Variable capacitor energy harvesting based on polymer dielectric and composite electrode

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Agenda

- Introduction
- The FP7 project MATFLEXEND
- Capacitive harvesting overview
- Measurements
- Demonstrator

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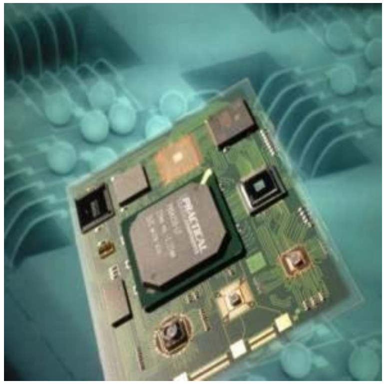
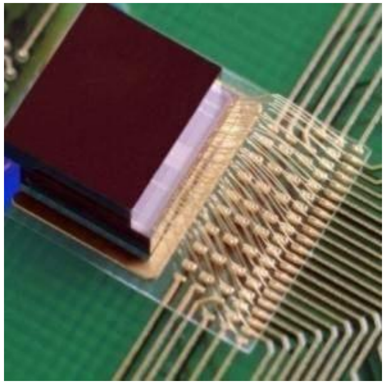
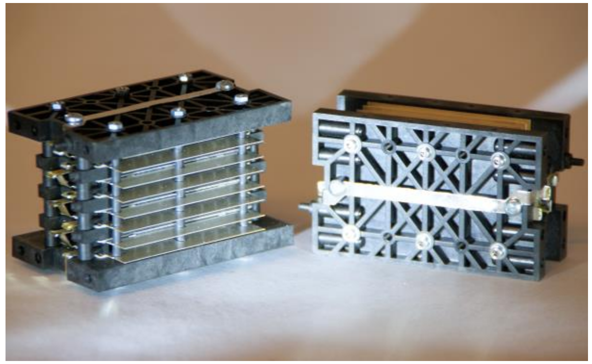


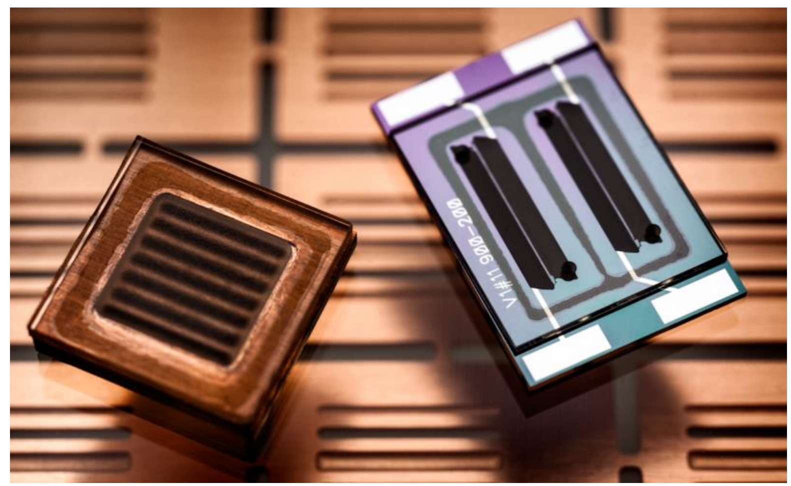


Micro Energy at Fraunhofer IZM, Berlin

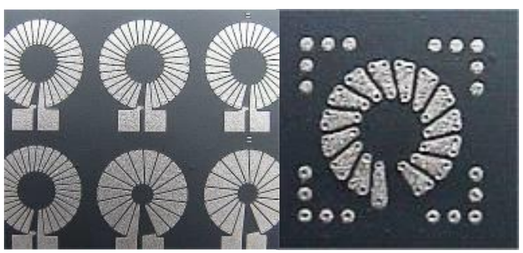
Micro fuel cell



Fuel cell stacks



Micro batteries



Micro DC-DC converter coils

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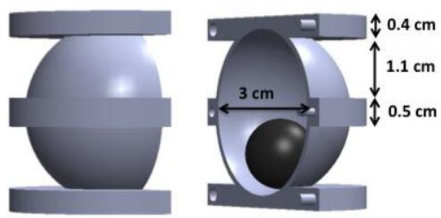
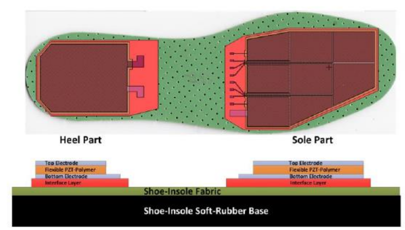
Human based mechanical energy harvesting

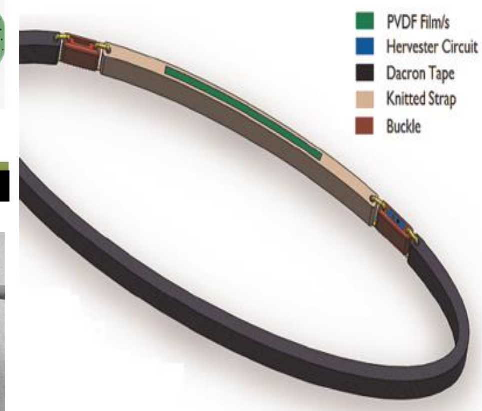
Many challenges:

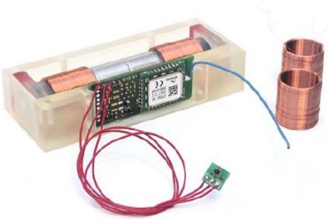
- Low frequency, random motion
- Low and medium forces, mechanical adaption
- Devices need to be tunable or broadband
- Power output limited by device size
- Conversion effectiveness needs to be as high as possible

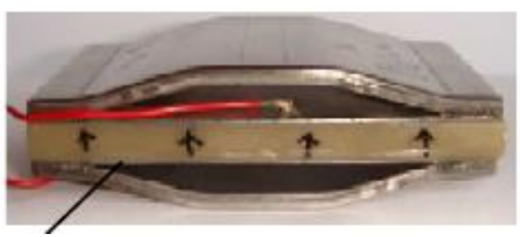
Many devices have been shown:

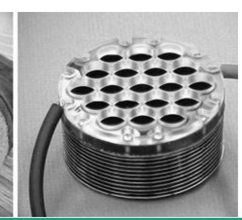












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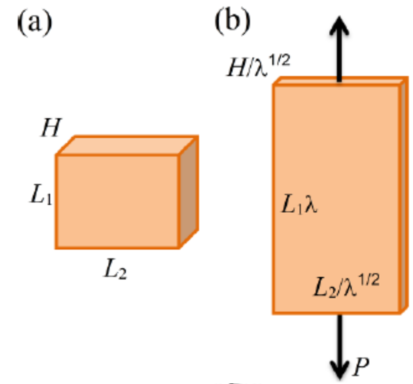
Electrostatic harvester comparison

$$E = \frac{1}{2} \cdot C \cdot V^2$$

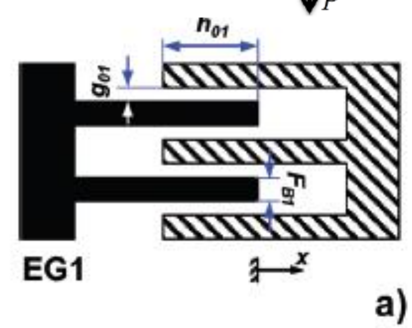
Dielectric elastomers:

- mechanical force stretches the dielectric, increases capacitor area and reduces dielectric thickness
- mechanical fixtures are required
- high voltage, high efficiency
- relative permittivity: ca. 3



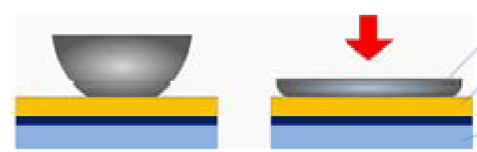
Electrostatic MEMS

- interdigitated electrodes a) area overlap b) gap closing
- mostly MEMS
- relative perittivity: ca. 1



MATFLEXEND

- capacity is changed by change of top electrode area
- relative permittivity: ca. 3 … 300
- flexible and low cost…



Electrostatic harvester comparison

Piezo, electrete and triboelectric:

- True emf, electric charges are being generated

Dielectric elastomers, Electrostatic MEMS and MATFLEXEND:

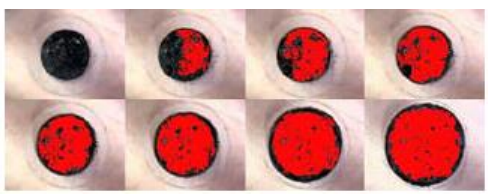
- These are variable capacitors which have to be pre-charged

MATFLEXEND Project Summary

Matflexend investigates

New materials which enable capacitive-mechanical energy harvesting based on

- high-k dielectric composites and
- electrically conducting elastomers as variable capacitor electrodes



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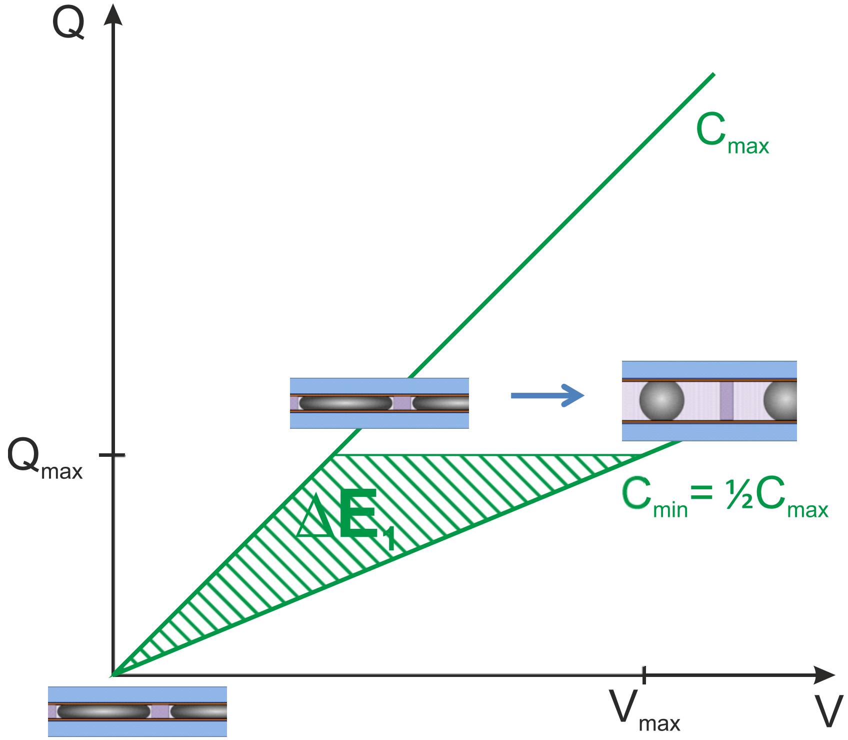
Capacitive Harvesting

