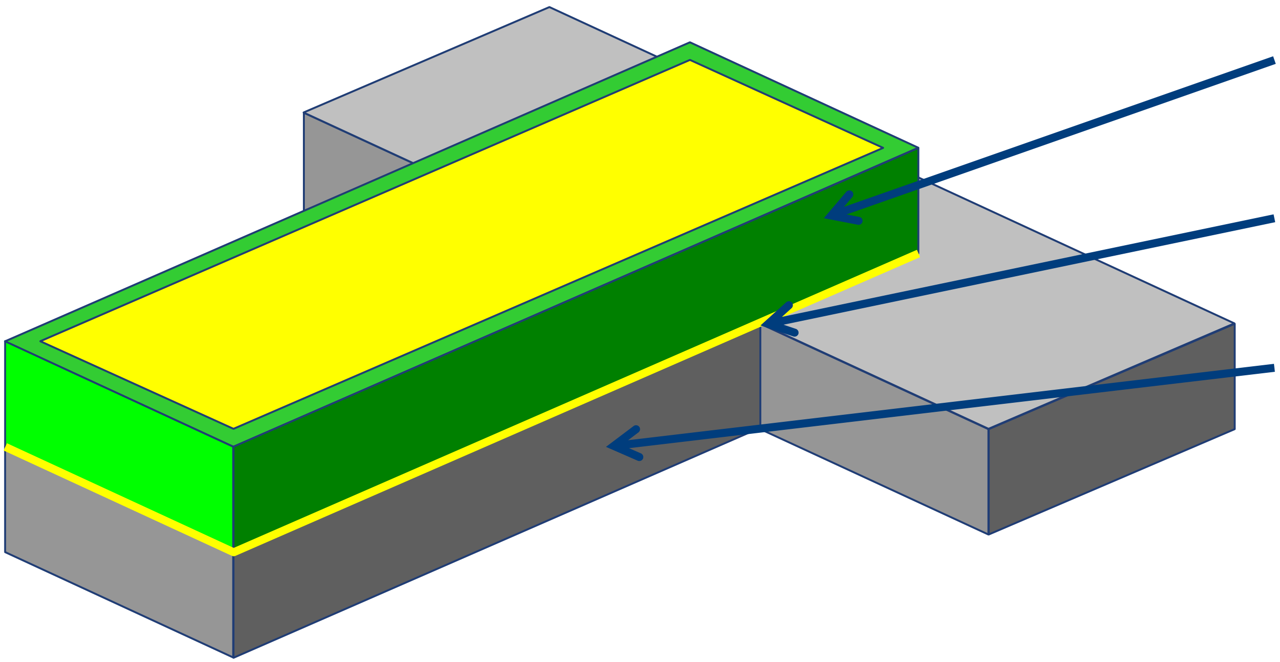
Integrated Powder-based Thick Films for Thermoelectric, Pyroelectric and Piezoelectric Energy Harvesting Devices

Robert A. Dorey

IEEE Sensors Journal, vol 14, no 7, pp 2177-2184, 2014

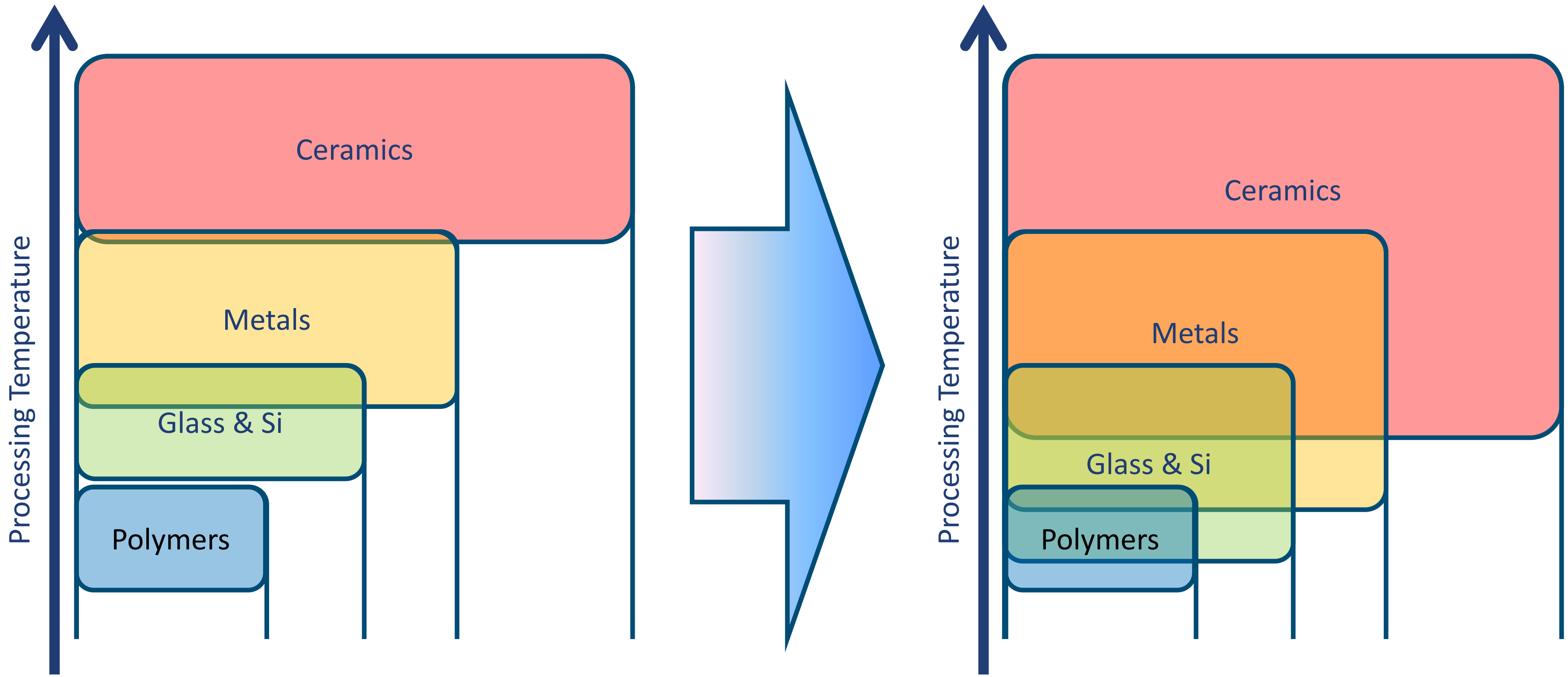

Environmentally friendly materials & processing
Environment & structural health monitoring
Personal energy generation

