measurement SPECIALTIES

Piezo Film for Energy Harvesting

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Embedded Sensing Technologies

MEAS in brief

- NASDAQ: MEAS
- ~$300 million sales
- HQ: Hampton, VA, USA
- Sensors and sensor-based systems
- 3108 employees
- 10 manufacturing sites in 6 countries

- Pressure
- Temperature
- Humidity
- Acceleration
- Force
- Position/Tilt
- Liquid Level
- SpO2
- Fluid Properties
- Piezo Film

Diversified & Integrated

measurement SPECIALTIES
sensing your world

Acquired brands

SCHAEVITZ SENSORS — A Division of Measurement Specialties, Inc.
Piezofilm Sensors
Intersema
BetaTHERM Sensors — TEMPERATURE SOLUTIONS

ELEKON
Encoderdevices
Entran® — Sensors & Electronics
Atexis
YSI Temperature

HUMIREL
ATEX — Assistance Technique Expérimentale
PRESSURE SYSTEMS
VISYX

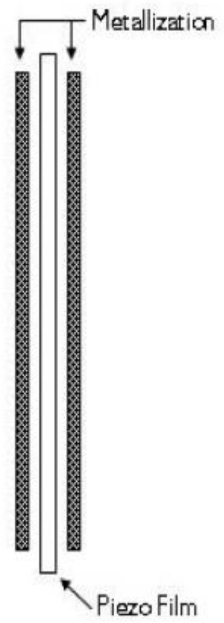
HLPLANAR TECHNIK
Sentelligence
FGP Sensors & Instrumentation
Gentech — SENSING SOLUTIONS

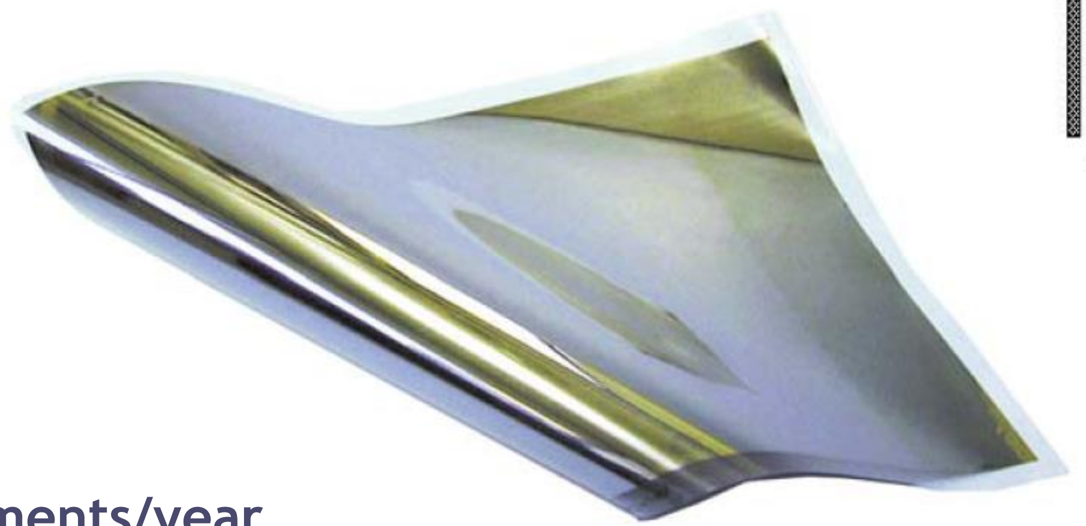
eureka™
COSENSE — The leader in patented ultrasonic liquid sensing
celesco
ICSENSORS

What is Piezo Film?

PVDF

- Polyvinylidene fluoride, PVF_2, PVDF
- High-purity grade, specially processed
- 28 µm, 52 µm or 110 µm thickness
- Continuous roll production, 40 cm width
- Electrodes applied to each surface





>3 million elements/year...