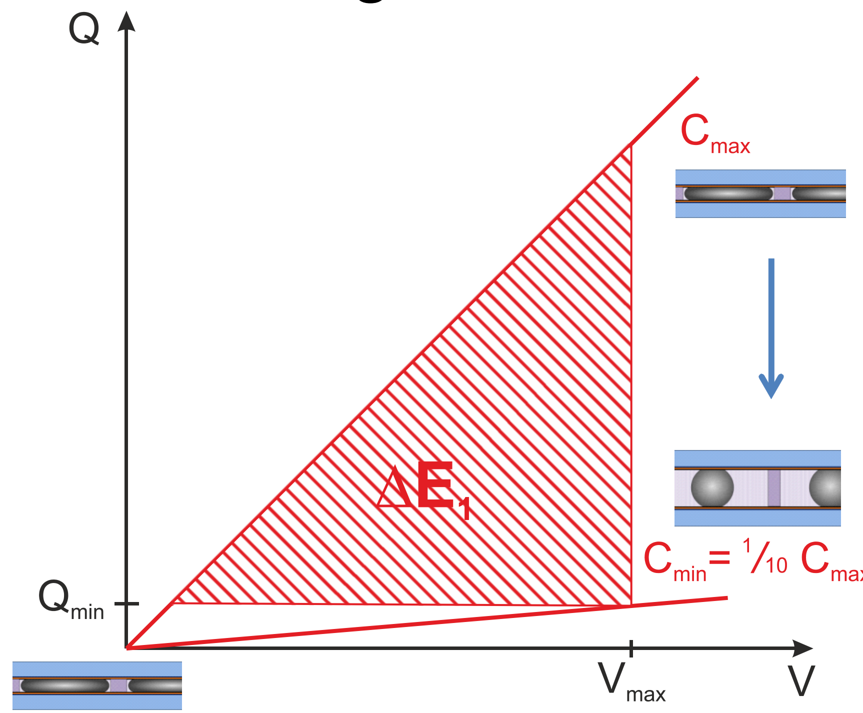
with variable electrode area

Charge constrained



$$\Delta E = \frac{1}{2} V_{max}{}^2 C_{min} \left(1 - \frac{C_{min}}{C_{max}}\right)$$

Voltage constrained



$$\Delta E = \frac{1}{2} V_{max}{}^2 \left(C_{max} - C_{min}\left(2 - \frac{C_{min}}{C_{max}}\right)\right)$$

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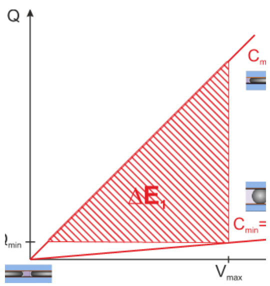
How much energy can be harvested ?

$$\Delta E = \frac{1}{2} V_{max}{}^{2} \left(C_{max} - C_{min} \left(2 - \frac{C_{min}}{C_{max}} \right) \right)$$

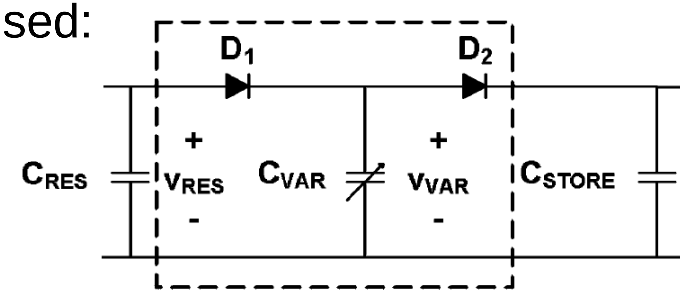


high power but the conversion cycle circuit requires sophisticated circuit

C_{max} = 10 nF
C_{min} = 0
V = 400 V
dE = 0.8 mWs
f= 0.5 Hz → **P = 0.4 mW**

(final demonstrator: 3 nF achieved)

therefore in most cases
this circuit is used:

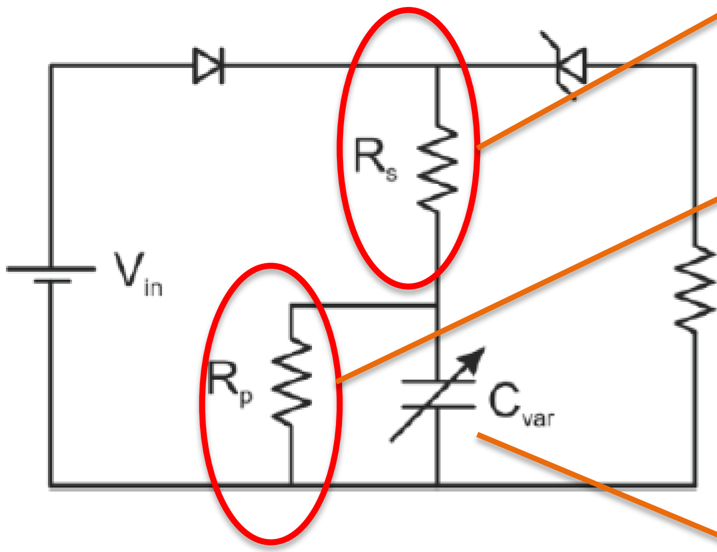


The voltage of C_{store} is increased stepwise from V_1 to $V_2 = 2V_1$

10 steps at f= 0.5 Hz:
P= 0,02 mW

Influence of parasitics

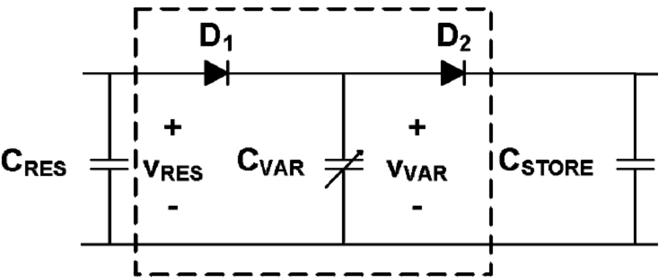
Equivalent circuit model

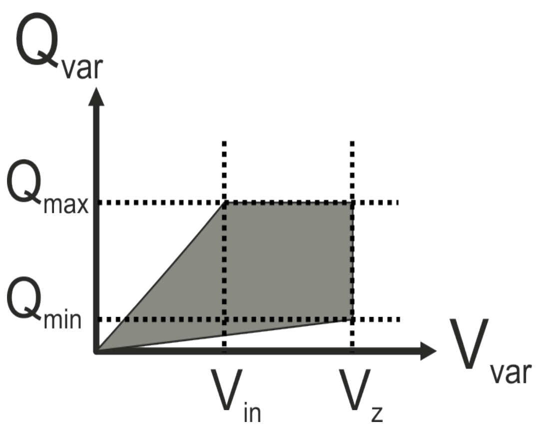


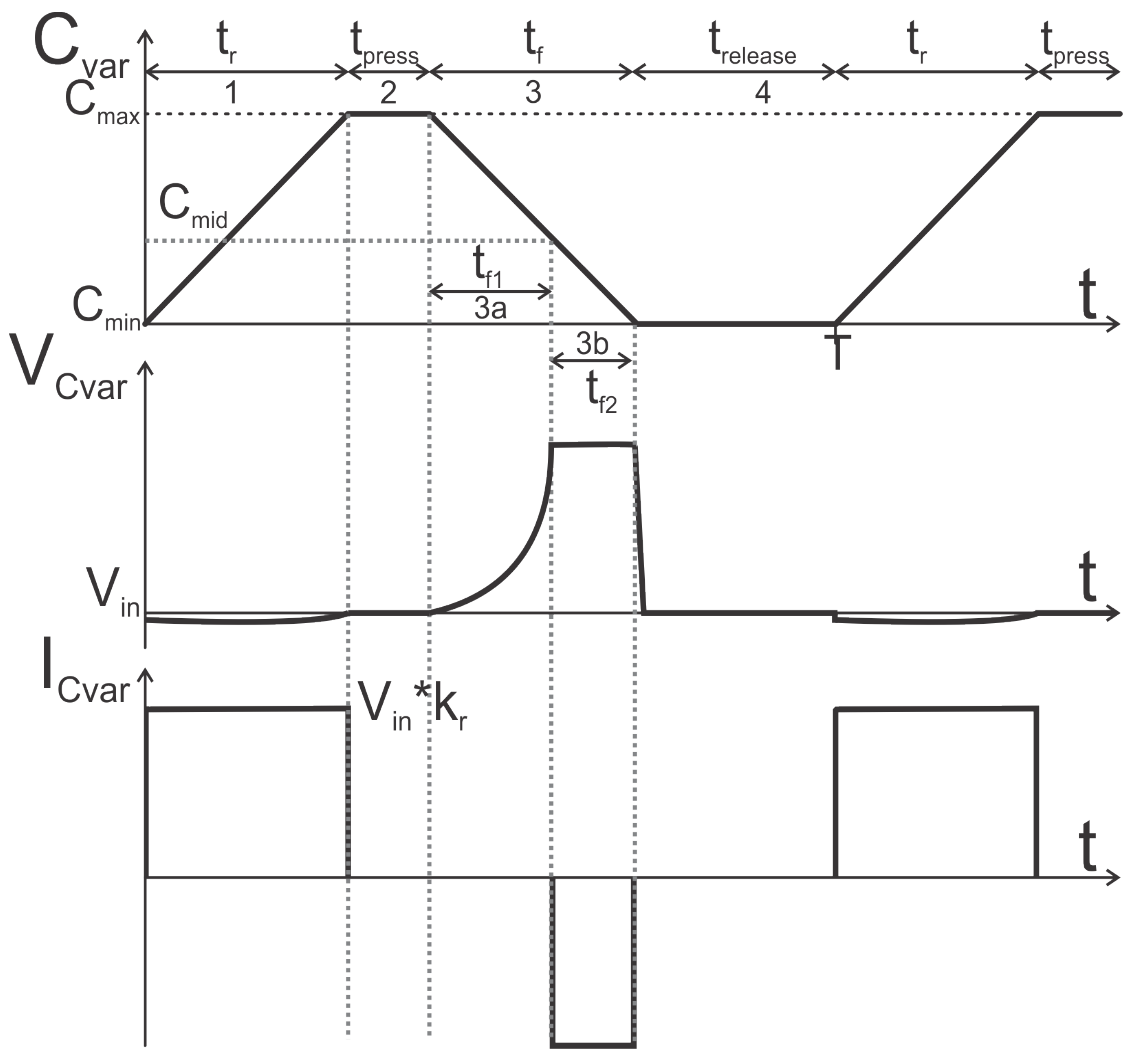
- R_s serial resistance, mainly ohmic resistance of the conductive elastomer electrode
- R_p parallel resistance, leakage current through the dielectric