Introduction – ‘typical’ architecture



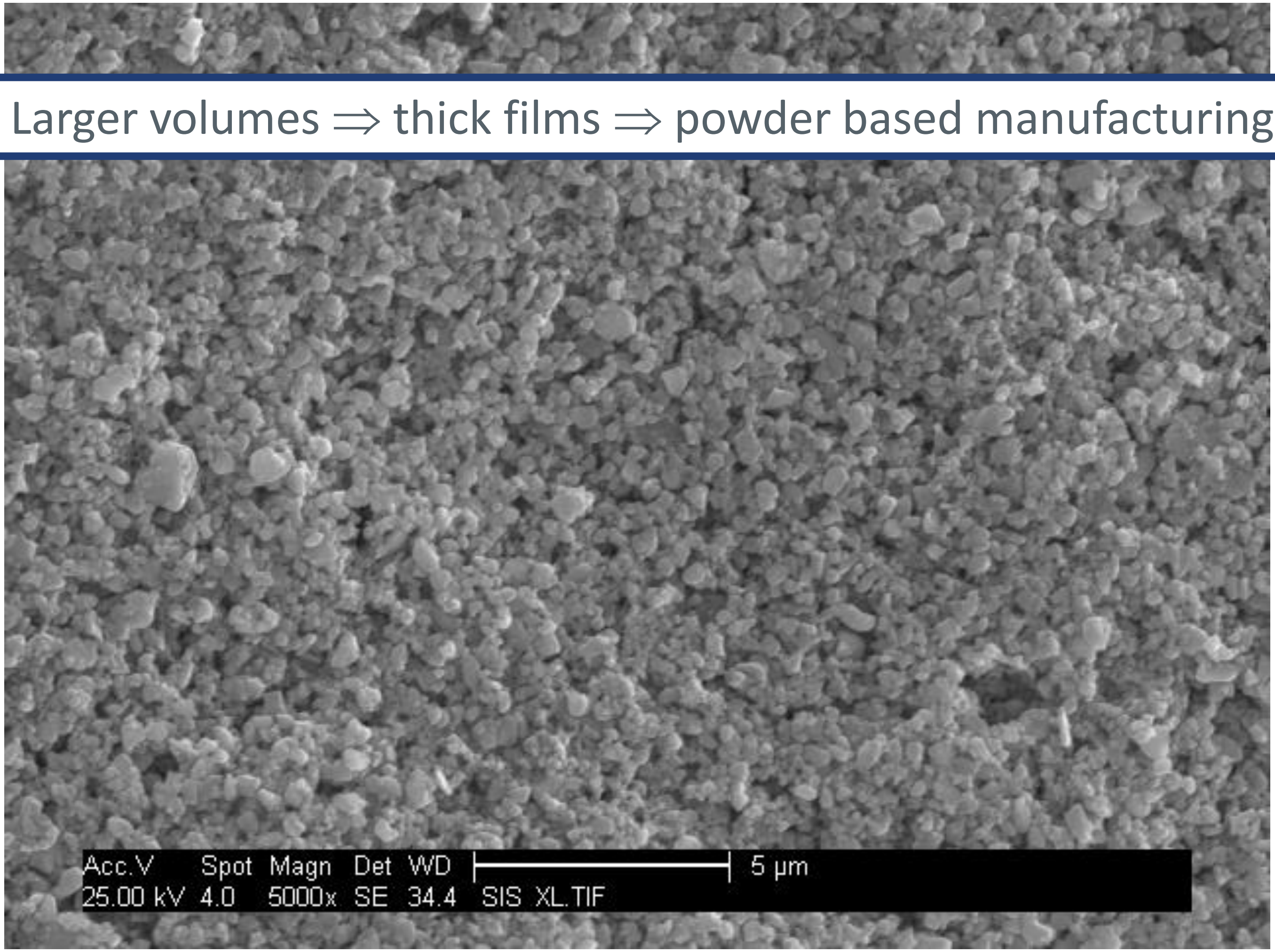
- Functional
- Conducting
- Structural

Co-processing



Powder based films

Power ⇒ Larger volumes ⇒ thick films ⇒ powder based manufacturing

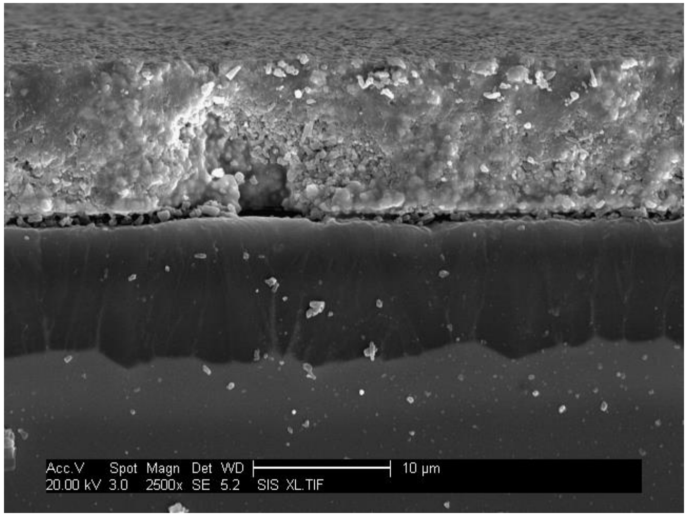


PZT film before sintering

Co-processing

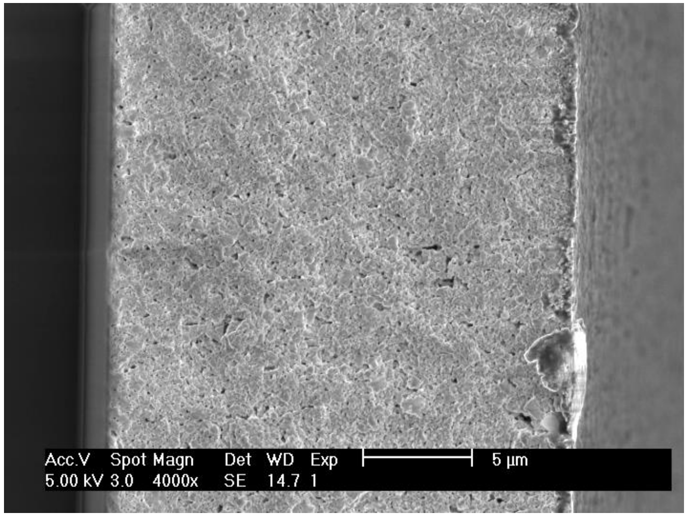
Temperature induced degradation:

- Interdiffusion
- Evaporation
- Degradation



Solutions:

- Low temperature
  e.g. < 750°C for PZT/Si
- Diffusion barrier e.g. ZrO_2

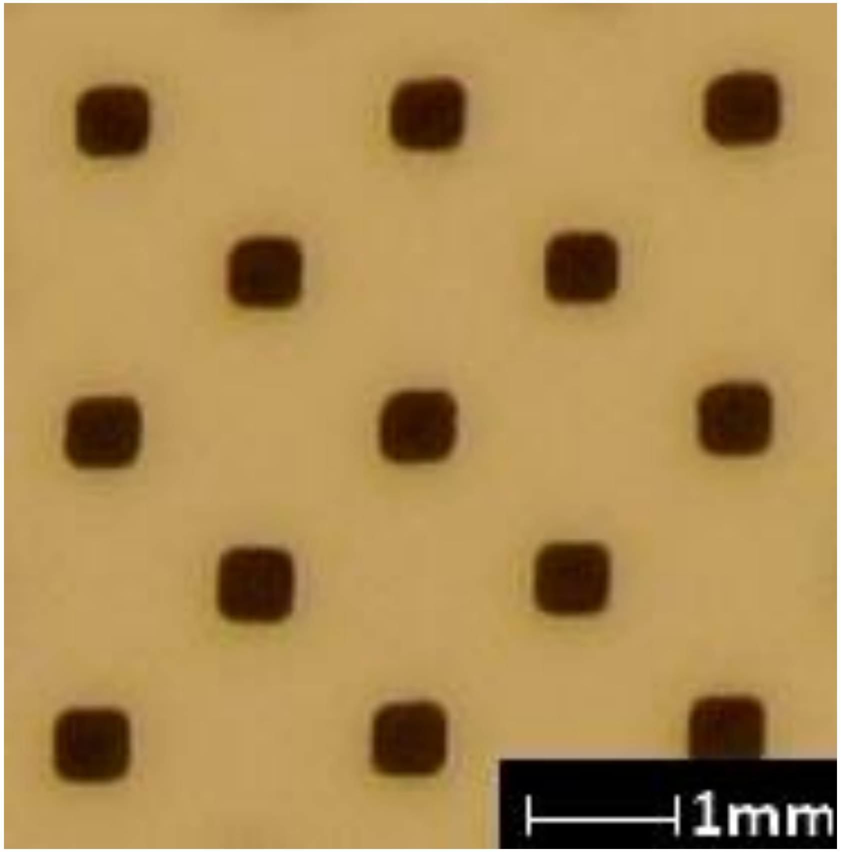


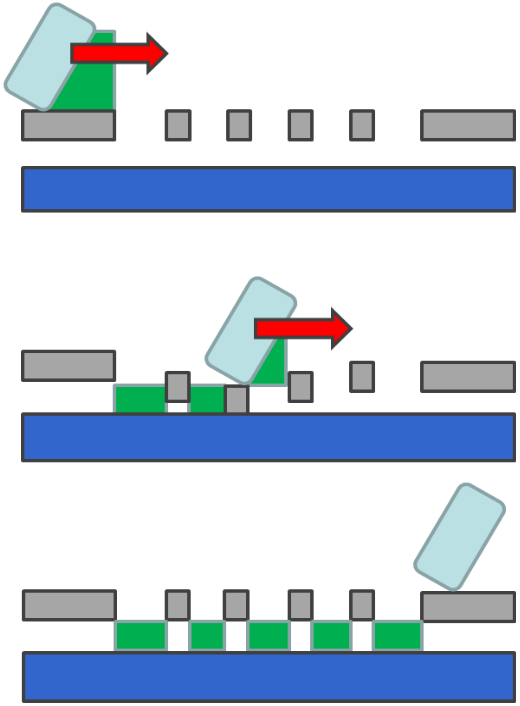
R.A. Dorey, S.B. Stringfellow, R.W. Whatmore, Effect of sintering aid and repeated sol infiltrations on the dielectric and piezoelectric properties of a PZT composite thick film, J.Euro.Ceram.Soc., 22, 2921-2926, 2002.