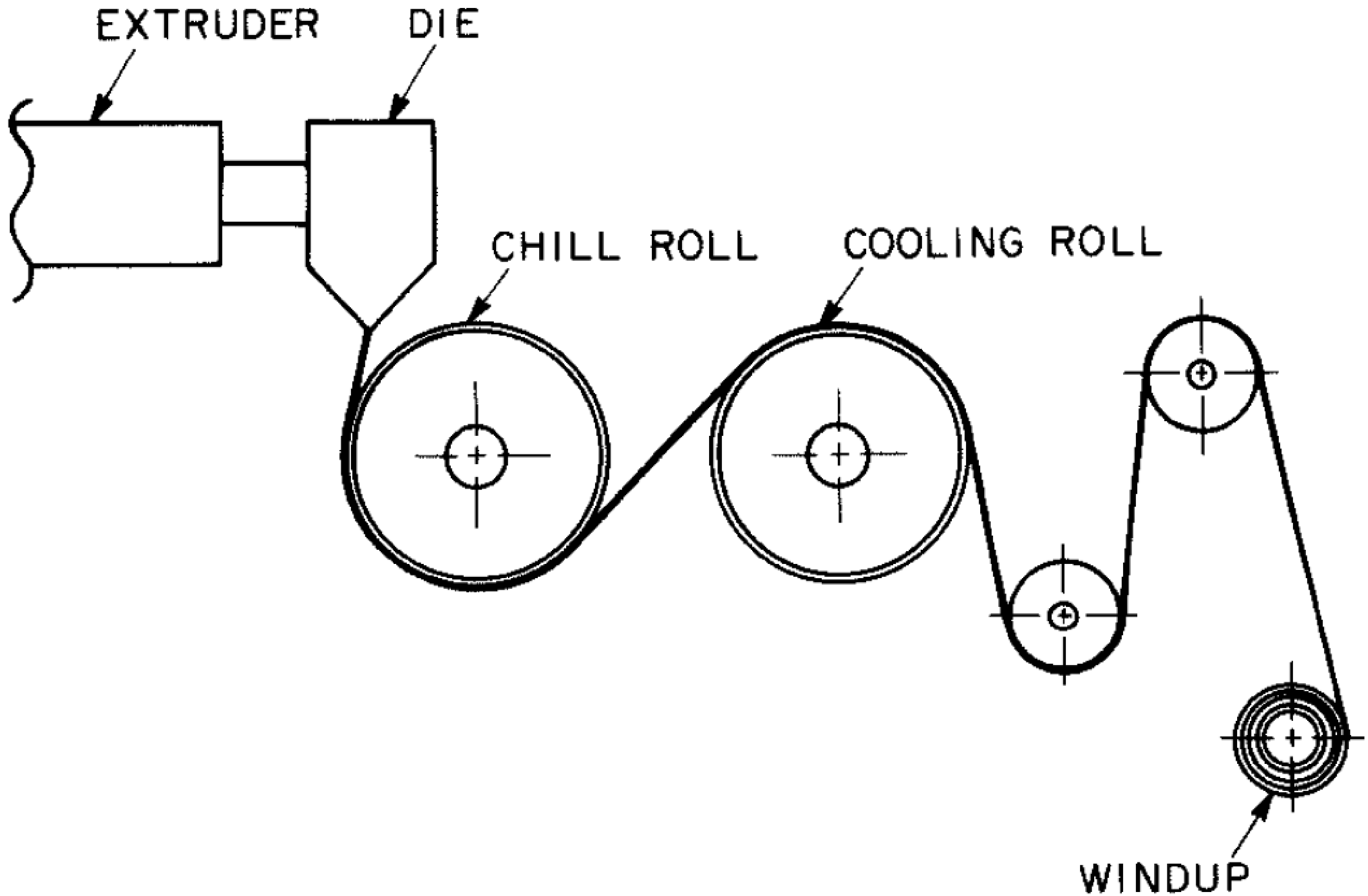
...from a few sq mm to 1 km lengths

Piezo Film History: >40 years

- 1969 Dr Kawai discovers strong piezoelectric effect in PVDF
- 1976 **Pennwalt** Corp starts basic R&D activity in piezo PVDF
- 1982 Pennwalt establishes new business unit at King of Prussia, later moving to Valley Forge, PA
- 1984 Syrinx Innovations established in Edinburgh as European sales and development centre, later renamed as Pennwalt Piezo Film Ltd
- 1990 Elf acquires Pennwalt Corp, and forms Elf Atochem North America. Piezo film group now **Elf Atochem** Sensors Inc
- 1993 **AMP** Inc acquires Piezo Film Sensors from Elf Atochem, renames as AMP Sensors.
- 1998 **Measurement Specialties** acquires Sensors division from AMP.

Manufacturing Piezo Film

Manufacturing Piezo Film



Summary of Piezo Film Features

Features

- High sensitivity to strain
- Flexible format - can wrap around objects
- High bandwidth - can detect into ultrasonic region
- Ultra-low power - needs no external supply to function
- Low cost, easy to customize

Limitations:

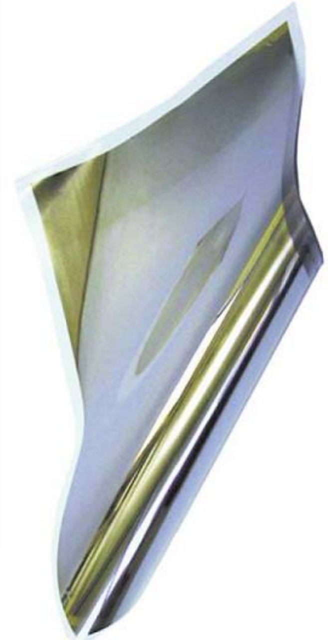
- No static pressure/force/strain detection
- May need external shielding
- Wide tolerance on most electrical parameters
- Limited upper temperature

Piezo Film Applications

Electrode choices

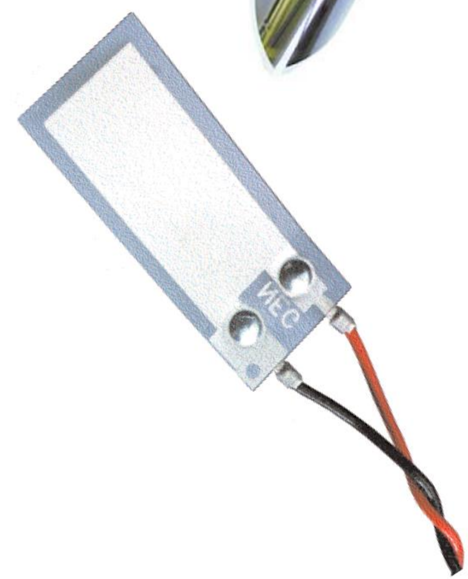
Sputtered Metal

- Normally only for experimentation
- 700 Å Cu with 100 Å Ni as standard
- Can be cut to any size/shape with sharp blade
- Difficult to make electrical contacts
- Metal layer easily damaged



Screen-printed silver ink

- 10 µm thickness (per side) typical
- 0.7 mm minimum line width/spacing
- Allows non-overlapping patterns for penetrative lead-attach
- Requires dedicated tooling
- Flexible and robust



Standard components: DT/FDT

Features

- High sensitivity to strain (dynamic strain gauge)
- <1 Hz to >100 kHz response possible
- Available with or without leads
- DT series - simple rectangle
- FDT series - extended "tail" with connector
- FDT1-028K w/adh - adhesive tape already applied

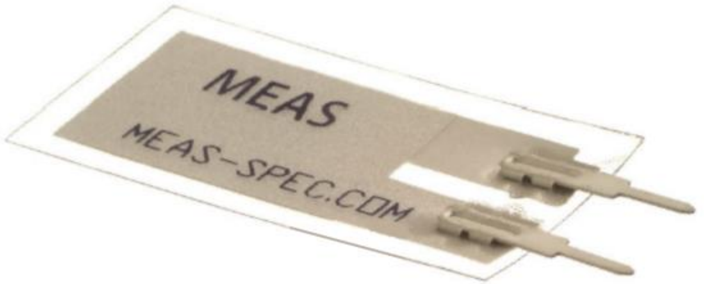
Customer Uses:

- Contact microphone for electronic dart board

Standard components: LDT series

Features

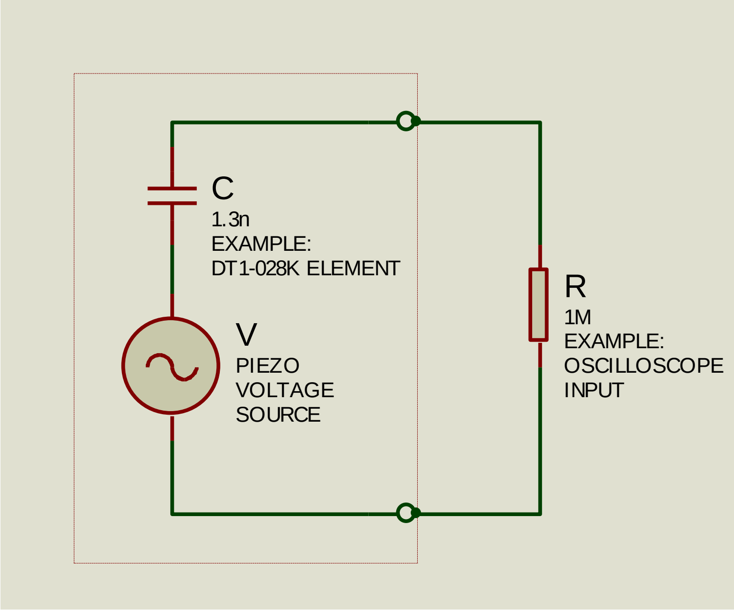
- High sensitivity to bending (>3 V/mm)
- One side laminated, makes asymmetric sandwich
- Used as cantilever beam
- Inertial or direct deflection possible
- FLDT series with extended tail & connector



Customer Uses:

