Influence of Structure Configuration on Strained Devices: A Piezoelectric-oriented Survey

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Abstract—**This paper is a short overview of some piezoelectric materials and devices for generating renewable electricity under mechanical motion actions. Piezoelectric materials, usually crystals or ceramics, have the capability to generate a small amount of current, when they are subjected to mechanical pressure, such as pushing, bending, twisting, and turning. A vibrating piezoelectric device differs from a typical electrical power source in that it has capacitive rather than inductive source impedance, and may be driven by mechanical vibrations of varying amplitude. Several techniques have been developed to extract energy from the environment. Generally, "vibration energy" could be converted into electrical energy by three techniques: electrostatic charge, magnetic fields and piezoelectric. Mechanical resonance frequency of piezoelectric bimorph transducers depends on geometric size (length, width, and thickness of each layer), and the piezoelectric coefficients of the piezoelectric material. This paper will discuss about the manufacturing processes and intended applications of several energy harvesting devices.**

Keywords-renewable electricity; energy harvesting; vibration energy; generator; converter; piezoelectric; silicon on insulator (SOI).

I. INTRODUCTION

Renewable energy replaces conventional fuels in four distinct areas: power generation, hot water / space heating, transport fuels, and rural (off-grid) energy services.

The concept of "harvesting" is relatively recent, and presumes the capturing of the normally lost energy surrounding a system and converting it into *electrical energy* that can be used to extend the lifetime of that system's power supply or possibly provide an endless supply of energy to an electronic device, namely power harvesting.

Energy harvesting or *Scavenging energy* is an attractive concept because so many energy sources, such as: light, heat, and mechanical ambient vibrations that exist in our ambient living could be converted into usable *electricity*.

Among *alternative energy sources* can include: water energy, water waves, wind, solar, heat, random vibration, noise, nonlinear mechanical rotations, mechanical shocks, etc.

Several techniques have been proposed and developed to extract energy from the environment. In general, vibration energy could be converted into electrical energy using one of three techniques: electrostatic charge, magnetic fields and piezoelectric.

Multiple such materials, placed near each other could increase the electrical energy. The process of energy conversion in a piezoelectric material is based on the principle of the piezoelectric effect. The piezoelectric elements store electrical energy as an electric field. The *direct piezoelectric effect* describes the material's ability to transform mechanical strain into electrical charge. Many conventional systems consist of a single piezoceramic in bending mode (unimorph) or two bonded piezoelectric in bending mode (bimorph). *Cantilevered piezoelectric energy harvesters* have been investigated in the literature for energy harvesting. *Piezoelectric generators* [1] appropriate to convert the smallest mechanical deformations directly into electrical energy. This solid state effect is free of degradation in a wide operation range.

Some structures can be tuned to have two natural frequencies relatively close to each other, resulting in the possibility of a *broader band energy harvesting system*. The energy produced by these materials is in many cases far too small to directly power an electrical device.

Advances in *low-power electronics* and in *energy harvesting technologies* have enabled the conception of truly *self-powered devices* [2].

By driving one element to expand while contracting the other one, the actuator is forced to bend, creating an out-of plane motion and vibrations [3]. *Cantilevered piezoelectric energy harvesters* have been investigated in the literature for energy harvesting [4]. *MEMS (Micro-electro-mechanical System) array* with multi-cantilevers was designed with single cantilever behaving closer resonance frequency one after another [5].

The paper was structured in five sections: I. Introduction; II. Piezoelectric conversion; III. Piezoelectric generators; IV. Piezoelectric devices, and V. Conclusions and future works.

II. PIEZOELECTRIC CONVERSION

Piezoelectric materials, usually crystals or ceramics, have the capability to generate a small amount of current, when they are subjected to mechanical pressure, such as pushing, bending, twisting, and turning.

Piezoelectric materials exhibit the property that if they are mechanically strained, they generate an electric field proportional to the strain [6]. Conversely, when an electric field is applied the material undergoes strain. These anisotropic relationships are described by the piezoelectric

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strain constant, d, which gives the relationship between applied stresses while the electro-mechanical coupling coefficient, k, describes the efficiency (η) with which energy is converted between mechanical and electrical forms, and Q the quality factor. This latter coefficient is important in determining the efficiency of a resonant generator since the overall efficiency of a piezo element clamped to a substrate and cyclically compressed at its resonant frequency is [6]:

$$\eta = \frac{\frac{k^2}{2\left(1-k^2\right)}}{\frac{1}{Q}+\frac{k^2}{2\left(1-k^2\right)}} \qquad (1)$$

A. Electrostatic convertions

Electrostatic conversion is based on the formation of a parallel plate capacitor onto which a charge is introduced from an external power source. Once the external source is disconnected then varying the capacitor configuration (plate overlap area or plate separation) causes the voltage and/or charge on the capacitor to vary. The varying voltage or charge may be extracted to provide electrical energy to a load.