MATFLEXEND variable capacitor

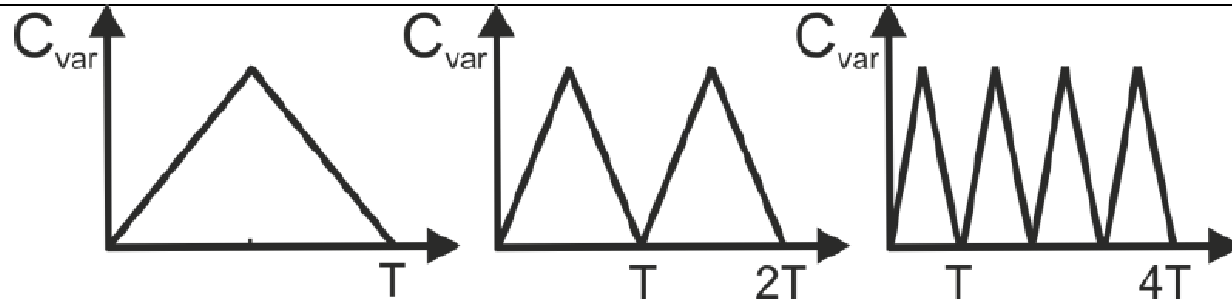
Voltage and current waveforms







Design example of circuit analysis

<table>
<tr><td colspan="2">Capacitance variation (10pF to 1nF@different frequencies):</td><td colspan="3">
</td></tr>
<tr><td rowspan="6">Input parameters</td><td colspan="2">Case 1</td><td colspan="2">Case2</td></tr>
<tr><td rowspan="3">R_s=50kΩ</td><td>R_{p1}=1GΩ</td><td rowspan="3">R_p=10GΩ</td><td>R_{s1}=5kΩ</td></tr>
<tr><td>R_{p2}=10GΩ</td><td>R_{s2}=50kΩ</td></tr>
<tr><td>R_{p3}=100GΩ</td><td>R_{s3}=500kΩ</td></tr>
<tr><td colspan="2">V_{in}=100V</td><td colspan="2">V_{in}=100V</td></tr>
<tr><td colspan="2">V_z=200V</td><td colspan="2">V_z=200V</td></tr>
</table>

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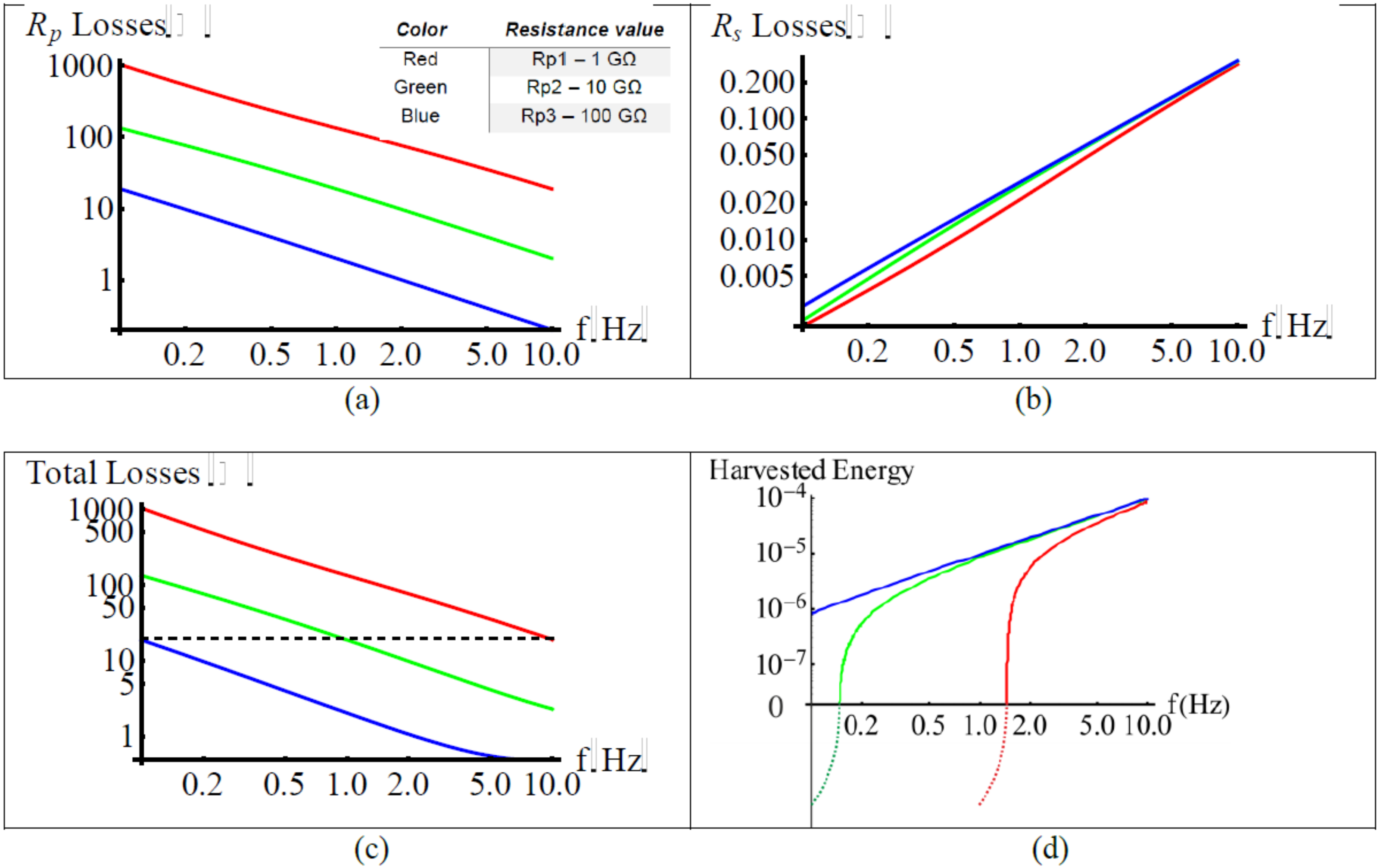
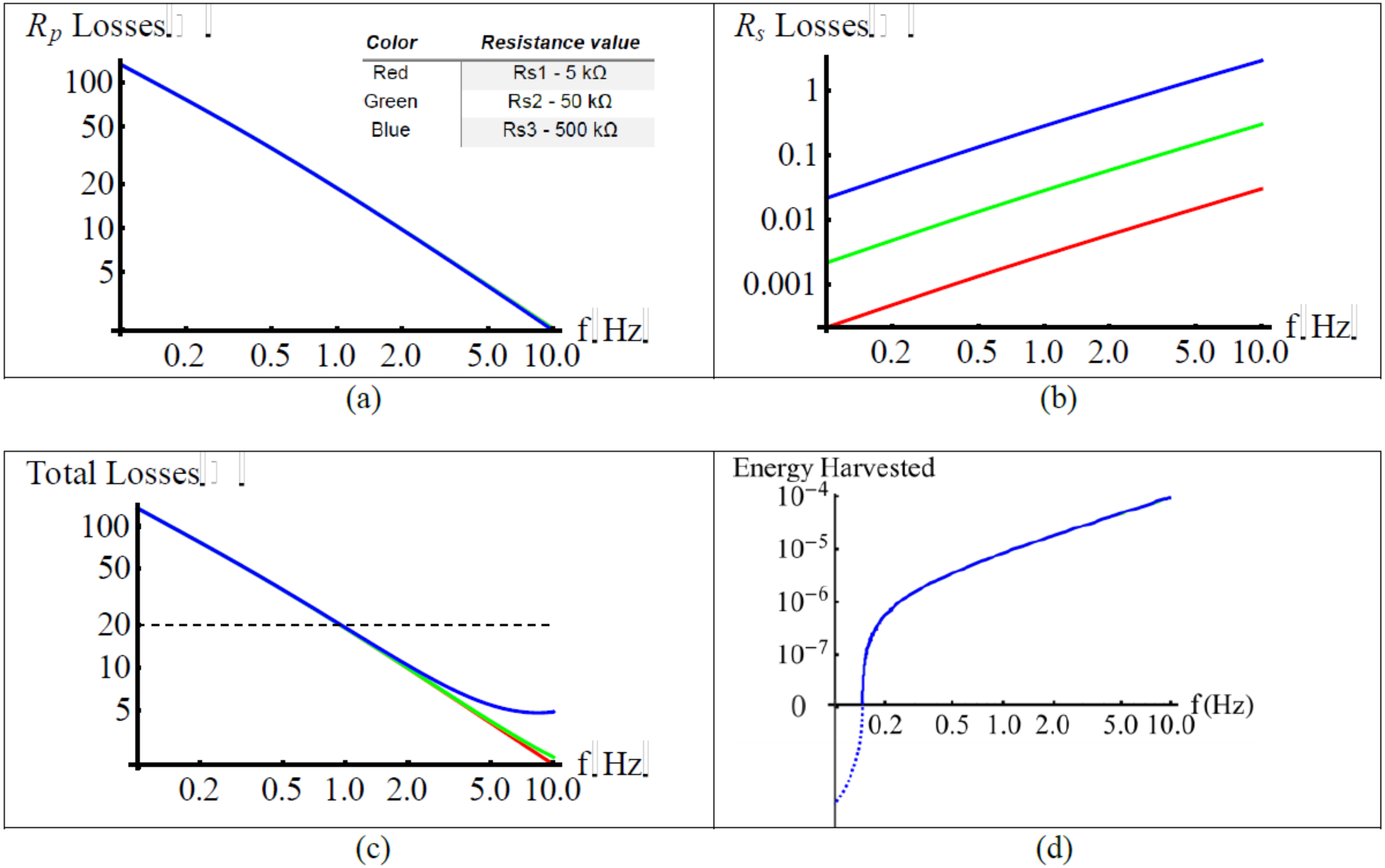
Case 1