- Vibration-based car alarm
- Neuromuscular transmission sensor

Electrical model



Voltage source in series with a capacitor

- Voltage V is directly proportional to strain
- Capacitance C is a function of piezo film area & thickness
- When connected to a resistive load (R), network forms a high-pass filter with -3dB freq at $1/2\pi RC$

Dynamic Strain

Direct piezoelectric principle:

- Change in length creates charge or voltage
- >10 mV/με (>10 mV/ppm) for dynamic strain
- Insensitive to pre-load or static strain
- Linear response to around 0.5% elongation (5000 με)
- Around 1% strain considered "repeatable"
- >5% elongation before failure
- Can generate up to 30 V/μm field strength
- Frequency response: "near DC" to 100 kHz typical
- Dynamic range estimated >280 dB (14 orders of magnitude)
- Flexible, robust (up to 100 million cycles at 500 με)

Energy Generation Capability

Mechanical-electrical conversion efficiency:

$$\eta = \frac{U_e}{U_m} = \frac{{d_{31}}^2}{\varepsilon} Y$$

For typical PVDF film, 1% < η < 2%

Piezo coefficient d31 typ 25 pC/N

Young's Modulus Y typ 3 GPa

Permittivity ε typ 107E-12 F/m

Energy Generation Capability

$$U_e = \frac{1}{2}\eta(vol)YS^2$$

$$\frac{U_e}{vol} = \frac{1}{2}\eta YS^2$$

$$\frac{U_e}{A} = \frac{1}{2}\eta tYS^2$$

Energy generated is proportional to volume of PVDF, and to the square of the applied strain

Energy Generation Capability

Basic principles:

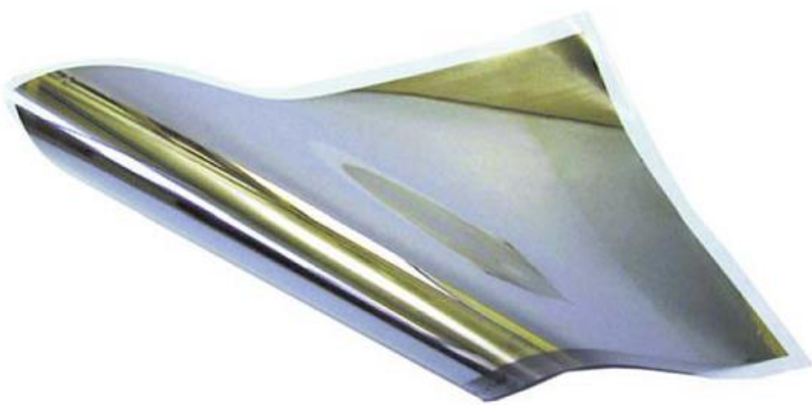
- Conversion efficiency (electrical energy output divided by mechanical energy input) is typically around 1-2%. This is quite low, but we can use large areas of film...
- Potential energy yield is a linear function of volume (surface area x thickness) of film receiving strain
- Generated energy increases with the square of the mechanical strain input. We may need to limit the strain to around 1% (10,000 με) for repetitive events (survives >5%)
- At 1% strain, the open-circuit voltage generated will be high (170 to 630 volts, depending on film thickness), therefore a down-conversion circuit may be required
- In simplest form, piezo film is non-resonant, therefore can operate over very wide frequency range (from <1 Hz upwards) with no single "preferred" frequency

Energy Generation Capability

Examples of generic sheets at 1% strain, energy generation from zero to peak strain (single transition). Including a "return stroke" from peak back to zero will generate <u>double</u> these values:

- 28 µm: 5 µJ/sq cm
- 52 µm: 10 µJ/sq cm
- 110 µm: 20 µJ/sq cm

- Approx 2000 J/m^3
- Approx 2 mJ/cc
- Approx 1 mJ/g

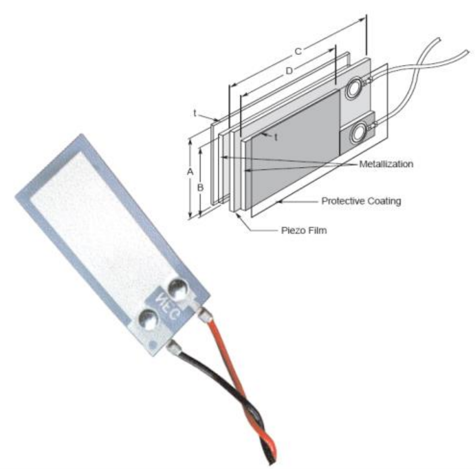


Energy Generation Capability

Examples of standard elements at 1% strain, energy generation from zero to peak strain (single transition):

- DT1-028K: 18 µJ
- DT2-028K: 38 µJ
- DT4-028K: 150 µJ

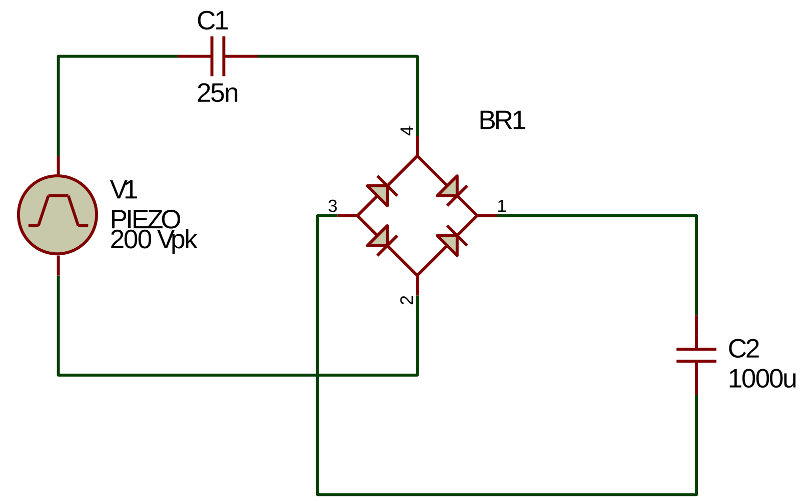
- DT1-052K: 32 µJ
- DT2-052K: 66 µJ
- DT4-052K: 260 µJ



DIMENSIONS in INCHES (mm)