For a parallel plate capacitor with plate area A and plate separation d, the capacitance is approximately

$$C = \varepsilon\frac{A}{d} = \frac{Q}{V} \qquad (2)$$

where ε is the dielectric constant of the insulating material between the plates, Q and V are the charge and the voltage on the capacitor, respectively. The energy stored on the capacitor is

$$E = \frac{1}{2}QV \qquad (3)$$

If the charge is held constant, then combining (9) and (10), the energy becomes

$$E = \frac{Q^2 d}{2\varepsilon A} \qquad (4)$$

while if the voltage is constrained, the energy becomes

$$E = \frac{\varepsilon A V^2}{2d} \qquad (5)$$

Attempts to change the stored energy by moving the capacitor plates cause a reaction force. This reaction force depends on whether the gap or the overlap area of the capacitor is varied and on whether the voltage or the charge is constrained.

III. PIEZOELECTRIC GENERATORS

Piezoelectric generators are appropriate to convert the smallest mechanical deformations directly into *electrical energy*. This solid state effect is free of degradation in a wide operation range.

The process of energy conversion in a piezoelectric material is based on the principle of the *direct piezoelectric effect.* When a piezoelectric element is mechanically stressed it generates *electrical charges*.

Piezo energy harvesting has been investigated only since the late '90s and it remains an *emerging technology*.

The piezoelectric elements store electrical energy as an electric field. The *direct piezoelectric effect* describes the material's ability to transform mechanical strain into electrical charge. Figure 1 presents the piezoelectric generators principle.

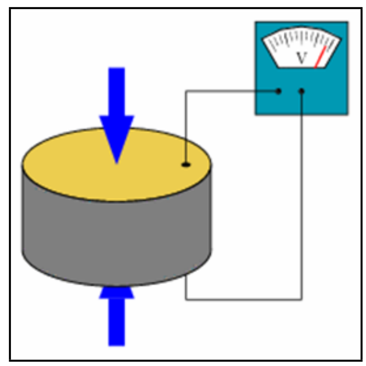

Figure 1. Piezoelectric generators principle.

A. Piezoelectric materials

Several types of piezoelectric materials used in for energy harvesting devices are: PZT, piezoceramic / polymer composites, piezoelectric polymers, etc.

The most common types of piezoelectric materials used in power harvesting applications are:

a) *Lead zirconate titanate*, a piezoelectric ceramic, or piezoceramic, known as PZT;

b) *Poly(vinylidene fluoride) (PVDF).* PVDF is a piezoelectric polymer that exhibits considerable flexibility when compared to PZT.

Other *piezoelectric materials* are *Fiber-based piezoelectric (piezofiber) material* consisting of PZT fibers of various diameters (15, 45, 120, and 250 µm) that were aligned, laminated, and molded in an epoxy (Macro Fiber Composite – MFC). The Macro Fiber Composite (MFC) is the leading low-profile actuator and sensor offering high performance, durability and flexibility in a cost − competitive device.

In the Table 1 we compared the electrical, piezoelectric and dielectric characteristics of piezoelectric materials from several companies (PZT - Brush Clevite Corporation, Morgan Advanced Materials; PXE – Philips; Piezolan - VEB

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KKW Hermsdorf), where noted: Coupling coefficients (K_{eff}, k), piezoelectric coefficients (g_{31}, d_{31}), strain coefficients (s), mechanical quality factor (Q_m), Curie temperature (T_c).

A vibrating piezoelectric device differs from a typical electrical power source in that it has capacitive rather than inductive source impedance, and may be driven by mechanical vibrations of varying amplitude.

A more attractive configuration is to form the piezoceramic into a cantilever arrangement, as shown in Figure 2, where layers of piezoceramics are bonded to a substrate, typically made from a suitable metal. This structure allows a lower resonant frequency to be achieved while producing large strains in the piezoceramic. Where two layers of piezo material are used, the structure is referred to as a bimorph. In this case, the piezo layers may either be connected in series or parallel. If only a single piezo layer is used, the structure is referred to as a *unimorph* [6].