UNIVERSITY OF SURREY

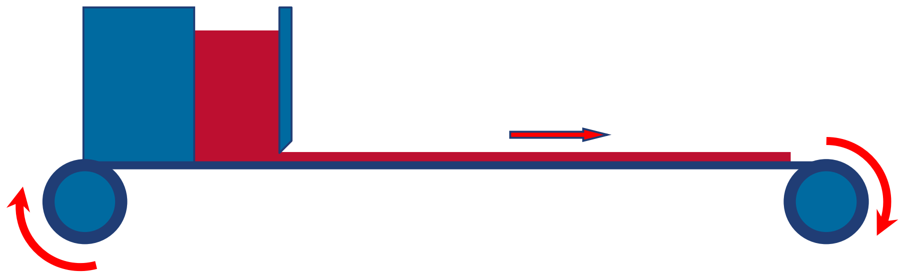
Manufacturing techniques

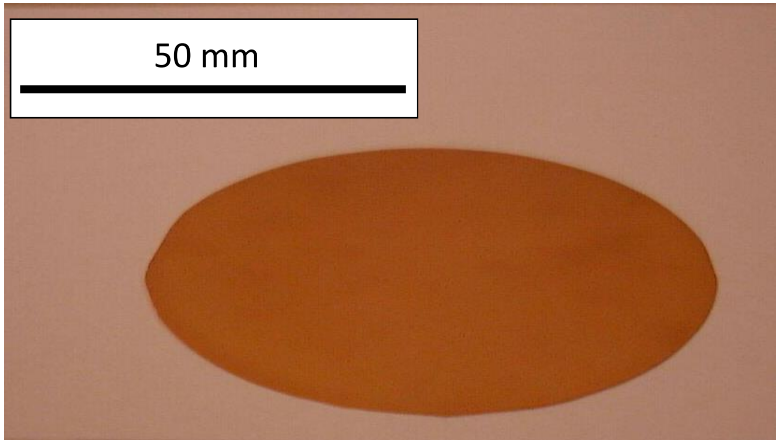
Deposition – screen printing



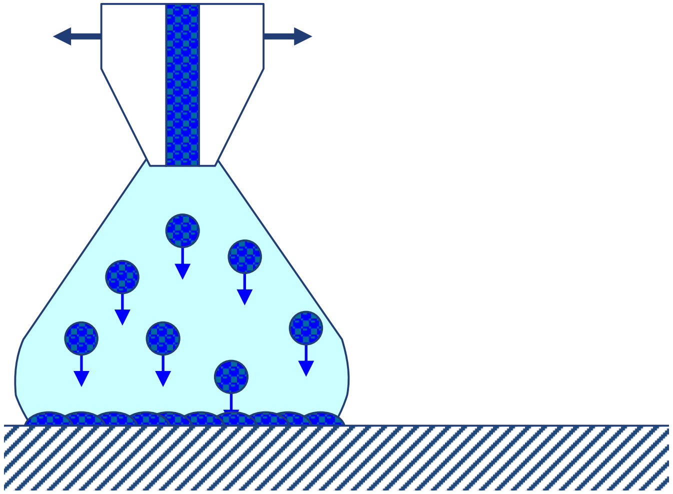


Deposition – tape casting & spray coating



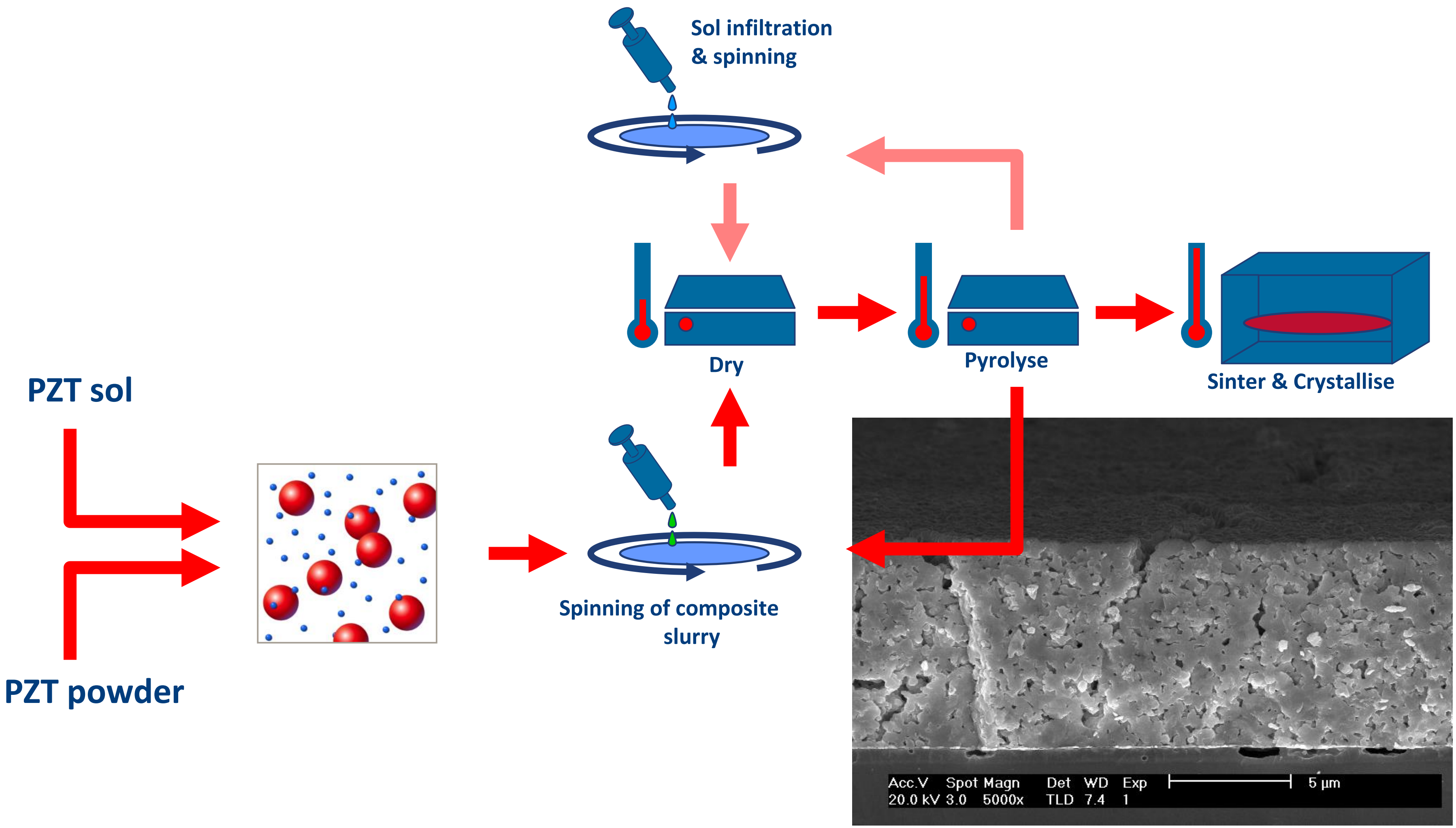


Tape casting