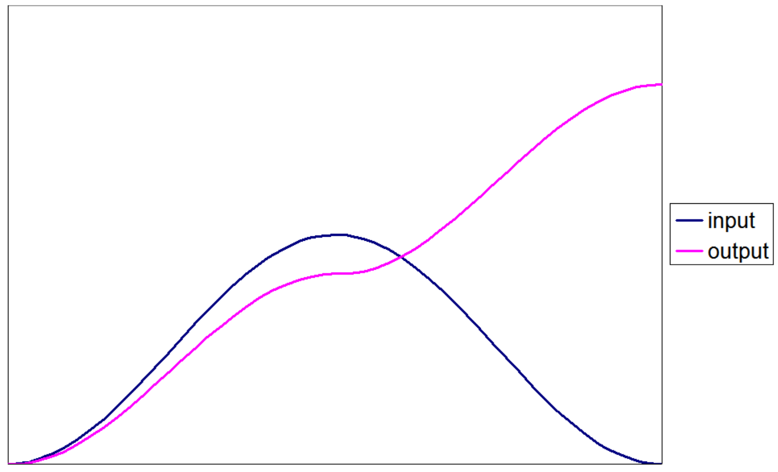
Description	A Film	B Electrode	C Film	D Electrode	t (µm)	Cap (nF)	Part Number
DT1-028K/L w/rivets	.64 (16)	.484 (12)	1.63 (41)	1.19 (30)	40	1.38	1-1002908-0
DT1-052K/L w/rivets	.64 (16)	.484 (12)	1.63 (41)	1.19 (30)	64	.740	2-1002908-0
DT2-028K/L w/rivets	.64 (16)	.484 (12)	2.86 (73)	2.42 (62)	40	2.78	1-1003744-0
DT2-052K/L w/rivets	.64 (16)	.484 (12)	2.86 (73)	2.42 (62)	64	1.44	2-1003744-0
DT4-028K/L w/rivets	.86 (22)	.740 (19)	6.72 (171)	6.13 (156)	40	11.00	1-1002150-0
DT4-052K/L w/rivets	.86 (22)	.740 (19)	6.72 (171)	6.13 (156)	64	5.70	2-1002150-0