R_p Losses
Color
Resistance value
Red
Rp1 – 1 GΩ
Green
Rp2 – 10 GΩ
Blue
Rp3 – 100 GΩ
1000
100
10
1
0.2
0.5
1.0
2.0
5.0
10.0
f Hz
(a)
R_s Losses
0.200
0.100
0.050
0.020
0.010
0.005
0.2
0.5
1.0
2.0
5.0
10.0
f Hz
(b)
Total Losses
1000
500
100
50
10
5
1
0.2
0.5
1.0
2.0
5.0
10.0
f Hz
(c)
Harvested Energy
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
0.2
0.5
1.0
2.0
5.0
10.0
f(Hz)
(d)

Case 2



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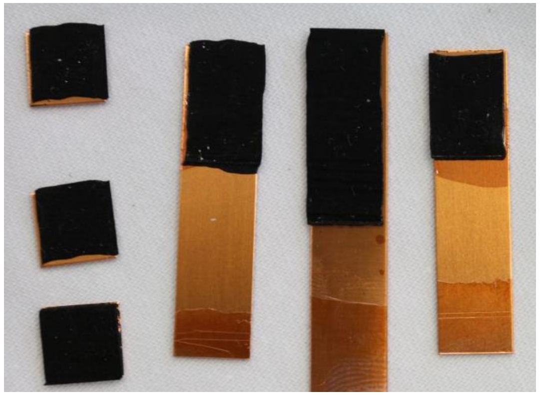
MATFLEXEND material choice

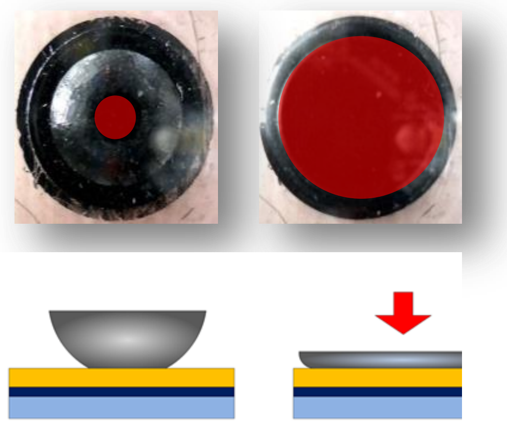
- Composite polymers which can be printed
- Thin, mechanically flexible packaging
- Low cost fabrication



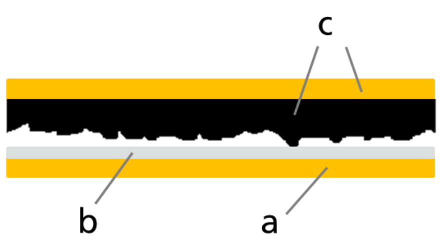
- Smaller capacity compared to metal electrode
- Material fatigue lower efficiency due to elastic/ viscoelastic deformation
- Adhesive forces between dielectric and elastomer electrode

Elastomer electrode configuration

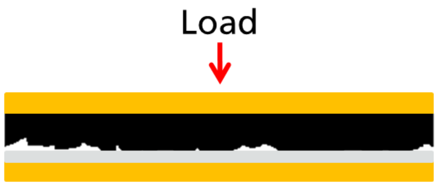
3D shape (molded)



planar, rough



planar, smooth



- material strain generates restoring force
- thicker device, lower power density

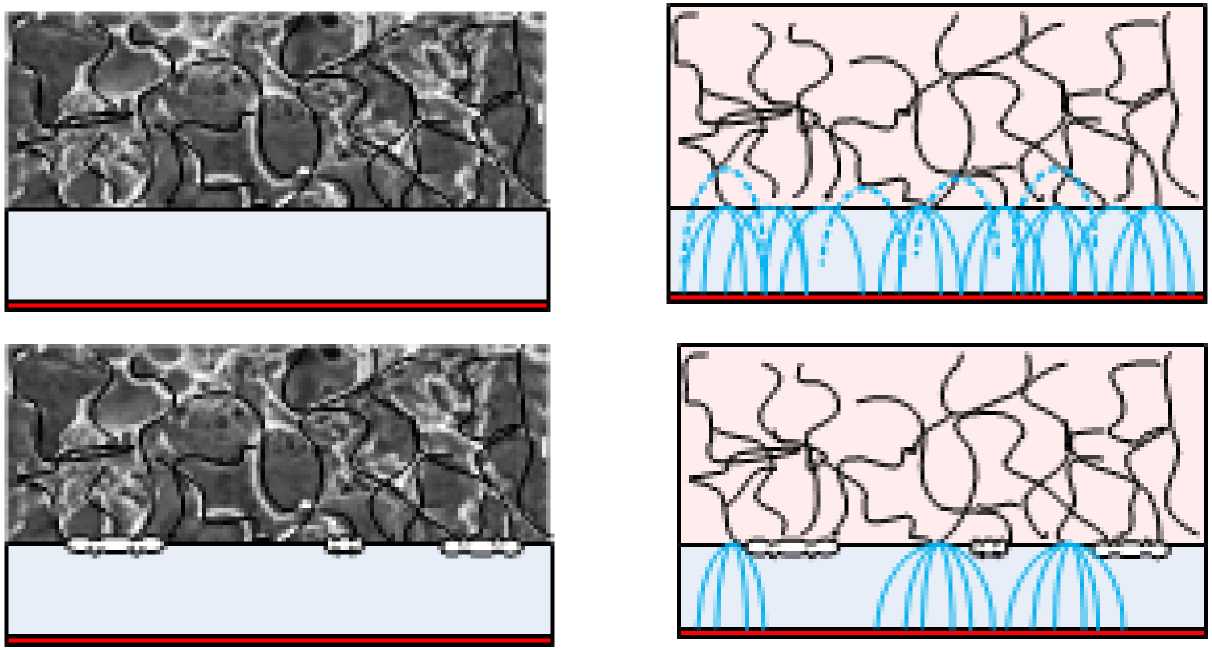
- thin device, high power density, stackable
- lower specific capacity (rough electrode
- additional spacer/spring elements required for detaching

Influence of material morphology and surface roughness

Composite electrode

Dielectric

Entrapped air at interface



Elastomer

Dielectric

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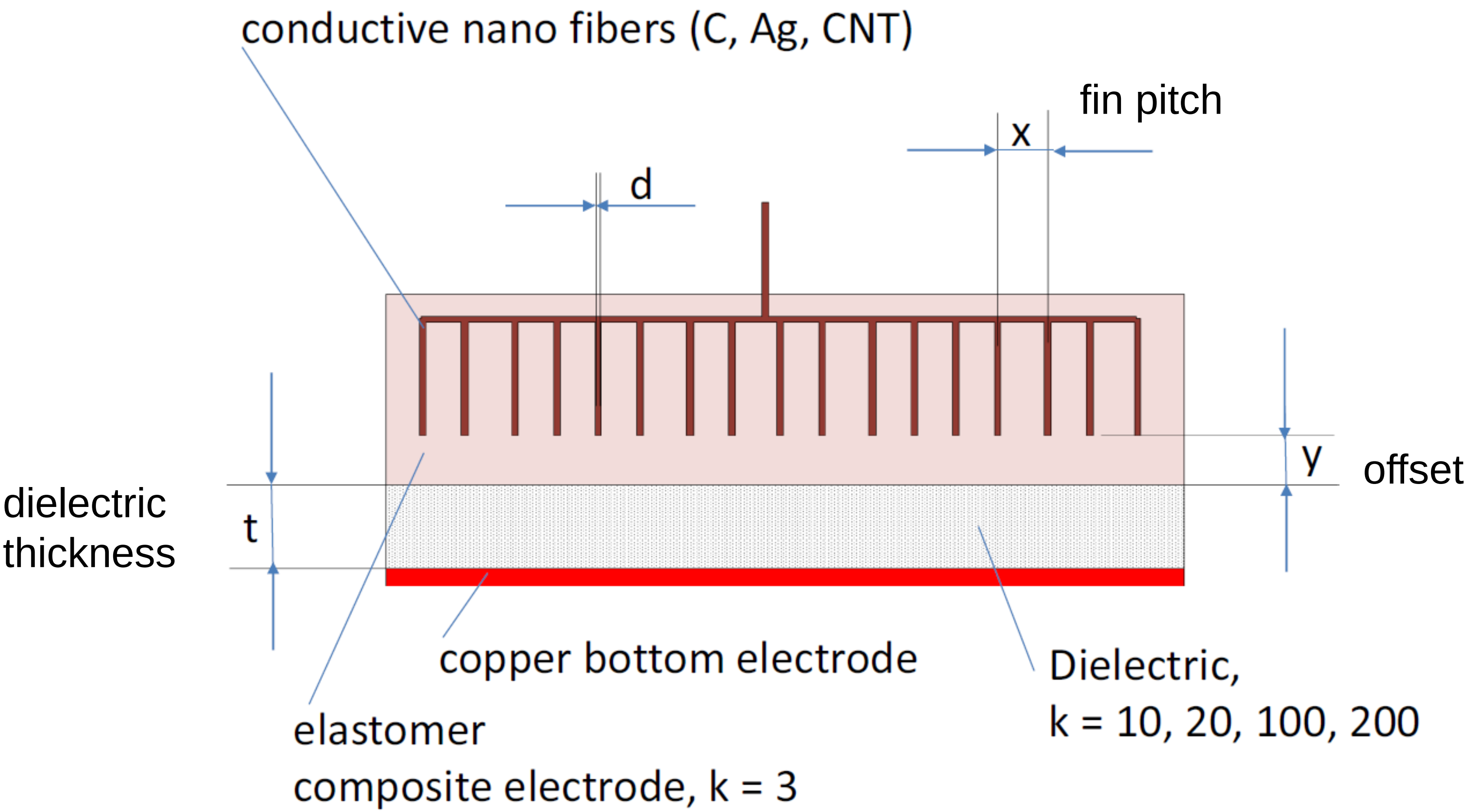
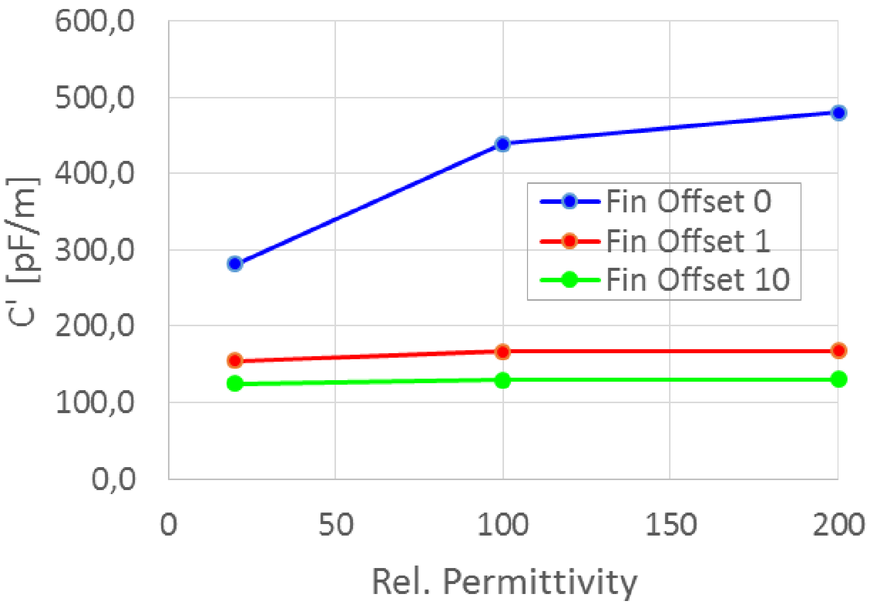
FEM Maxwell simulation of composite electrode on dielectric