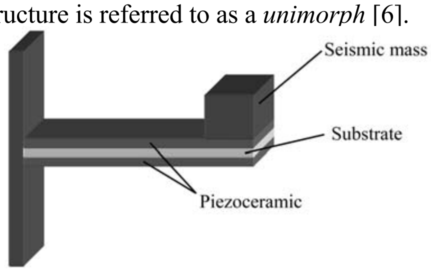

Figure 2. Piezoceramic cantilever resonator [6].

Piezoelectric unimorph cantilever consists of a piezoelectric layer which is sandwiched between two conducting electrodes and positioned on the top of shim layer. Alomari et al. [7] proposed a mathematical analysis of dynamic magnifier model for the piezoelectric unimorph beam.

Bimorph actuators consist of two independent flat piezoelectric elements, stacked on top of the other. By driving one element to expand while contracting the other one, the actuator is forced to bend, creating an out-of plane motion and vibrations. Series and parallel operation modes for bimorph actuators are function of electrical connection and the polarization (P) orientation of piezoelectric layers (Figure 3).

Series Operation refers to the case where supply voltage is applied across all piezo layers at once. The voltage on any individual layer is the supply voltage divided by the total number of layers. A 2-layer device wired for series operation uses only two wires, one attached to each outside electrode (Figure 3a). *Parallel Operation* refers to the case when a metallic blade is fixed between both piezoelectric layers and connected like in Figure 3b).

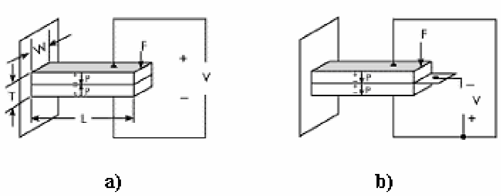

Figure 3. Series (a) and parallel (b) operation modes for bimorph actuators [2].

Figure 4 compares three piezoelectric sensor configurations: (a) A series triple layer type piezoelectric sensor. (b) A parallel triple layer type piezoelectric sensor. (c) A unimorph piezoelectric sensor [8].

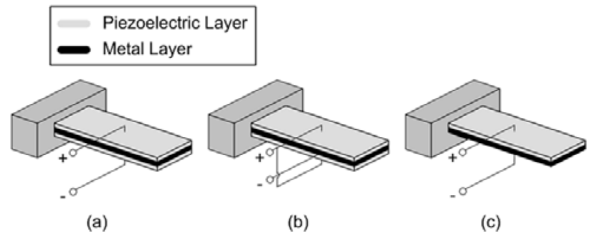

Figure 4. (a) A series triple layer type piezoelectric sensor. (b) A parallel triple layer type piezoelectric sensor. (c) A unimorph piezoelectric sensor [8].

B. *Spark generation*

An important application of PZT elements is the conversion of mechanical energy into electrical energy, with maximum efficiency and amount of energy [9].

A PZT cylinder hit with a mechanical shock can generate a high voltage electrical spark that processed by electronic circuits is stored in special batteries (Figure 5).

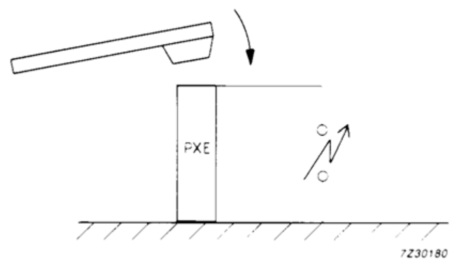

Figure 5. The principle of high voltage and spark generation [8].

In the experimental works we performed a set-up with a mechanical pendulum, which applied mechanical shocks on a fixed PZT tore of 6 mm thickness. According to the direct piezoelectric effect, PZT element converted the mechanical energy into an electrical one. The electrical signal picked up on the electrodes of PZT element has been detected and measured with a Tektronix oscilloscope with memory. The voltage peak can reach hundreds of volts (Figure 6).

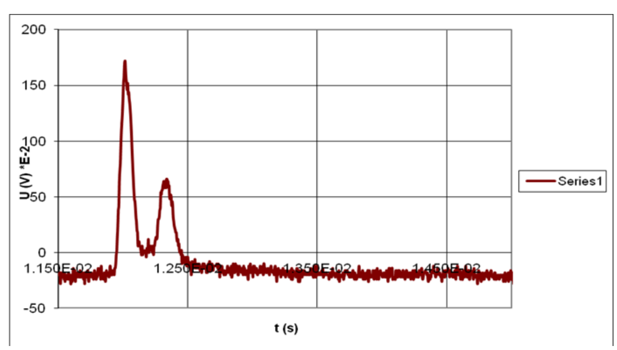

Figure 6. Electrical signal generated by a PZT tore of 6 mm thickness hit by mechanical shocks.