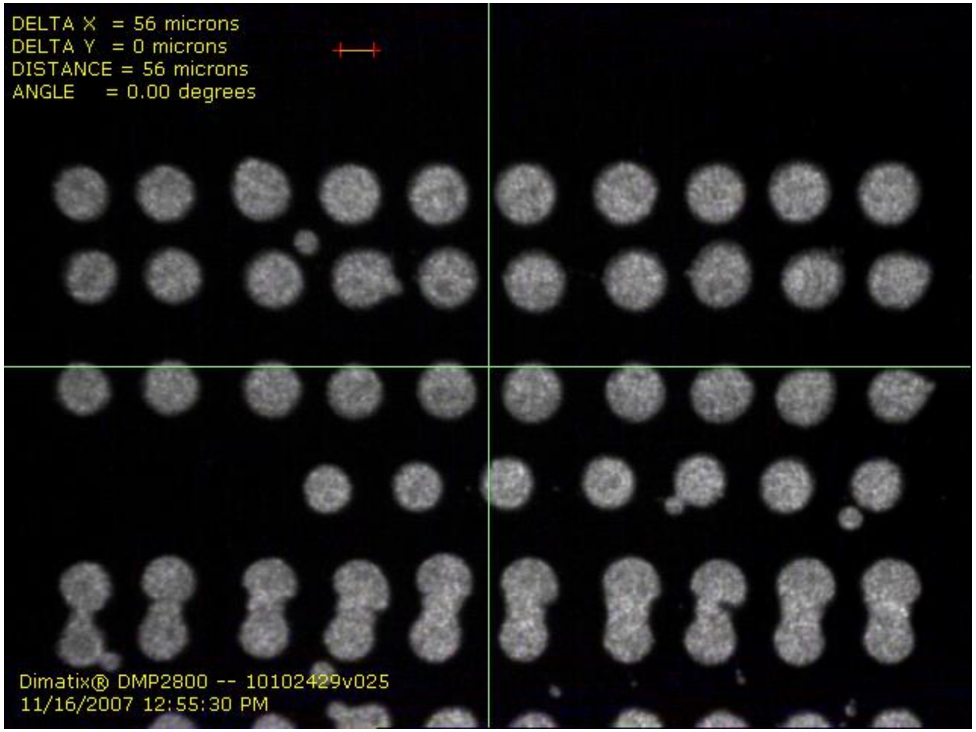
Spray coating

Powder sol gel

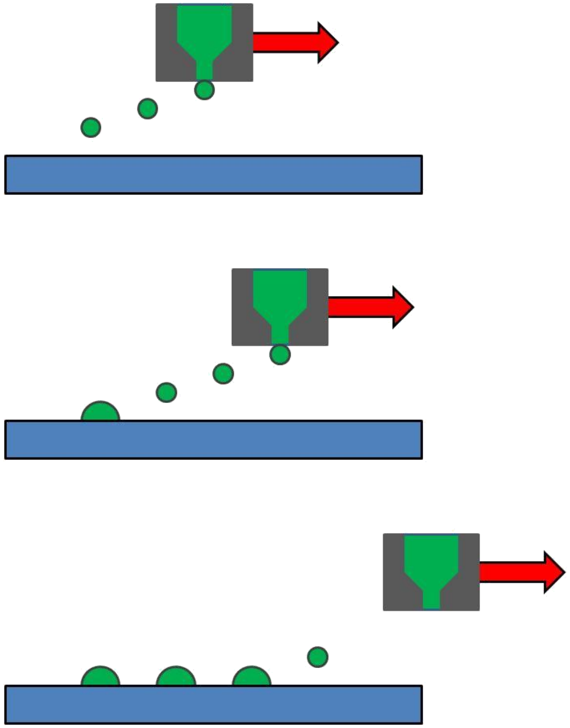


Future manufacturing techniques…

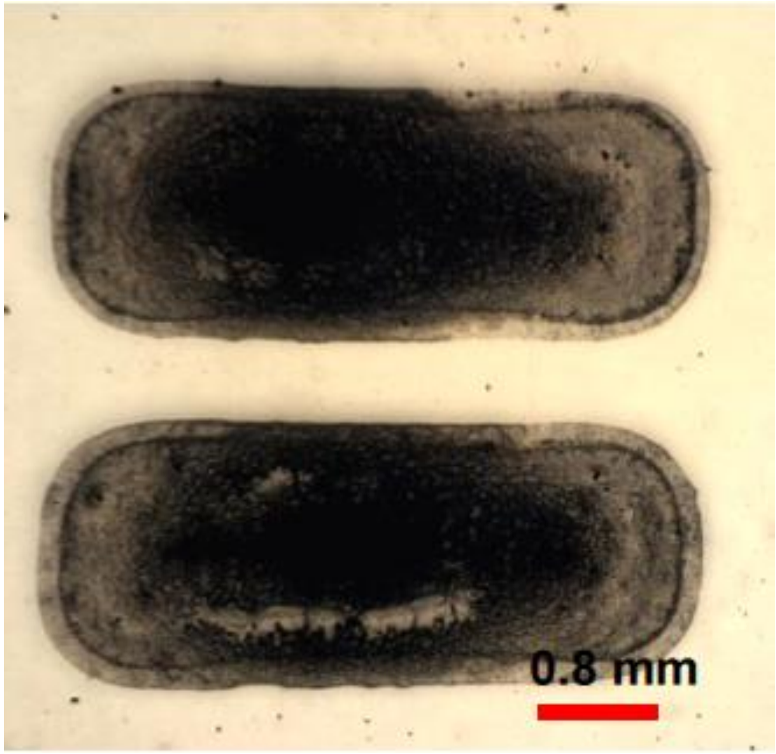
Structuring – direct writing



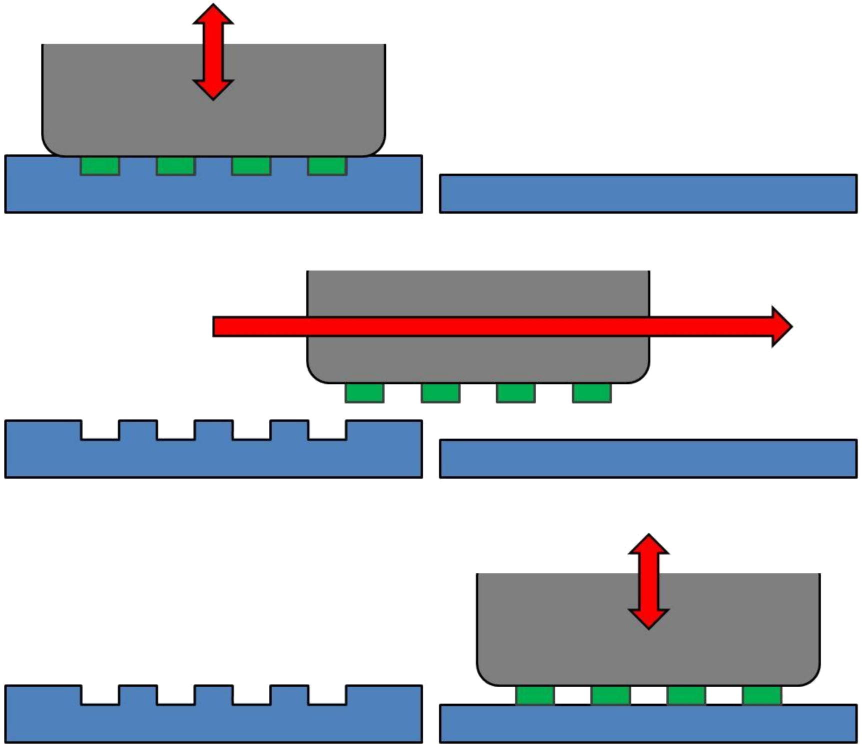
PZT features created by ink jet printing