Field simulations of composite electrode on dielectric



Dielectric thickness: 10 µm
Nono-fiber pitch: 10 µm

- thin layers of dielectric over the nano-conductors (fin offset) degrade capacity greatly
- even if there is no fin offset a large distance between the fibers (10 µm) reduces the resulting capacity to a great extend

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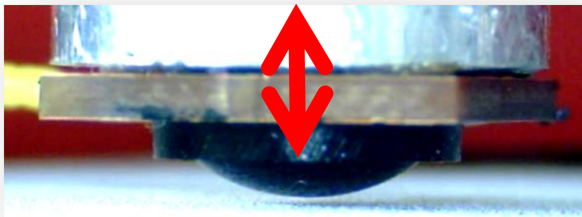
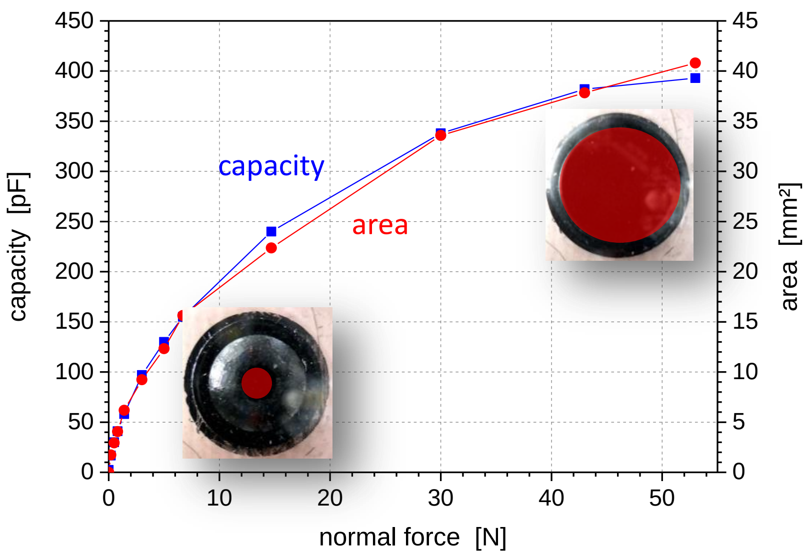
Measurements

- Capacity of composite electrode as function of mechanical pressure
- Current flow during cycling
- Voltage rise at output capacitor

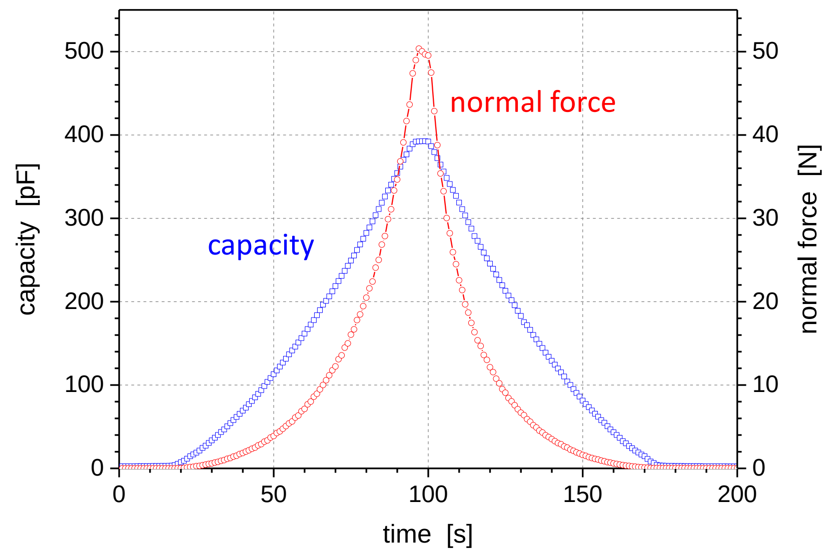
Capacity change with 3D shaped electrodes

Spherical electrode ∅ 7.5 mm





BaTiO_3-dielectric



Simultaneous measurement of force, capacity and electrode area

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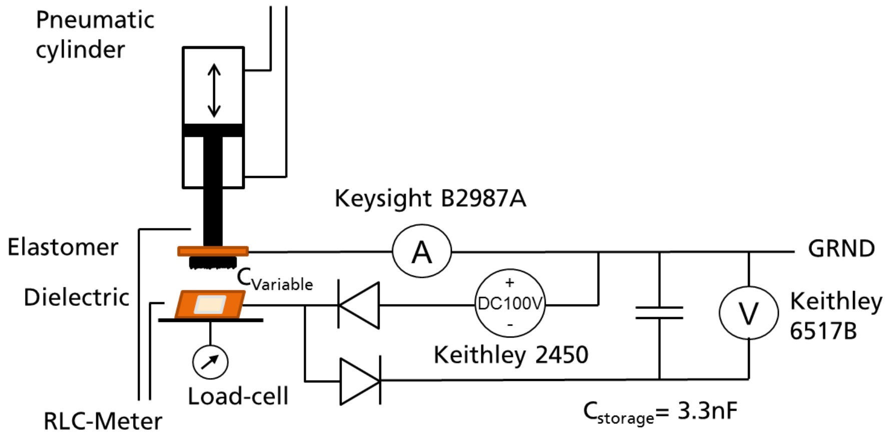
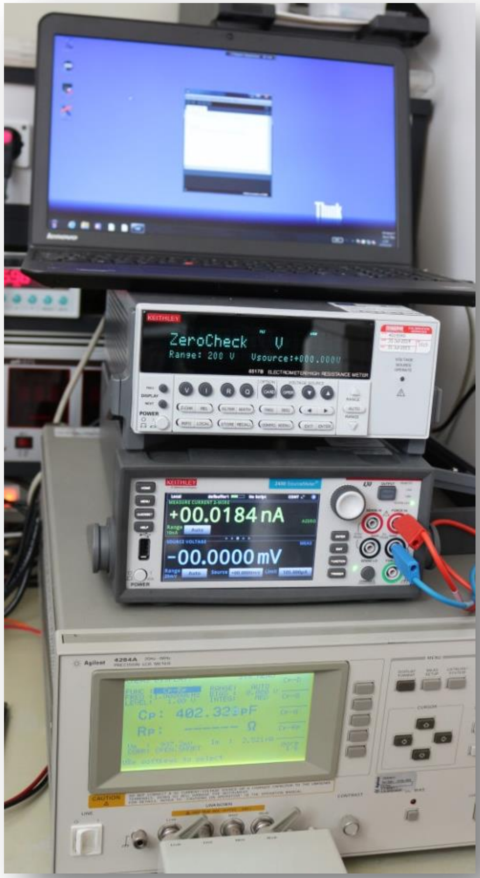
Specific capacity on Mylar dielectric (2)

Electrode	F N	I_{leak} nA	C pF/cm²
PDMS+filler MATFLEXEND	5	< 1	143
PolyHIPE covered		< 1	230
PolyHIPE noncovered		< 1	237
MATFLEXEND filled elastomer	10	< 5	398
	50		578
	100		720
Reference, silicone	5	< 5	250
	10		280
	50		640
	100		680

Experimental Setup





Parameter control

voltage at storage capacitor

Voltage Source DC 100V

capacity C_{var}

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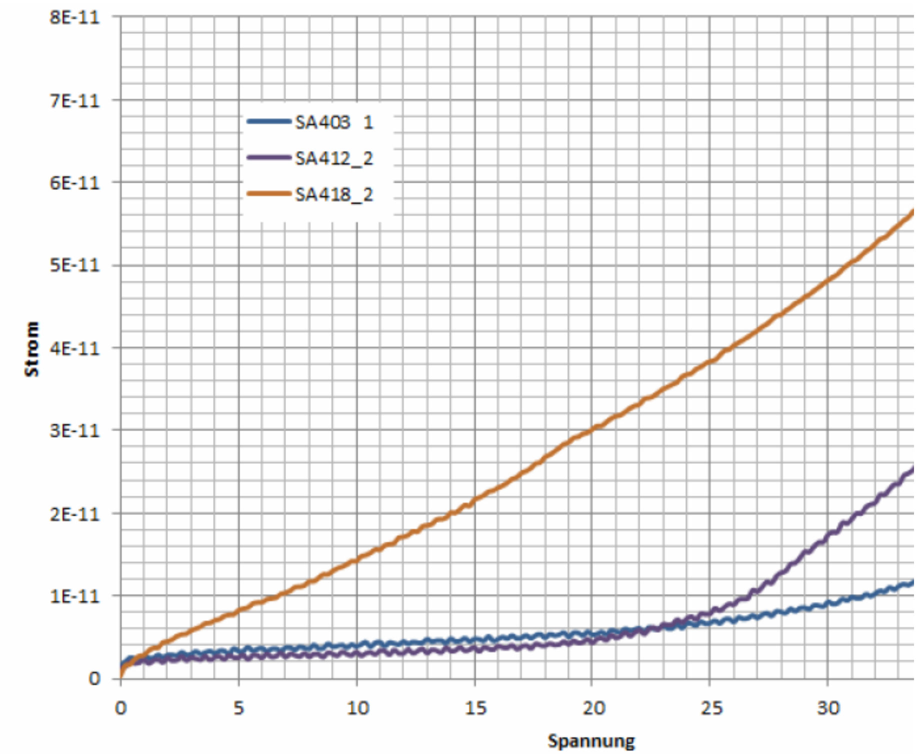
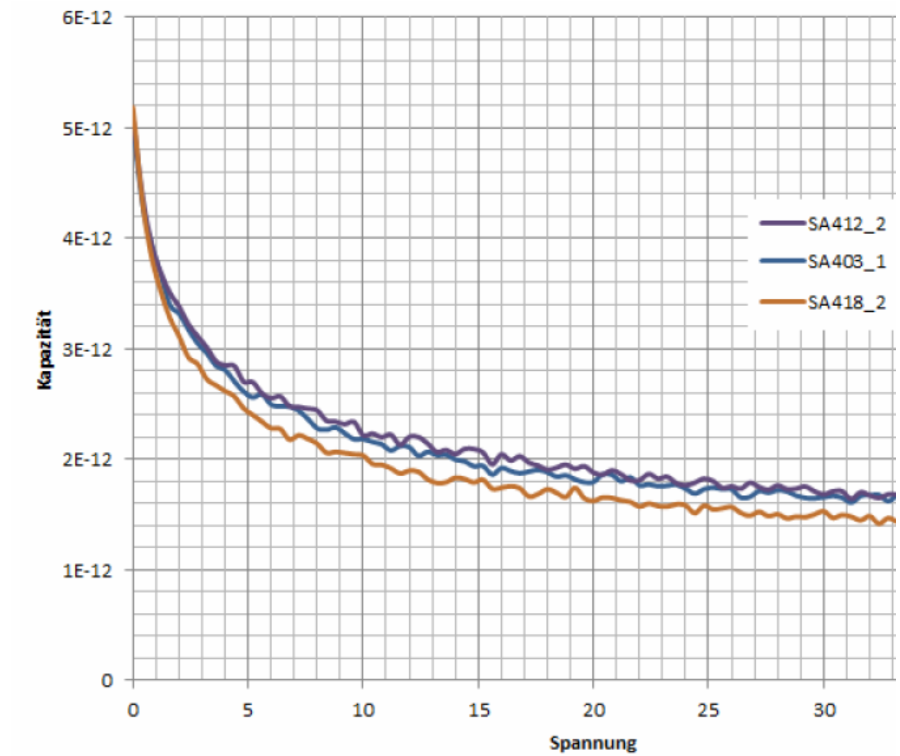
The diodes of the harvesting circuit