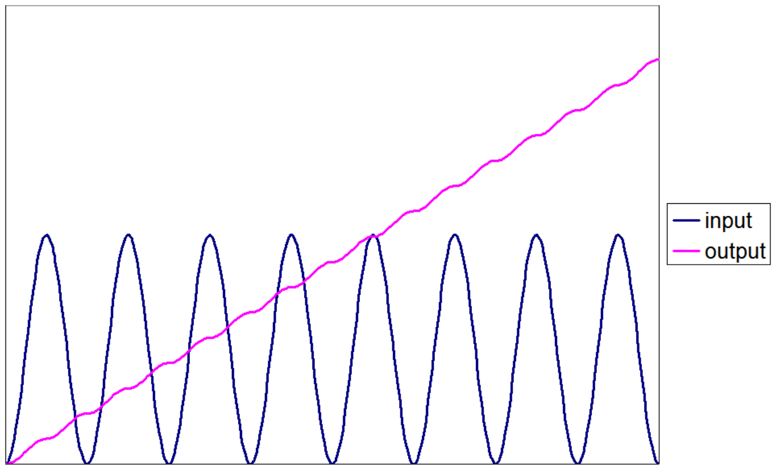
Bridge rectifier action



When $V_{piezo} >> V_{load}$

- Two "hits" per uni-polar cycle

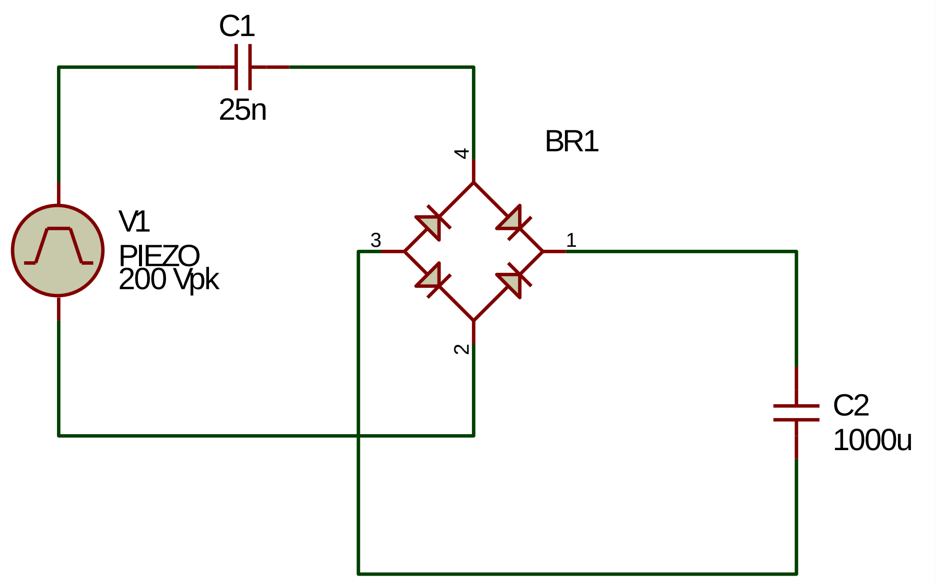




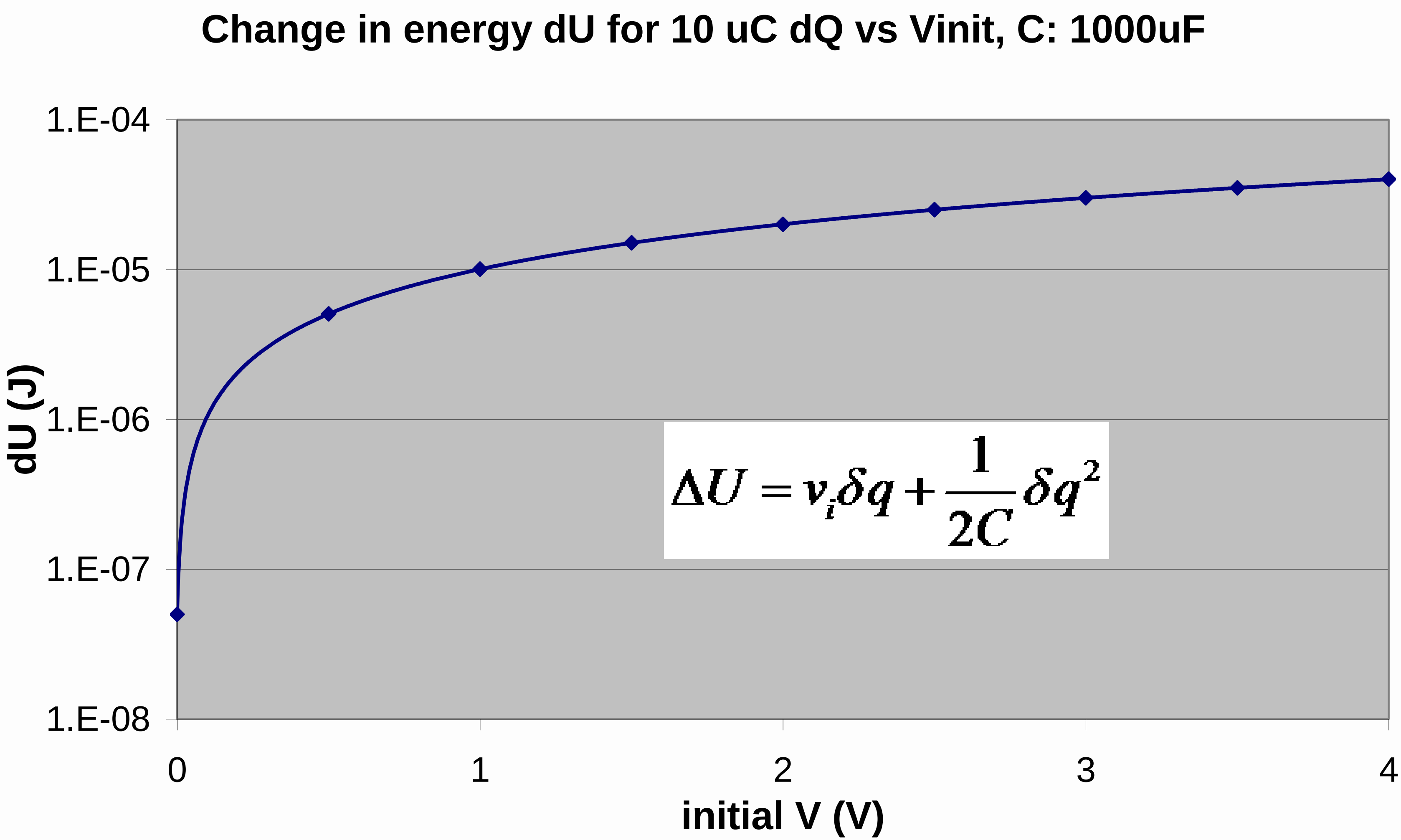
Electrical conversion

Problem: a simple diode-bridge scheme is very inefficient for initial charging cycles from zero volts

- Let V1 (piezo open-circuit voltage) = 200 V pulse, 1.0 mJ event
- C2 charges to 10 mV, 50 nJ is stored
- In this example, the initial charging pulse is converted with just 0.005% efficiency



Electrical conversion



$$\Delta U = v_i \delta q + \frac{1}{2C} \delta q^2$$

Electrical conversion

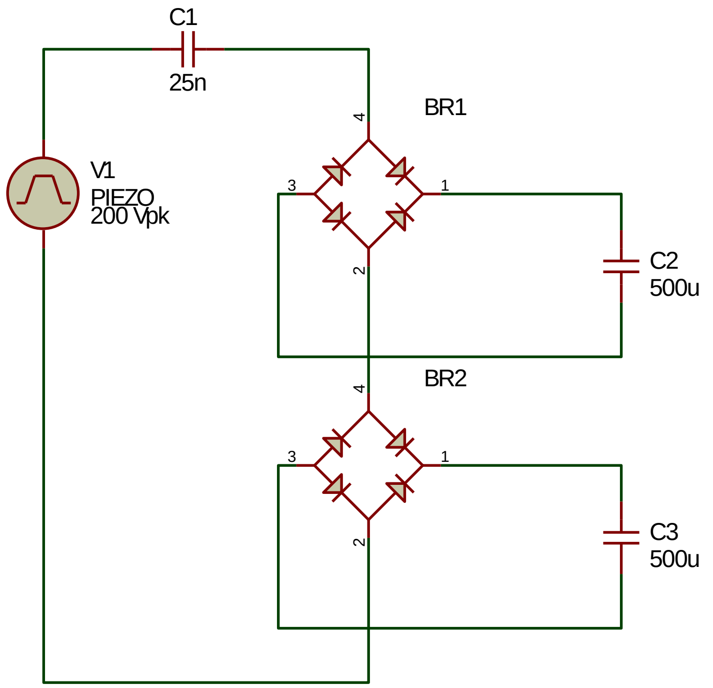
Issue:

- Piezo film generators produce relatively small quantities of charge (typ 1-10 μC per cycle)
- Each ΔQ produces a change in energy in a load, which depends on the initial voltage of the load
- ΔQ produces very small ΔU when initial voltage is zero

Possible solutions:

- Synchronized switched inductor networks (requires timing logic, generally intended for continuous sinusoidal input)
- MEAS proprietary scheme (in development): charge multiplication
- Under certain circumstances, direct charging of secondary cells (or supercapacitors) may be practical using simple diode bridge

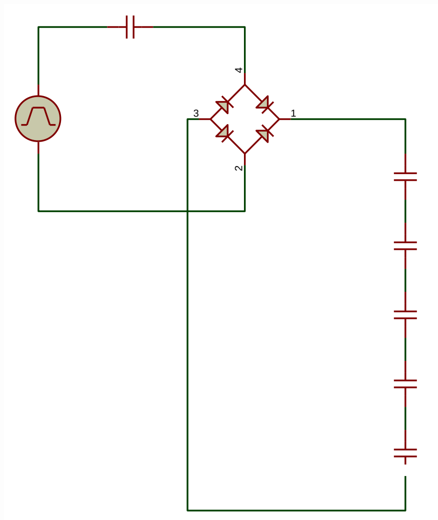
Charge multiplication

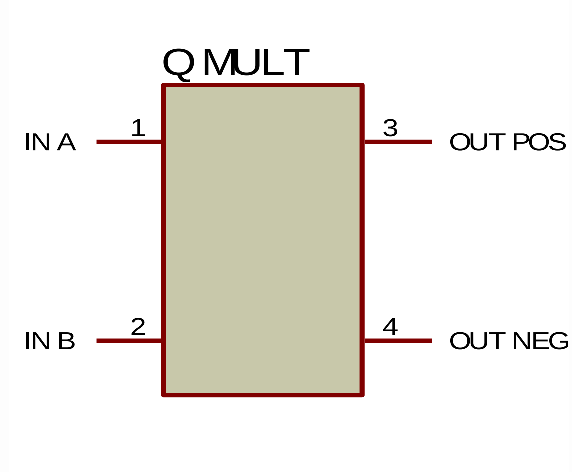


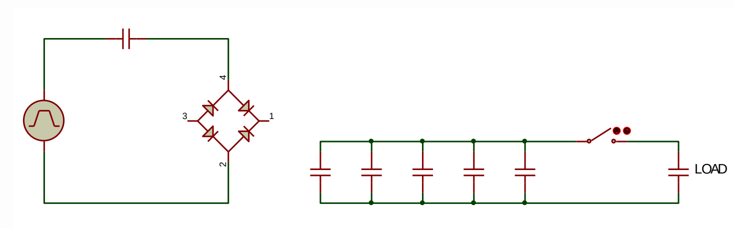
Example: two bridges in series:

- Series combination of load capacitors is 250 µF
- Each cap charges to 20 mV (Q = 10 µC on each)
- Caps can be discharged in parallel (20 µC, 20 mV, 1000 µF)
- Stored energy now 200 nJ, 0.02% efficient (4X ref single 1000µF)