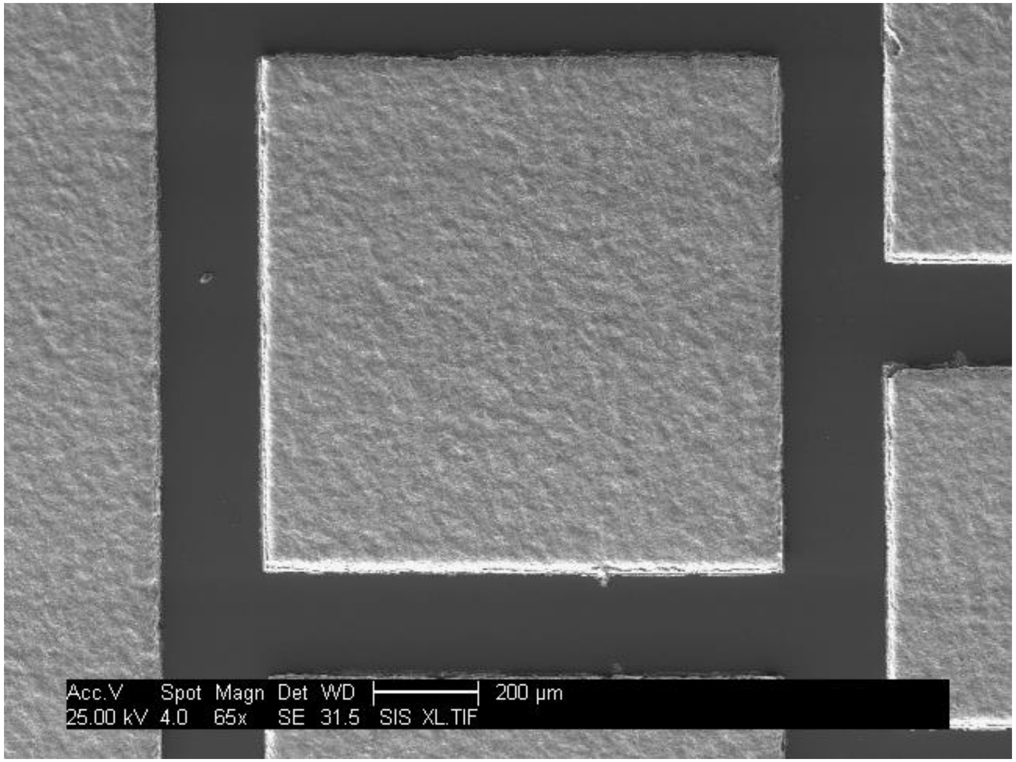
Structuring – pad printing



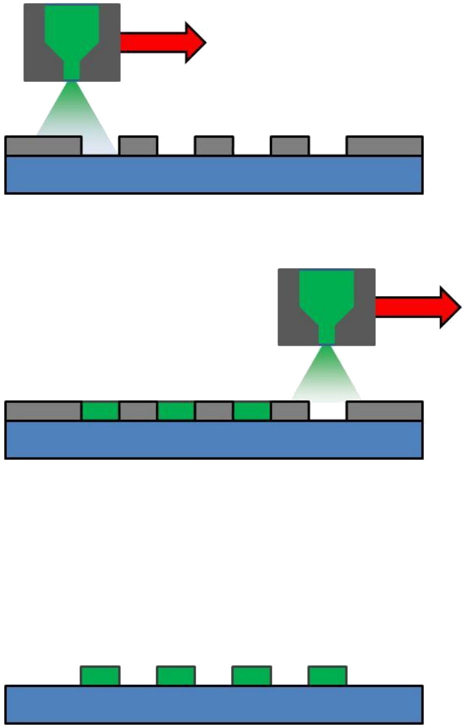
Silver NPs deposited by pad printing



Structuring – micromoulding

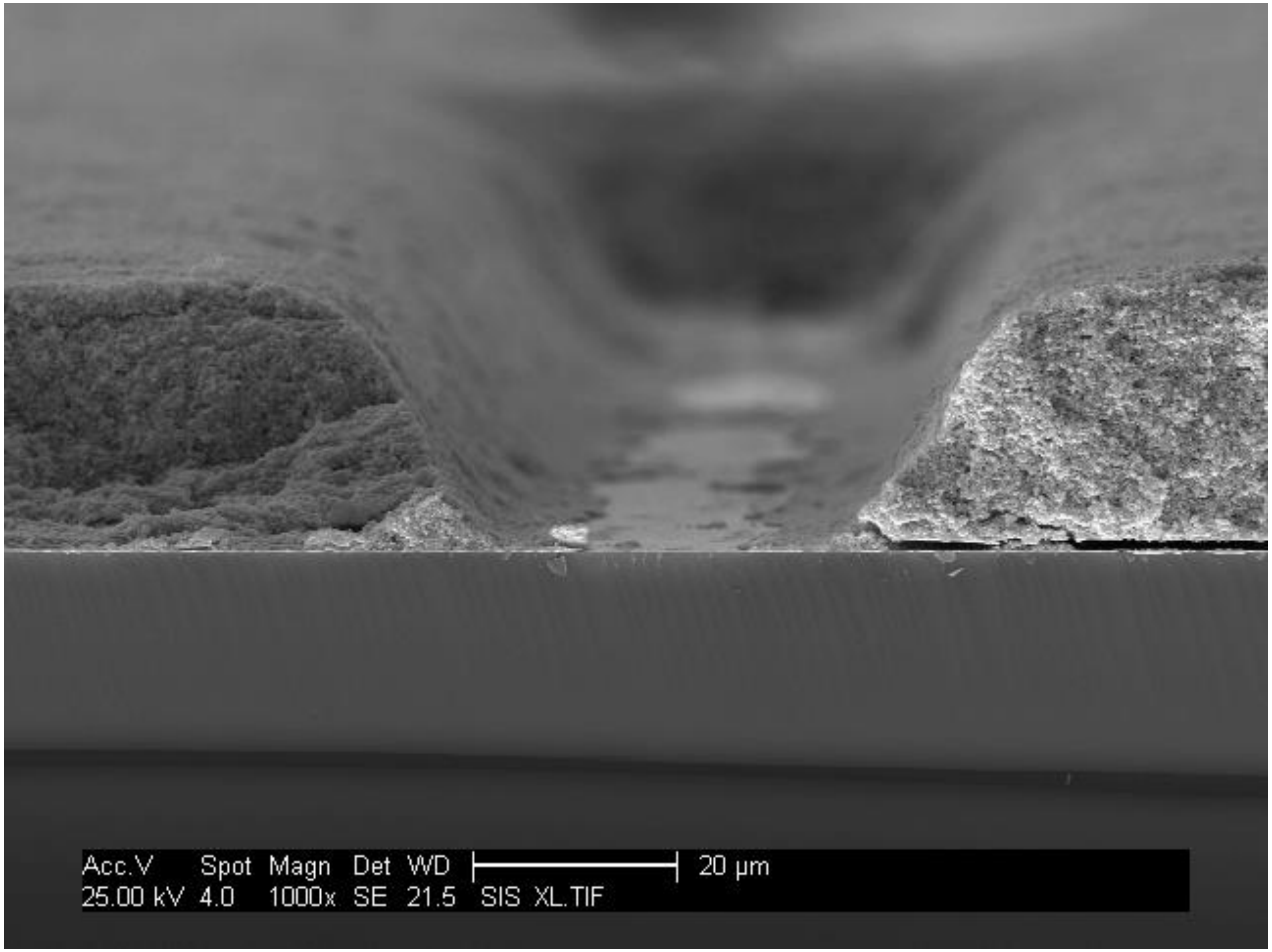


PZT features created by micro moulding

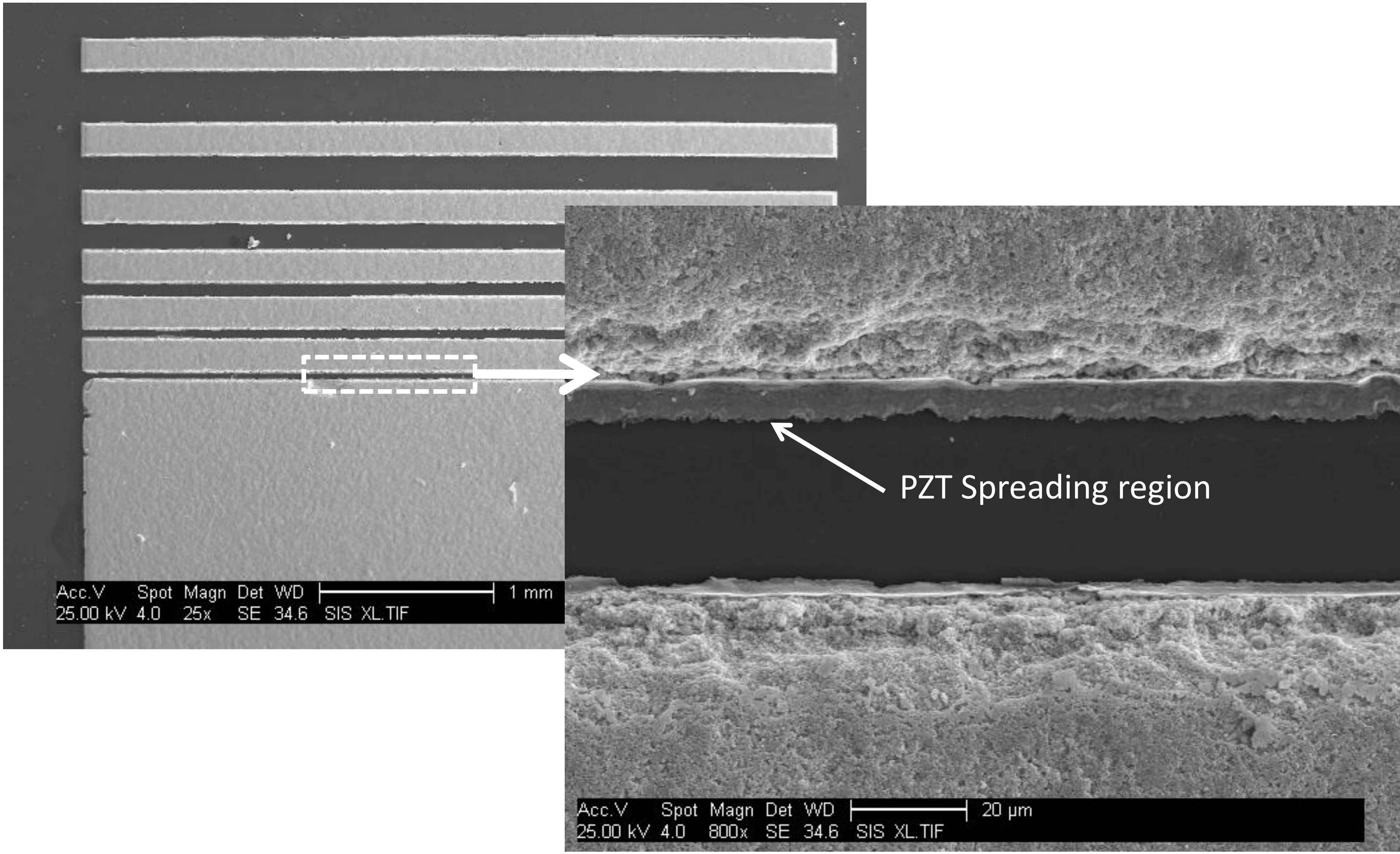


D. Wang, S.A. Rocks, R.A. Dorey, Micromoulding of PZT film structures using electrohydrodynamic atomization mould filling, J.Euro.Ceram.Soc., 29, 1147–1155, 2009. .