Diodes leakage current



junction capacity



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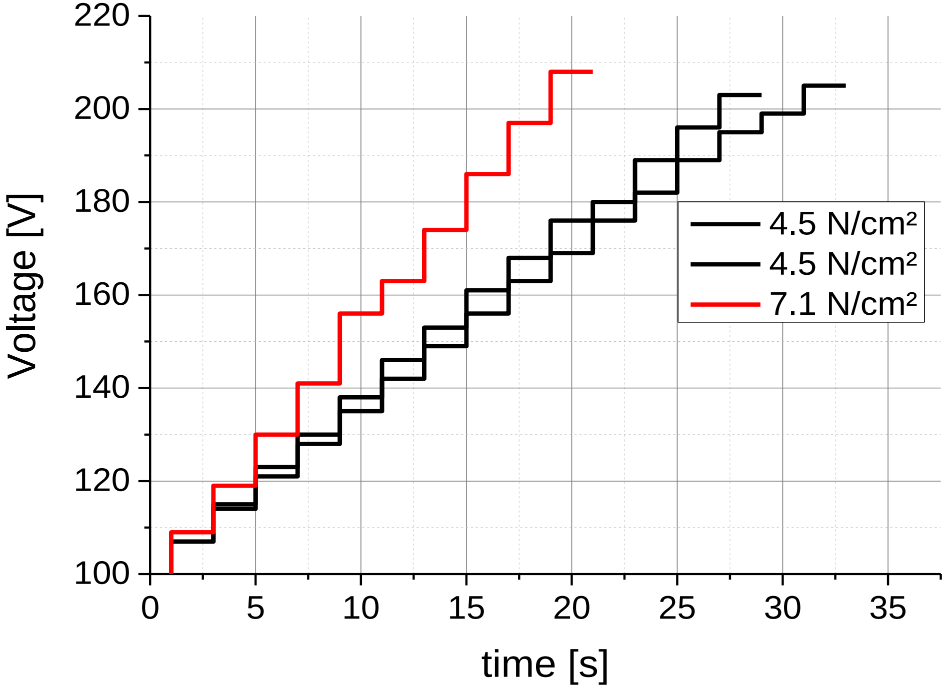
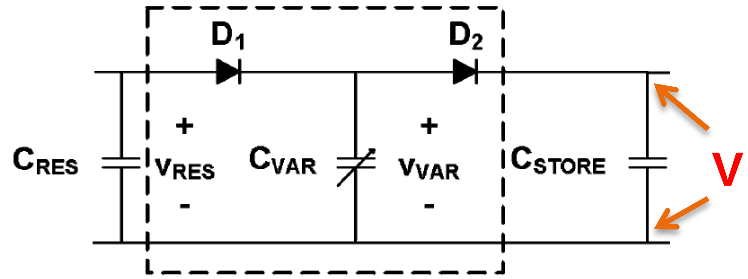
Charging the output capacitor

Voltage at C_{store}





C_{min} = 10 pF/cm^2

C_{max} = 400 pF/cm^2

C_{store} = 3.3 nF

Top Electr.	**Elastomer**
Dielectric	***Mylar* 13**
Bottom El.	**Cu**

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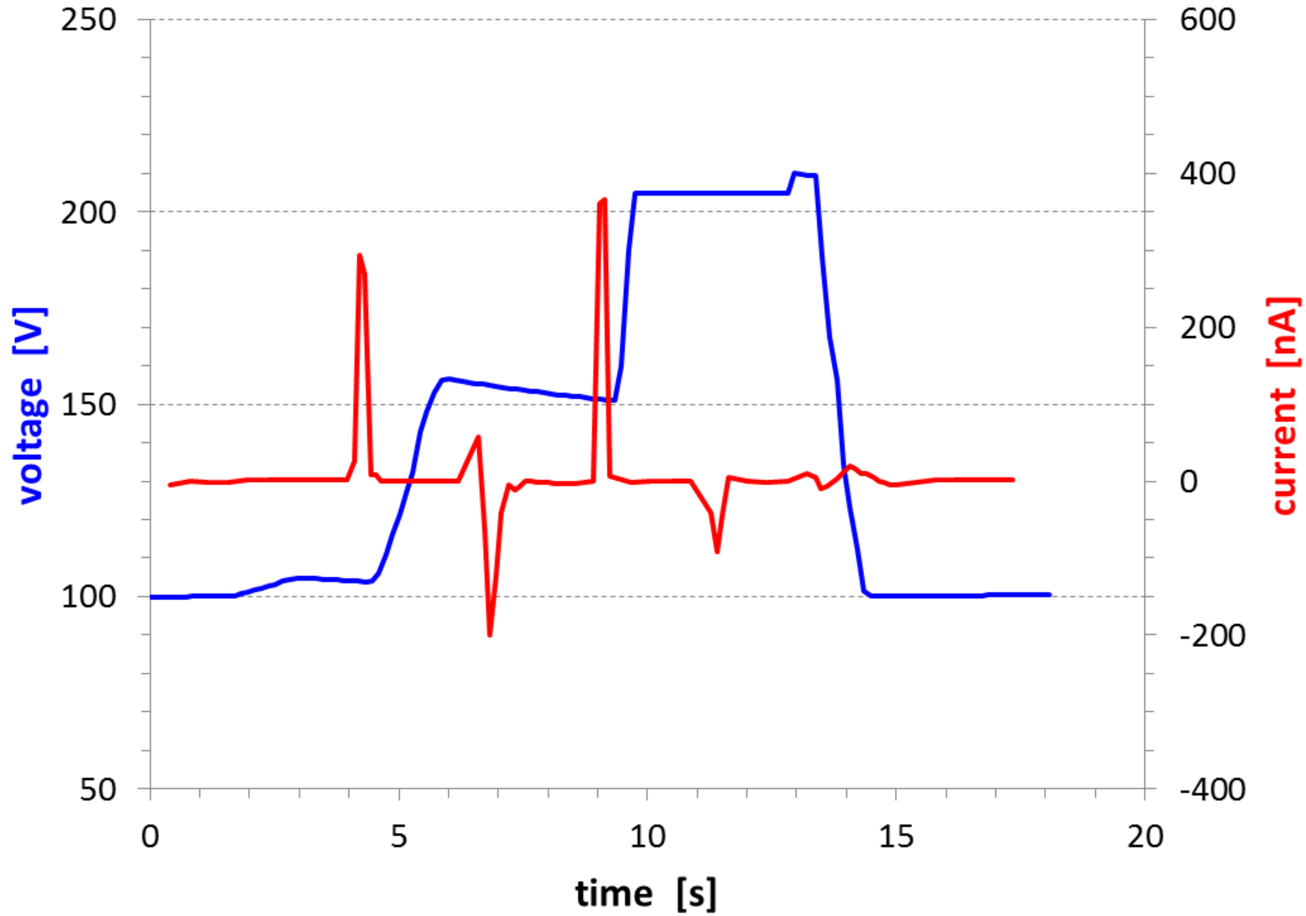
Harvesting



Current through $C_{harvest}$ and voltage at output capacitor
C_{max} = 508 pF, F_{max}= 30 N, A= 1cm^{2}, composite dielectric