Charge multiplication



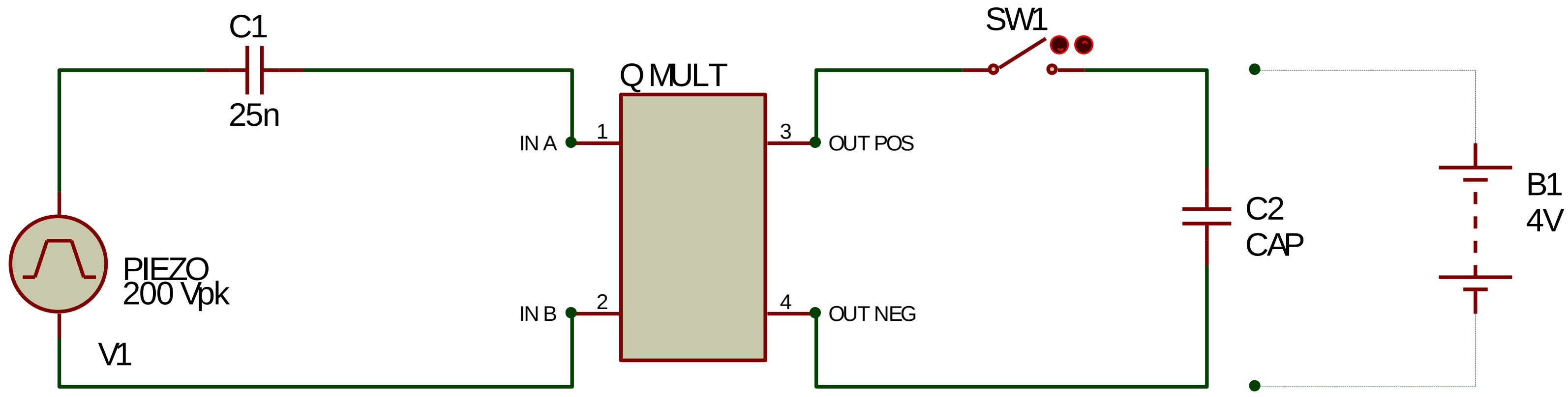




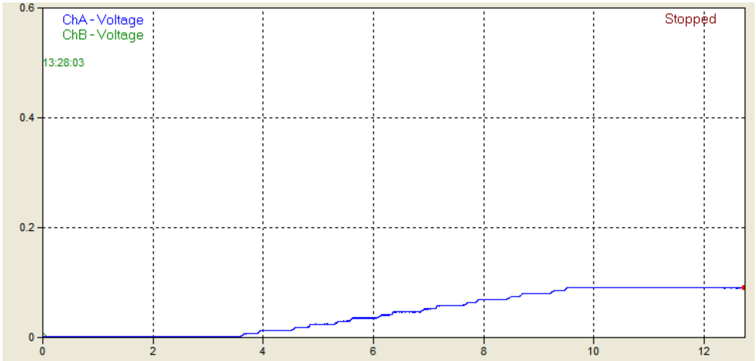
Patent applied for

- Charge capacitors in series, discharge in parallel
- Can match source C with array series C combination for optimum energy transfer
- Voltage division by N
- Charge multiplication by N

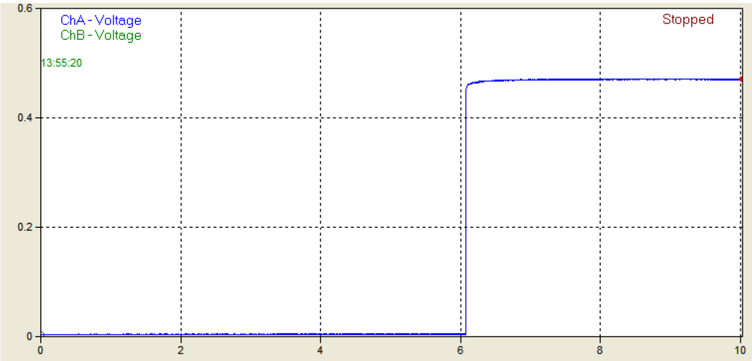
Charge multiplication



Without Q multiplication (90 mV, 4 µJ)



With Q multiplication (470 mV, 109 µJ)



Charge multiplication

	1 x 1000 μF	10 x 100 μF array	20 x 47 μF array
Limiting V for 220 V input	(110 V)	10.4 V	4.98 V
# flex to reach +3 V from 0 V init	291	36 (42)[1]	23 (28)[1]
# flex to reach +4 V from 0 V init	390	51 (58)[1]	40 (52)[1]
# flex to recharge from +3 V to +4 V	99	15 (16)	17 (24)

Notes:

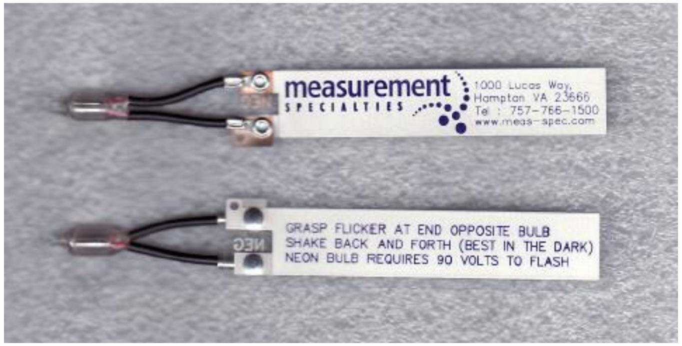
1 The first number denotes the number of flexes required to achieve the stated voltage in individual cells of the array. The figure in brackets is the number of flexes required in order to achieve the stated voltage at start of discharge into a resistive load through the network of schottky diodes.

Excitation of Piezo Film Generator

Possible methods of excitation:

- Direct strain (stretching, film in tension)
- Bending/flexing (using bimorphs or laminated unimorphs)
- Vibration/acceleration (using mass-loaded cantilever)
- Thermal - >8 V/K, 30 μC/sq m/K