Structuring – micromoulding

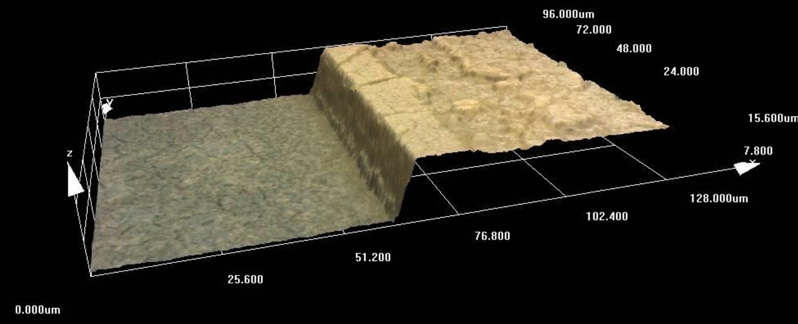


Structuring – micromoulding

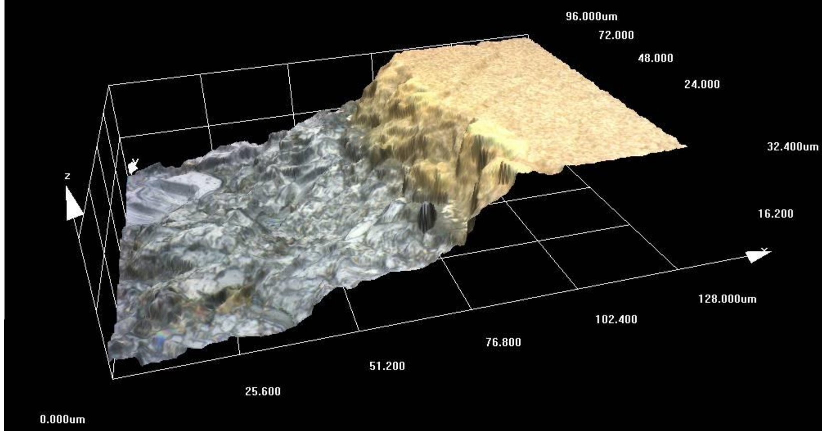


Structuring – additive vs subtractive

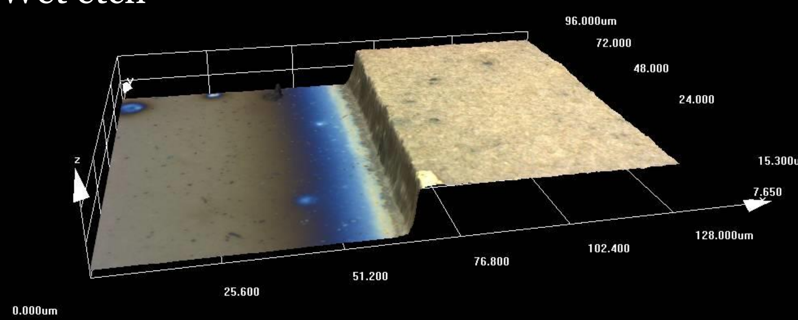
DRIE



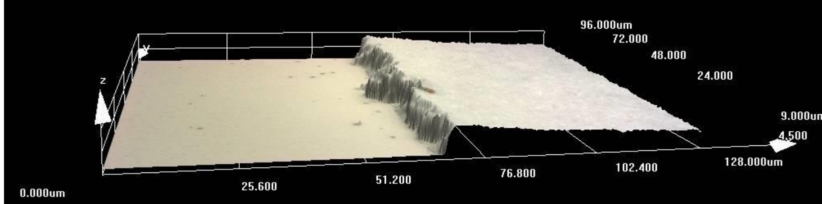
Powder blast



Wet etch



Micromould



Powders, inks & processing temperatures

	Powder Synthesis	Powder	Carrier	Binder	Thickness (µm)	Temperature (°C)		
						Drying	Burnout	Sinter
Screen	Mech	76 wt% Bi-Te	22 wt% Toluene	2 wt% Polystyrene	80	60 (hours)	250/10 m	-
Screen	In situ	75 wt% Bi-Te	20.3 wt%	-	-	120/15 m	200/5 m	400/30 m (N_2) 550 (N_2)
Screen	In situ	79.6% ZnSb	18%	None	171	150/10 m	330°C/20 m	380/20 m (N_2)
Screen	Mech	36-64 vol% Bi-Te	64-36vol% epoxy resin	n/a	100-120	-	-	300 (Ar)
Screen	Calcination	80 wt% PZT	19.2 wt%	0.8 wt%	80-200	150	-	950
Screen	Calcination	PZT	Terpineol	Ethyl cellulose	20-40	120/30 m	550/1 h 700/30 m	900/60 m
Screen	Calcination	PZT	-	-	30	120/10 m	-	925/30 m
Screen	Calcination	PZT	Terpineol & ethyl acetate	PVB-PVAc	22	-	-	800/10 m
Screen	Calcination	Complex perovkites	Terpineol	Ethyl cellulose	24-30	-	-	1000-1250/2 h
Tape	Calcination	PZT	-	PVB	30	vacuum	600/3 h	950-1150
PSG	Calcination	98 wt% PZT	4 wt% sol	None	4	450/3 m	700/10 m	700/15 m
PSG	Calcination	60 wt% PZT	40 wt% sol	None	20	250/60 s	450/15 s	720/20 m
EPD	Calcination	PZT	Acetic acid	None	25	-	-	900 (low O_2)
EPD	Calcination	30 wt% Al_2O_3	ethanol	PVB/PVAc	-	-	-	-

Powders, inks & processing temperatures

	Powder Synthesis	Powder	Carrier	Binder	Thickness (µm)	Temperature (°C)		
						Drying	Burnout	Sinter
Screen	Mech	76 wt% Bi-Te	22 wt% Toluene	2 wt% Polystyrene	80	60 (hours)	250/10 m	-
Screen	In situ	75 wt% Bi-Te	20.3 wt%	-	-	120/15 m	200/5 m	400/30 m (N_2) 550 (N_2)
Screen	In situ	79.6% ZnSb	18%	None	171	150/10 m	330°C/20 m	380/20 m (N_2)
Screen	Mech	36-64 vol% Bi-Te	64-36vol% epoxy resin	n/a	100-120	-	-	300 (Ar)
Screen	Calcination	80 wt% PZT	19.2 wt%	0.8 wt%	80-200	150	-	950
Screen	Calcination	PZT	Terpineol	Ethyl cellulose	20-40	120/30 m	550/1 h 700/30 m	900/60 m
Screen	Calcination	PZT	-	-	30	120/10 m	-	925/30 m
Screen	Calcination	PZT	Terpineol & ethyl acetate	PVB-PVAc	22	-	-	800/10 m
Screen	Calcination	Complex perovkites	Terpineol	Ethyl cellulose	24-30	-	-	1000-1250/2 h
Tape	Calcination	PZT	-	PVB	30	vacuum	600/3 h	950-1150
PSG	Calcination	98 wt% PZT	4 wt% sol	None	4	450/3 m	700/10 m	700/15 m
PSG	Calcination	60 wt% PZT	40 wt% sol	None	20	250/60 s	450/15 s	720/20 m
EPD	Calcination	PZT	Acetic acid	None	25	-	-	900 (low O_2)
EPD	Calcination	30 wt% Al_2O_3	ethanol	PVB/PVAc	-	-	-	-