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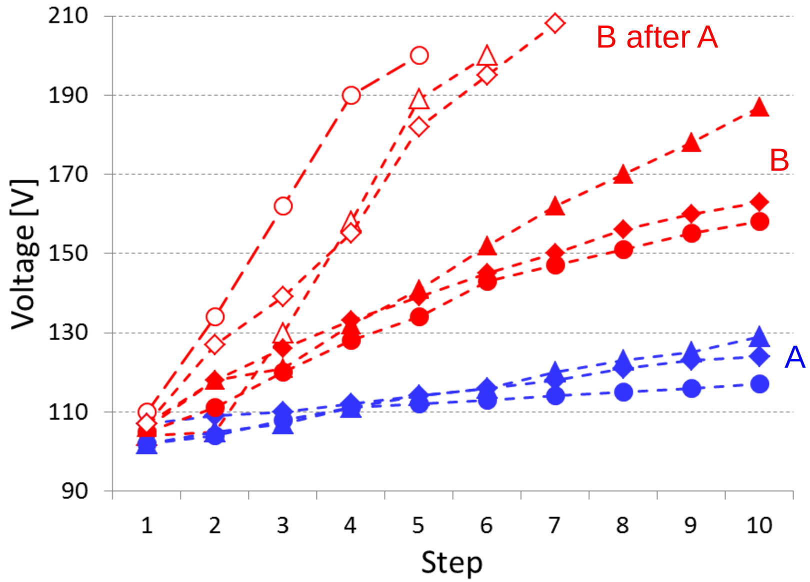
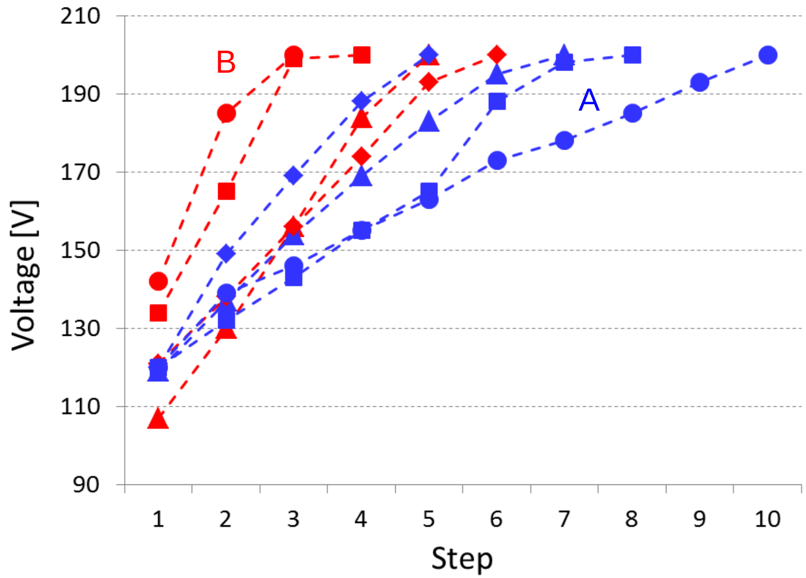
Influence of polarity

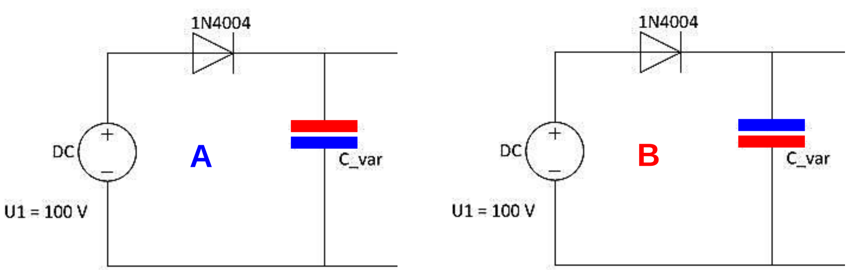
50wt% STO particles, 110T mesh



Mylar



-- Dielectric -- Elastomer



- Polarity B gives larger voltage steps
- Tribo-electricity ?
- More pronounces effect for composite dielectric

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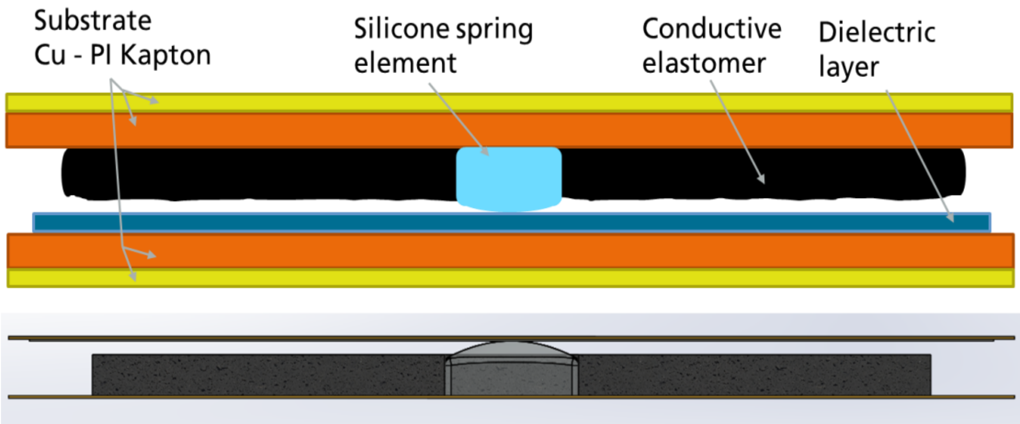
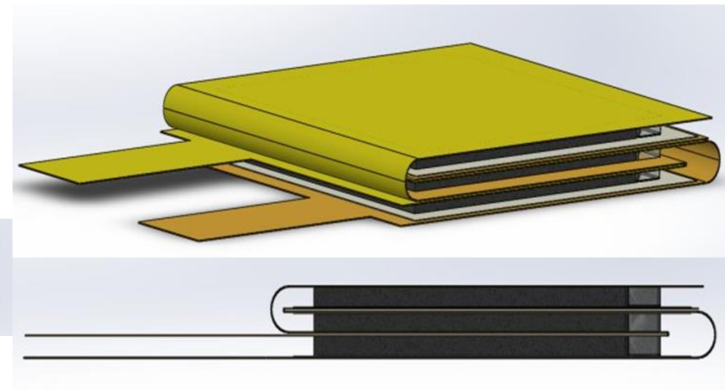
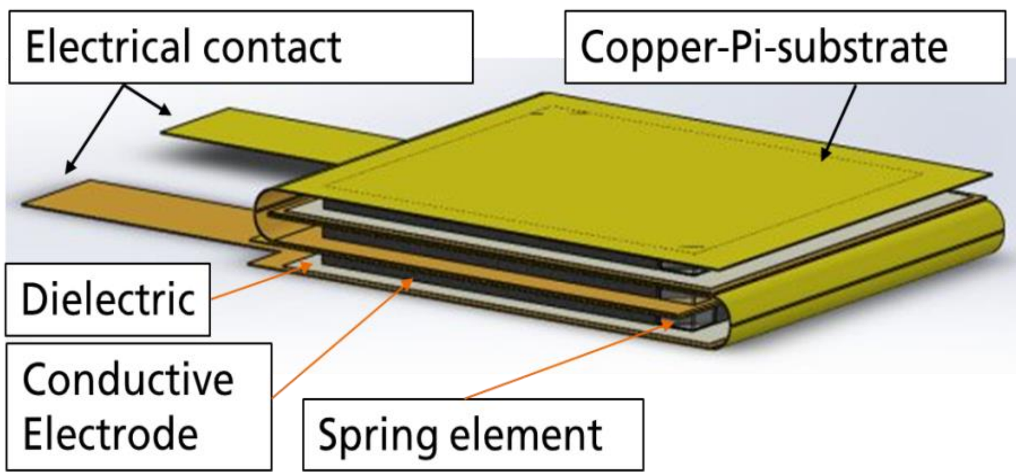
Demonstrator







Folding of stacked dielectric and electrode layers

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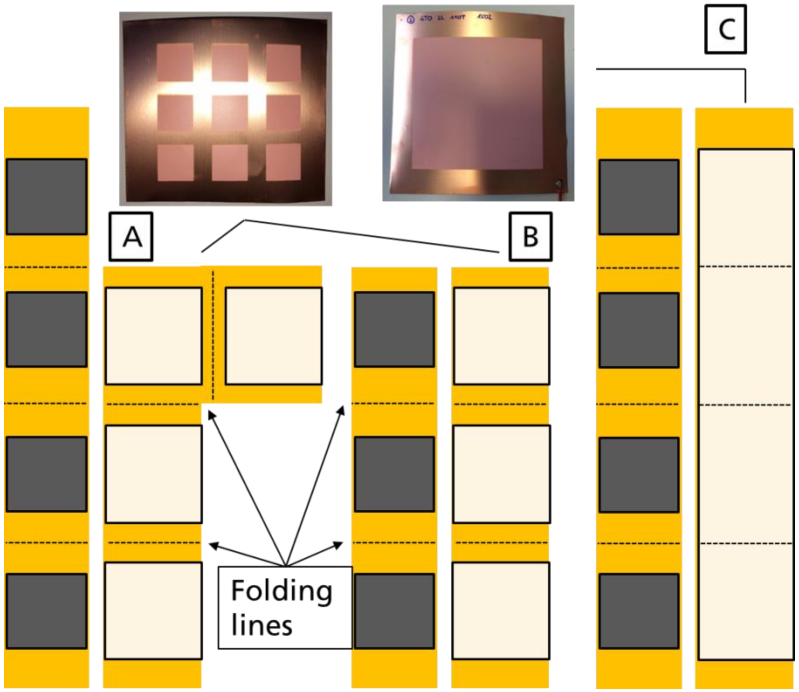
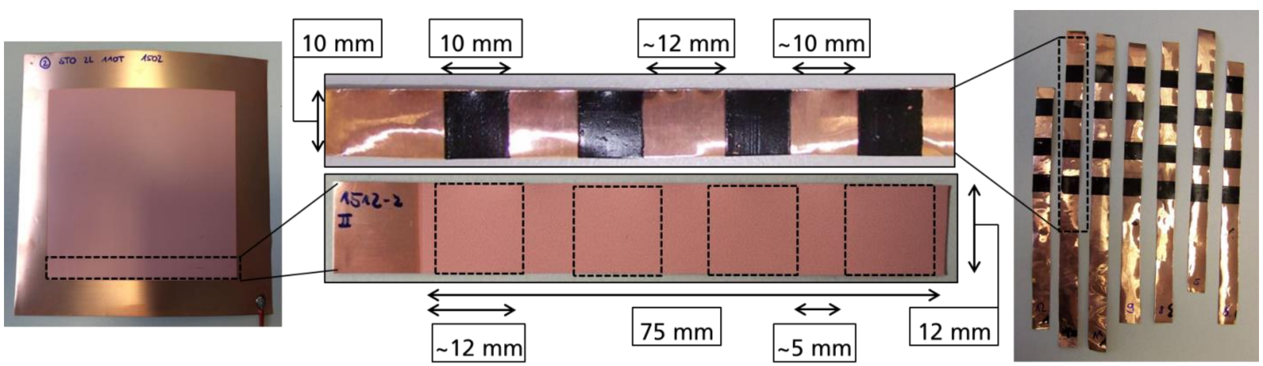
Fabrication of Harvester Device



Stacked capacitor built up from PI/Cu-stripes with dielectric and conductive elastomer