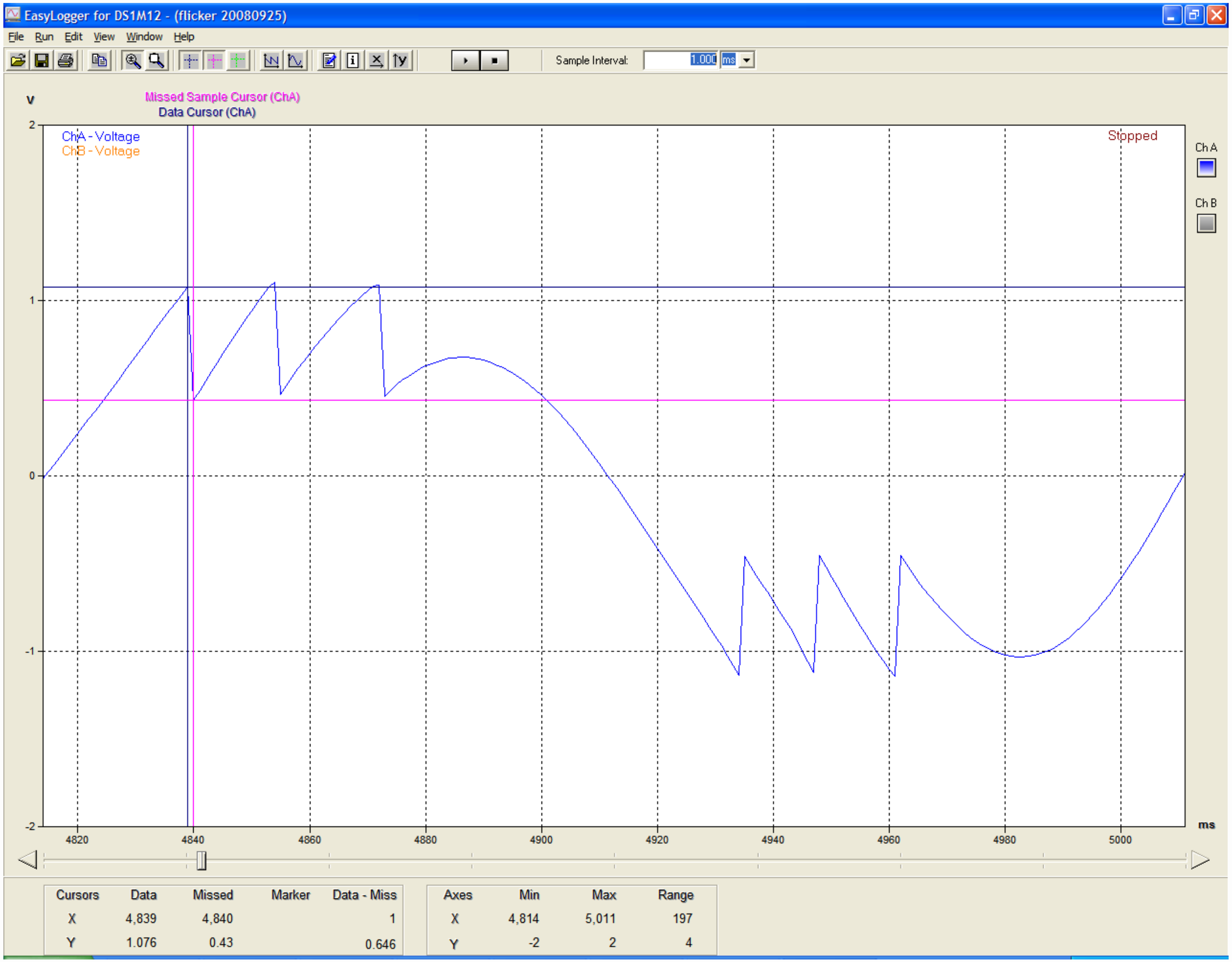
Cantilever beam unimorph



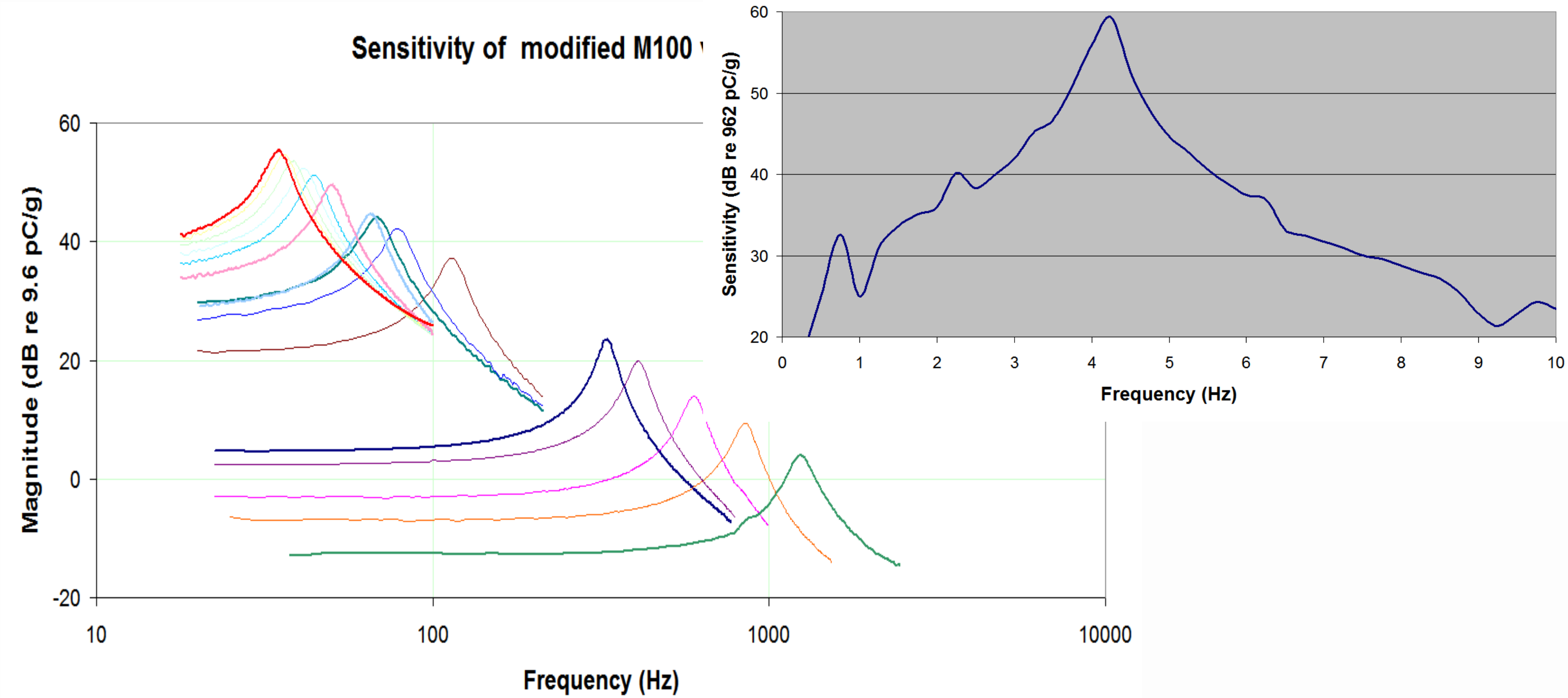
The Flicker – as seen on TV! (BBC News Channel, Click, 02/06/2012)

- Neon bulb acts as inertial mass
- PET laminate causes net strain on PVDF layer for bending
- ~600 V pk-pk open-cct from human shaking at a few Hz
- Neon clamps signal to approx +/- 110 V
- 180 µW typical average power dissipation
- 14 mA discharge current during flash

Cantilever beam



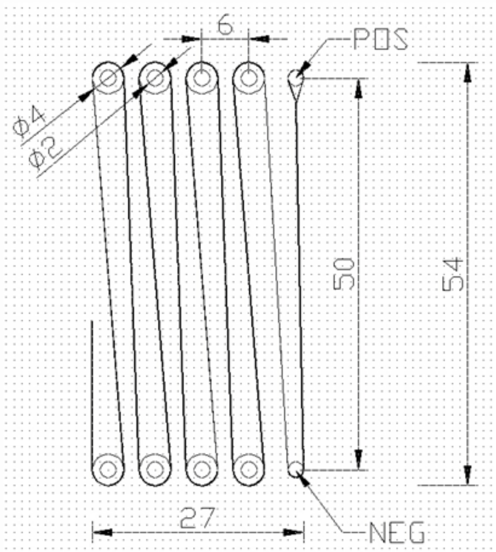
Mass-loaded cantilever beam



By varying tip mass and beam dimensions, we can modify baseline sensitivity and resonance