Powders, inks & processing temperatures

	Powder Synthesis	Powder	Carrier	Binder	Thickness (µm)	Temperature (°C)		
						Drying	Burnout	Sinter
Screen	Mech	76 wt% Bi-Te	22 wt% Toluene	2 wt% Polystyrene	80	60 (hours)	250/10 m	-
Screen	In situ	75 wt% Bi-Te	20.3 wt%	-	-	120/15 m	200/5 m	400/30 m (N_2) 550 (N_2)
Screen	In situ	79.6% ZnSb	18%	None	171	150/10 m	330°C/20 m	380/20 m (N_2)
Screen	Mech	36-64 vol% Bi-Te	64-36vol% epoxy resin	n/a	100-120	-	-	300 (Ar)
Screen	Calcination	80 wt% PZT	19.2 wt%	0.8 wt%	80-200	150	-	950
Screen	Calcination	PZT	Terpineol	Ethyl cellulose	20-40	120/30 m	550/1 h 700/30 m	900/60 m
Screen	Calcination	PZT	-	-	30	120/10 m	-	925/30 m
Screen	Calcination	PZT	Terpineol & ethyl acetate	PVB-PVAc	22	-	-	800/10 m
Screen	Calcination	Complex perovkites	Terpineol	Ethyl cellulose	24-30	-	-	1000-1250/2 h
Tape	Calcination	PZT	-	PVB	30	vacuum	600/3 h	950-1150
PSG	Calcination	98 wt% PZT	4 wt% sol	None	4	450/3 m	700/10 m	700/15 m
PSG	Calcination	60 wt% PZT	40 wt% sol	None	20	250/60 s	450/15 s	720/20 m
EPD	Calcination	PZT	Acetic acid	None	25	-	-	900 (low O_2)
EPD	Calcination	30 wt% Al_2O_3	ethanol	PVB/PVAc	-	-	-	-

Powders, inks & processing temperatures

	Powder Synthesis	Powder	Carrier	Binder	Thickness (µm)	Temperature (°C)		
						Drying	Burnout	Sinter
Screen	Mech	76 wt% Bi-Te	22 wt% Toluene	2 wt% Polystyrene	80	60 (hours)	250/10 m	-
Screen	In situ	75 wt% Bi-Te	20.3 wt%	-	-	120/15 m	200/5 m	400/30 m (N_2) 550 (N_2)
Screen	In situ	79.6% ZnSb	18%	None	171	150/10 m	330°C/20 m	380/20 m (N_2)
Screen	Mech	36-64 vol% Bi-Te	64-36vol% epoxy resin	n/a	100-120	-	-	300 (Ar)
Screen	Calcination	80 wt% PZT	19.2 wt%	0.8 wt%	80-200	150	-	950
Screen	Calcination	PZT	Terpineol	Ethyl cellulose	20-40	120/30 m	550/1 h 700/30 m	900/60 m
Screen	Calcination	PZT	-	-	30	120/10 m	-	925/30 m
Screen	Calcination	PZT	Terpineol & ethyl acetate	PVB-PVAc	22	-	-	800/10 m
Screen	Calcination	Complex perovkites	Terpineol	Ethyl cellulose	24-30	-	-	1000-1250/2 h
Tape	Calcination	PZT	-	PVB	30	vacuum	600/3 h	950-1150
PSG	Calcination	98 wt% PZT	4 wt% sol	None	4	450/3 m	700/10 m	700/15 m
PSG	Calcination	60 wt% PZT	40 wt% sol	None	20	250/60 s	450/15 s	720/20 m
EPD	Calcination	PZT	Acetic acid	None	25	-	-	900 (low O_2)
EPD	Calcination	30 wt% Al_2O_3	ethanol	PVB/PVAc	-	-	-	-

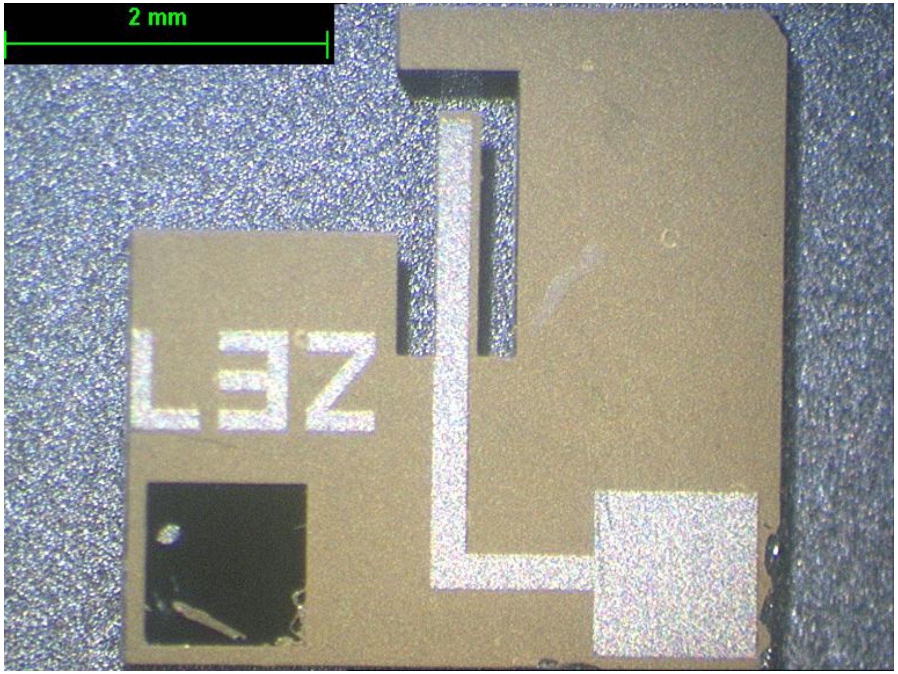
Powders, inks & processing temperatures

	Powder Synthesis	Powder	Carrier	Binder	Thickness (µm)	Temperature (°C)		
						Drying	Burnout	Sinter
Screen	Mech	76 wt% Bi-Te	22 wt% Toluene	2 wt% Polystyrene	80	60 (hours)	250/10 m	-
Screen	In situ	75 wt% Bi-Te	20.3 wt%	-	-	120/15 m	200/5 m	400/30 m (N_2) 550 (N_2)
Screen	In situ	79.6% ZnSb	18%	None	171	150/10 m	330°C/20 m	380/20 m (N_2)
Screen	Mech	36-64 vol% Bi-Te	64-36vol% epoxy resin	n/a	100-120	-	-	300 (Ar)
Screen	Calcination	80 wt% PZT	19.2 wt%	0.8 wt%	80-200	150	-	950
Screen	Calcination	PZT	Terpineol	Ethyl cellulose	20-40	120/30 m	550/1 h 700/30 m	900/60 m
Screen	Calcination	PZT	-	-	30	120/10 m	-	925/30 m
Screen	Calcination	PZT	Terpineol & ethyl acetate	PVB-PVAc	22	-	-	800/10 m
Screen	Calcination	Complex perovkites	Terpineol	Ethyl cellulose	24-30	-	-	1000-1250/2 h
Tape	Calcination	PZT	-	PVB	30	vacuum	600/3 h	950-1150
PSG	Calcination	98 wt% PZT	4 wt% sol	None	4	450/3 m	700/10 m	700/15 m
PSG	Calcination	60 wt% PZT	40 wt% sol	None	20	250/60 s	450/15 s	720/20 m
EPD	Calcination	PZT	Acetic acid	None	25	-	-	900 (low O_2)
EPD	Calcination	30 wt% Al_2O_3	ethanol	PVB/PVAc	-	-	-	-