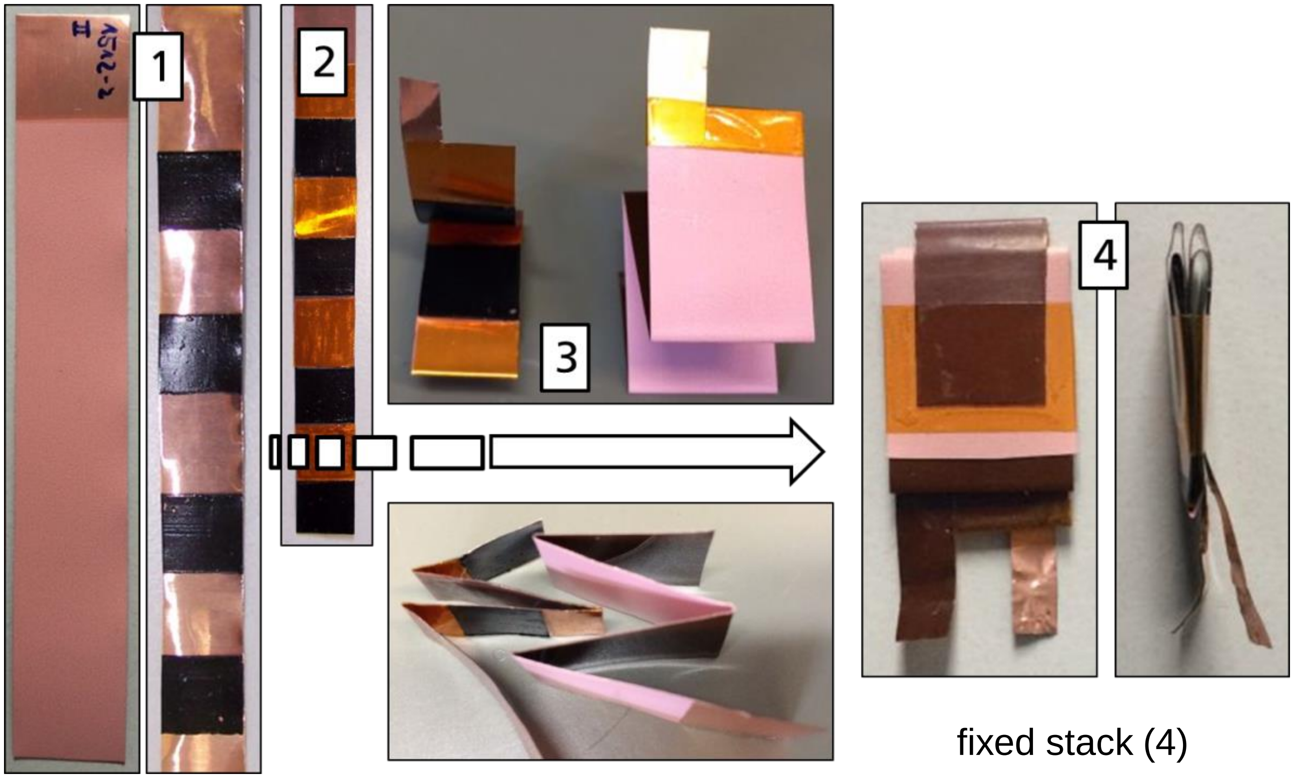
Variants

- 4 separated L-shaped dielectrics (A)
- 3 separated linear dielectrics (B)
- 4 dielectrics without separation



Example of variant C

Assembly of harvester demonstrator



dielectric and elastomer (1) with insulation (2)

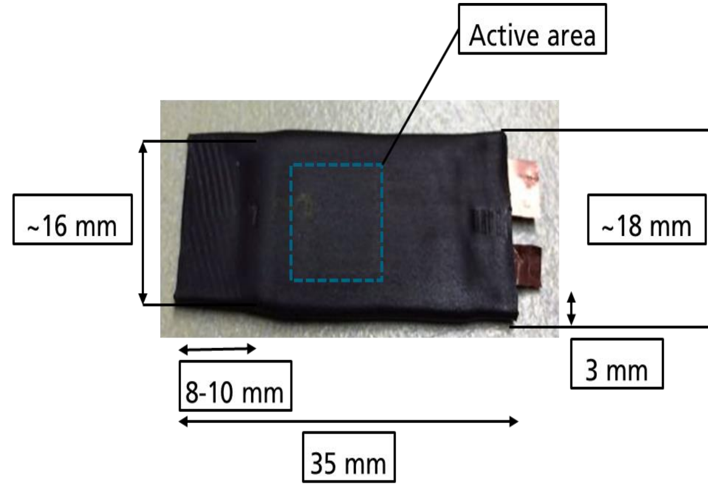
folded stripes (3)

fixed stack (4)

Harvester demonstrator packaging

before & after shrinking

Packaging of fixed folded stack by a polyolefin heat shrink tube



- Maximum outer dimension of the package 35 x 20 x 3 mm³
- 4 layer stack: 2.3 - 2.8 nF
  3 layer stack: 1.5 – 2.0 nF
  (manually pressed)

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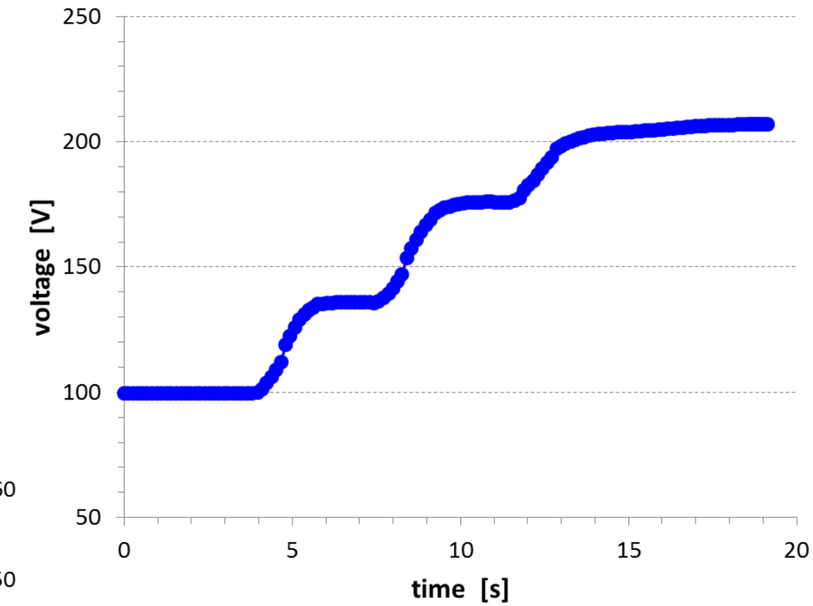
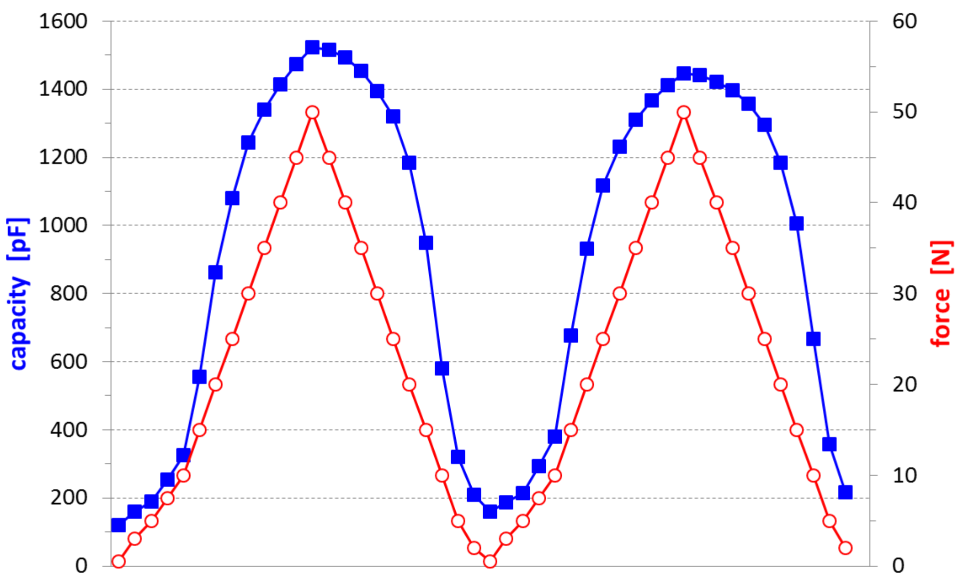
Characterization of Harvester Demonstrator

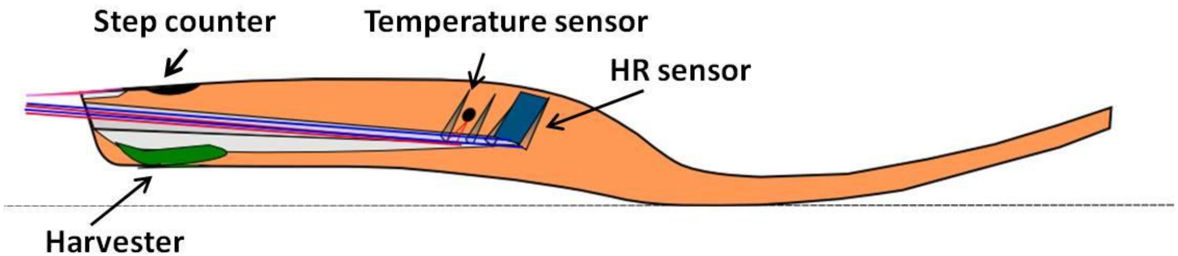


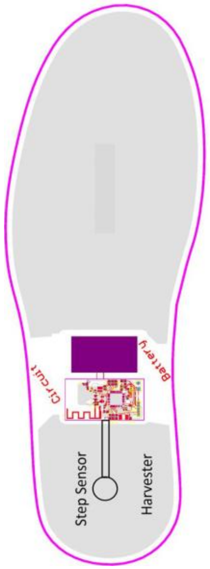


Folded stack with three active surfaces

- capacity 180 pF (rest) to 1550 pF (pressed)
- leakage current 15 nA
- stroke 30 V at U_{source} = 100 V

Applications





SMARTEX + EURECAT

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Conclusions

- Capacitive energy harvesting principle with elastomer electrode proven.
- Numerical simulation was used to identify the influence of material parameters and parasitic circuit elements on the harvester performance as function of actuation frequency.
- Charges between 25 and 70 nAs per cm^2 have been transferred per cycle at 100 V/200 V .
- Novel composite materials show better mechanical robustness and maximum capacity at lower force. Point defects of printed dielectrics lead to leakage current – deposition process must be improved.
- Demonstrators with C_{max} = 1.5 … 3 nF have been fabricated

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SEVENTH FRAMEWORK PROGRAMME

MAT FLEX END

Thank you for your attention

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