- >500 V/g has been demonstrated with extreme mass-loading
- Approx 1 μC/g @ 4.3 Hz
- Resonance frequencies from <5 Hz to >1 kHz

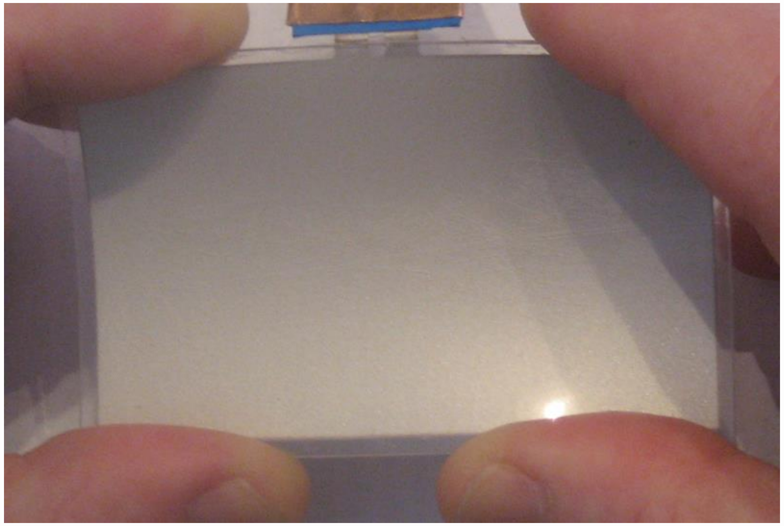
Direct Stretching



Experimental film/roller assembly:

- Approx 0.5 m strip of PVDF, 52 µm, 6.3 mm wide (30 sq cm)
- Finger press to plunger yields 4.6 µC charge, approx 1.4 mJ open-circuit energy (same quantity is available on plunger release)
- Typ 600 V pk open-circuit, 6 nF, >75 µJ/sq cm

Bending/flexing



Credit-card-sized laminate of PET and PVDF:

- Flexing yields up to 6 μC charge
- Typ 200 V peak, 24 nF
- Approx 1 mJ for full flex/release cycle
- 80 sq cm PVDF, 12.5 μJ/sq cm

Experimental results

Credit-card flex generator (using charge multiplication):

- 1 flex: 6-7 mA
- 2 flex: >25 mA
- 3 flex: >50 mA

- All the above are peak currents with exponential decay, approx 2 ms time constant, into LED (with 1 ohm series R)

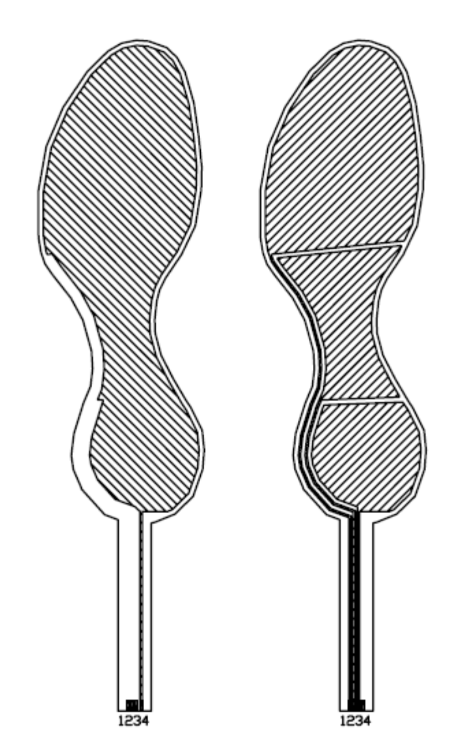
Bluetooth Low Energy requires:

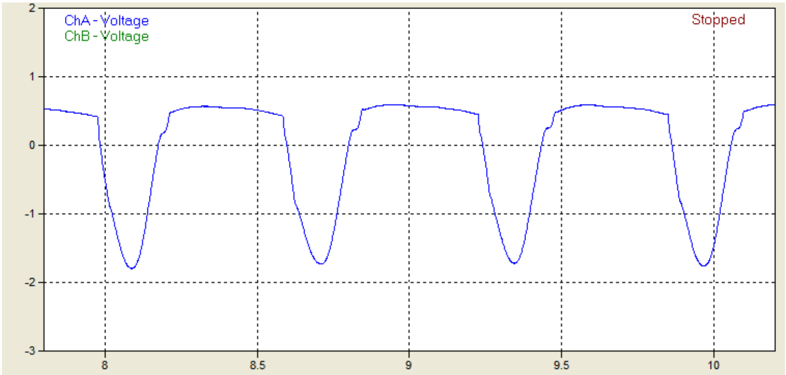
- <20 mA peak current
- <3 ms to send data word

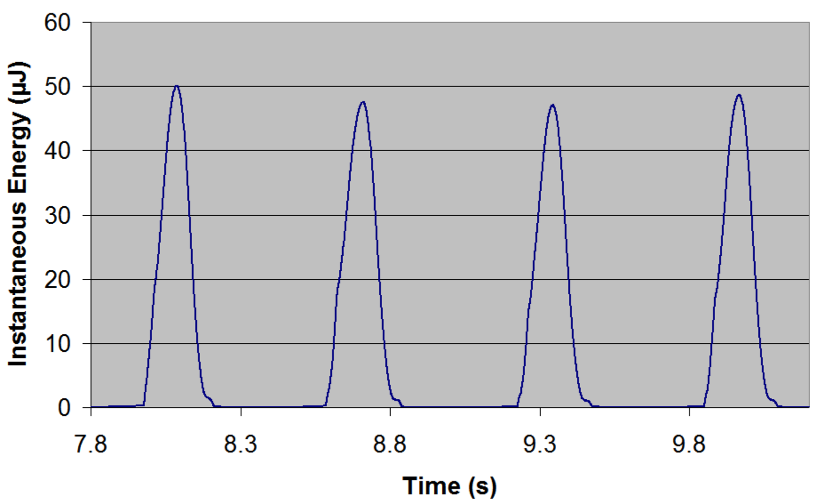
Bending/flexing

In-shoe element:

- 1 flex: 2-4 µC, 100-300 µJ open-circuit







Conclusions

Piezo film offers great design flexibility:

- Lightweight, flexible, durable fluoropolymer
- Inherently non-resonant behaviour - suitable for manual excitation or continuous vibration over wide freq range
- Low cost, Pb-free base material (RoHS compliant)
- Up to 40 μJ/sq cm from single event (strain then release)
- Large area sheets/rolls
- Use when large area, flexible generator is required

MEAS can offer:

- Poled, electroded PVDF in roll or sheet form
- Fabricated elements with lead-attach, lamination
- Complete custom assemblies
- Assistance with electronic interface/conversion