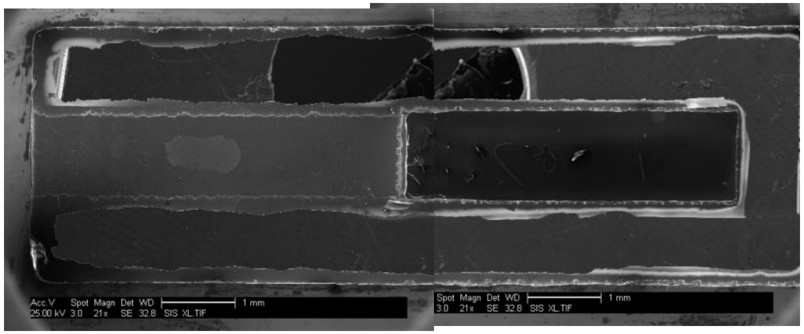
Powders, inks & processing temperatures

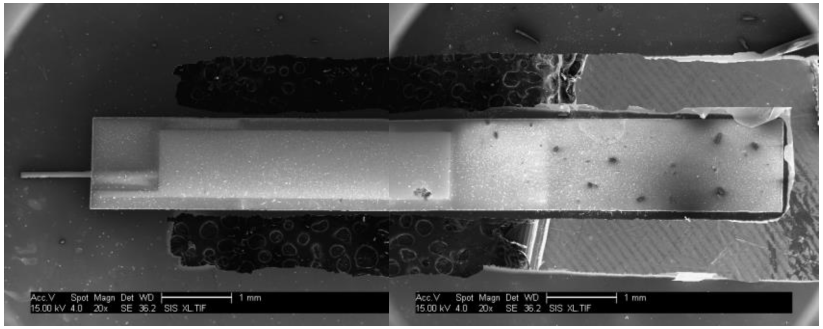
	Powder Synthesis	Powder	Carrier	Binder	Thickness (µm)	Temperature (°C)		
						Drying	Burnout	Sinter
Screen	Mech	76 wt% Bi-Te	22 wt% Toluene	2 wt% Polystyrene	80	60 (hours)	250/10 m	-
Screen	In situ	75 wt% Bi-Te	20.3 wt%	-	-	120/15 m	200/5 m	400/30 m (N_2) 550 (N_2)
Screen	In situ	79.6% ZnSb	18%	None	171	150/10 m	330°C/20 m	380/20 m (N_2)
Screen	Mech	36-64 vol% Bi-Te	64-36vol% epoxy resin	n/a	100-120	-	-	300 (Ar)
Screen	Calcination	80 wt% PZT	19.2 wt%	0.8 wt%	80-200	150	-	950
Screen	Calcination	PZT	Terpineol	Ethyl cellulose	20-40	120/30 m	550/1 h 700/30 m	900/60 m
Screen	Calcination	PZT	-	-	30	120/10 m	-	925/30 m
Screen	Calcination	PZT	Terpineol & ethyl acetate	PVB-PVAc	22	-	-	800/10 m
Screen	Calcination	Complex perovkites	Terpineol	Ethyl cellulose	24-30	-	-	1000-1250/2 h
Tape	Calcination	PZT	-	PVB	30	vacuum	600/3 h	950-1150
PSG	Calcination	98 wt% PZT	4 wt% sol	None	4	450/3 m	700/10 m	700/15 m
PSG	Calcination	60 wt% PZT	40 wt% sol	None	20	250/60 s	450/15 s	720/20 m
EPD	Calcination	PZT	Acetic acid	None	25	-	-	900 (low O_2)
EPD	Calcination	30 wt% Al_2O_3	ethanol	PVB/PVAc	-	-	-	-

Piezoelectric energy harvesters



PZT micro energy harvesting cantilever





Performance

Printed piezoelectrics & pyroelectrics

Architecture	Process	Active material thickness (µm)	Substrate thickness (µm)	Dimensions L x W (mm)	Power (µW)	Power density (µW/cm^3)	Operational frequency (Hz)
Bimorph	Screen	20 (x2)	n/a	6.5 x 5.5	33.2 @ 1 g	-	344
Bimorph	Screen	55	none	18 x 9	-	25-33@0.5 g	227
Unimorph	Screen	65 (x2)	250	20 x 8	400	-	230
Unimorph	Screen	22	12.3	(0.38-0.58) x 0.4	-	-	68-154 x 10^3
Unimoph	PSG/spin	4	50	5 x 17	15.4 @ 1 g	97.9 @ 1 g	89
Unimorph	Aerosol	15	20	8 x 6	200 @ 1.5 g	137.5 @ 1.5 g	112
Unimorph	Tape cast	230	250	60 x 30	-	2083	8.2
Pyroelectric	Screen	60-100	500	-	-	-	~ 10^{-3}

Printed piezoelectrics & pyroelectrics

Architecture	Process	Active material thickness (µm)	Substrate thickness (µm)	Dimensions L x W (mm)	Power (µW)	Power density (µW/cm³)	Operational frequency (Hz)
Bimorph	Screen	20 (x2)	n/a	6.5 x 5.5	33.2 @ 1 g	-	344
Bimorph	Screen	55	none	18 x 9	-	25-33@0.5 g	227
Unimorph	Screen	65 (x2)	250	20 x 8	400	-	230
Unimorph	Screen	22	12.3	(0.38-0.58) x 0.4	-	-	68-154 x 10^3
Unimoph	PSG/spin	4	50	5 x 17	15.4 @ 1 g	97.9 @ 1 g	89
Unimorph	Aerosol	15	20	8 x 6	200 @ 1.5 g	137.5 @ 1.5 g	112
Unimorph	Tape cast	230	250	60 x 30	-	2083	8.2
Pyroelectric	Screen	60-100	500	-	-	-	~ 10^{-3}

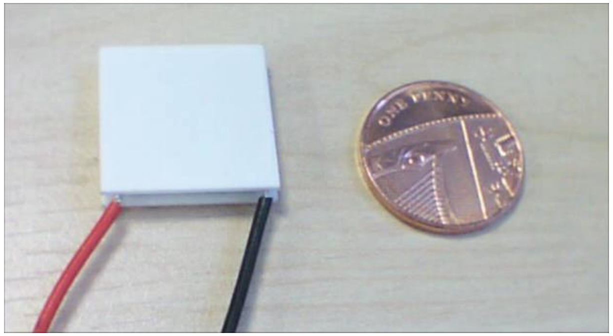
Likely to be pW level

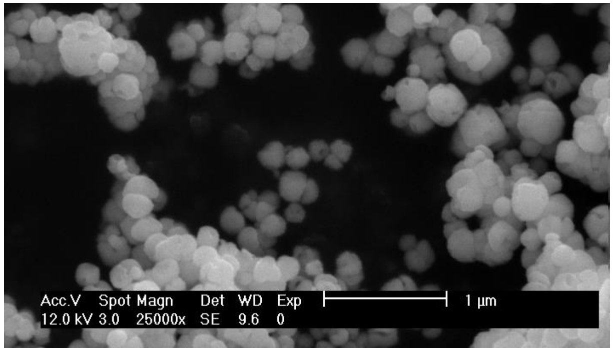
Printed thermoelectrics

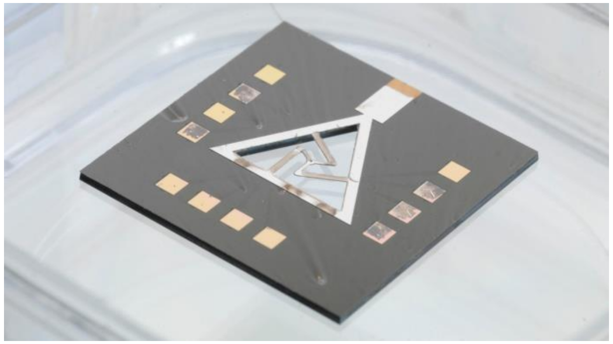
Architecture	Processing	Active material thickness (µm)	Elements	Seebeck coef. (µV/K)	ZT	Power factor ($\alpha^2\sigma$) mW/m^2K	Power density ($\mu W/cm^3$)
In-plane (n) $(Bi,Sb)_2Te)_3$ (p) $Bi_2(Se,Te)_3$	Screen	80	5	123	-	0.06	-
In-plane (unimat) Bi_2Te_3	Dispenser	120	62	200 @ RT	0.31	0.27	130 (20 K ΔT)
Film only Bi_2Te_3	Screen	80	-	140	0.61 (@RT)	2.1	-
Film only $Ca_3Co_4O_9$	Aerosol	55	-	150-170 (@300-700°C)	-	-	-
Film only ZnSb	Screen	-	-	355-365 (@ 330-480K)			
$Bi_{0.85}Sb_{0.15}$/epoxy	Screen			97			
Ag-Ni	Screen			22-25 @RT		0.6-1.1 @ ~RT	30 (200 K ΔT)
Multilayer (n) $LaSrTiO_3$ (p) Ni-Mo	Multilayer	(n) 100 (p) 25	50	(n) 20 @ RT (p) 153 @ RT	(n) 0.32 @623K (p) 0.04 @623K		450 (360 K ΔT)
In-plane (n) Bi_2Te_3 (p) Sb_2Te_3	Co-evaporation	-	8	(n) 248 (p) 188	(n) 0.93 @ 300K (p) 0.26 @ 300K	(n) 4.87 @ 300K (p) 2.81 @ 300K	-
Π Cu/Ni	Electro-plate	150	51	20.6	-	-	0.012 (0.12 K ΔT)

Summary

- Film based harvesters can be fabricated
- Thick films are reliant on consolidation of powders
  i.e. heat required
- Film forming techniques are continually improving
- Cheaper & quicker to fabricate than bulk systems







Based on:
Integrated Powder-based Thick Films for Thermoelectric, Pyroelectric and Piezoelectric Energy Harvesting Devices
Robert A. Dorey
IEEE Sensors Journal, vol 14, no 7, pp 2177-2184, 2014

Contact details

Professor Robert Dorey
Chair in Nanomaterials

Department of Mechanical Engineering Sciences,
Faculty of Engineering and Physical Sciences,
University of Surrey
Guildford
Surrey
UK
GU2 7XH

r.dorey@surrey.ac.uk
www.twitter.com/Robert_Dorey
www.surrey.ac.uk

Ceramic Thick Films for MEMS and Microdevices ISBN: 978-1-4377-7817-5