A piezoelectric ceramic can be depolarized by a strong electric field with polarity opposite to the original poling voltage. The typical operating limit is between 500V/mm and 1 000V/mm for continuous application.

High mechanical stress can depolarize a piezoelectric ceramic. The limit on the applied stress is dependent on the type of ceramic material, and duration of the applied stress.

A part of the energy generated by the PZT transducer can be stored in a capacitor and can be used to power a circuit.

IV. PIEZOELECTRIC DEVICES

Some examples of piezoelectric devices and their applications are presented below.

A. *PVDF bimorph transducer*

PVDF is a piezoelectric polymer that exhibits considerable flexibility when compared to PZT.

PVDF pre-polarized piezoelectric bimorph structure was realized on two PVDF thin films, with 25 µm thickness and 31 pC/N d31 piezoelectric coefficient. The PVDF bimorph transducer started vibration at low alternative voltage, such as 10 V, developing more than 1 mm aperture displacement at its end. The piezoelectric bimorph actuators [3] can be well suited to be implemented in devices for laser system micrometry displacement. PVDF bimorph transducers have advantages, such as: small size and weight, greater flexibility, however they do not have sufficient mechanical rigidity so they cannot bear heavy seismic masses.

B. *MEMS piezoelectric energy harvesting device*

Micromachined piezoelectric cantilever having low resonant frequency range between 60 Hz and 200 Hz, was developed by Shen at al. [10] appropriate for frequency range, common for environmental vibration sources.

As an application, we mention the MEMS PZT cantilever with an integrated Si proof mass, fabricated on a silicon on insulator (SOI) wafer, and a Pt/PZT/Pt/Ti/SiO_2/Si/SiO_2 multilayer device is generated for low frequency vibration energy harvesting [9]. In manufacturing MEMS, thin film deposition and etching with patterns are used, as shown in Figure 7.

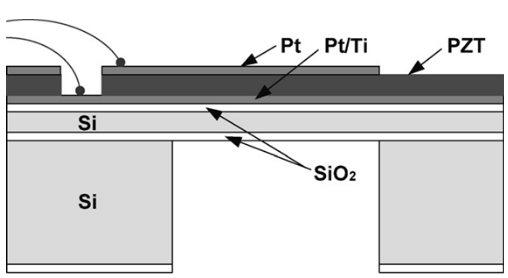

Figure 7. The schematic of the side view of a piezoelectric energy harvesting cantilever based on a silicon on insulator (SOI) wafer [9].

The measured impedance and phase angle of the PZT cantilever versus the exciting frequency are shown in Figure 8. The resonant frequency peak in the phase angle is about 184.16 Hz [10].

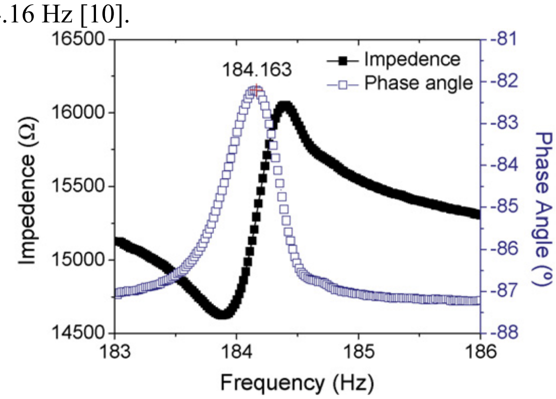

Figure 8. Measured resonant frequency of the PZT cantilever device [10].

A *MEMS (Micro-electro-mechanical System) array* with multi-cantilevers was designed with single cantilever behaving closer resonance frequency one after another [11]. Each cantilever is one spring–mass–damper system with one degree of freedom. When cantilevers with closer resonance frequency are connected together as an array, the available bandwidth covers the range of minimum to maximum resonance value of the cantilevers in the array. MEMS fabrication technology ensures the advantage of mass production of cantilevers with various structure parameters in an array.

In the application described by Shen et al. [10], a *made-up power generator array* was realized by the MEMS process using cantilevers with different sizes (Figure 9): 12 mm silicon layer thickness, 3.2 mm PZT layer thickness, the length and width in range of 2000–3500 mm and 750–1000 mm respectively, having the resonant frequency in the range of 200–400 Hz. The *micro-power generator array* device was made by many PZT film transducers, in order to capture low-level vibrations from the environment.

Serial connection among cantilevers of the array was investigated and the prototype performed well, such as: 3.98 mW effective electrical power and 3.93 V_{DC} output voltage on the load resistance. This device is promising to support networks of ultra-low-power, peer-to-peer, wireless nodes.

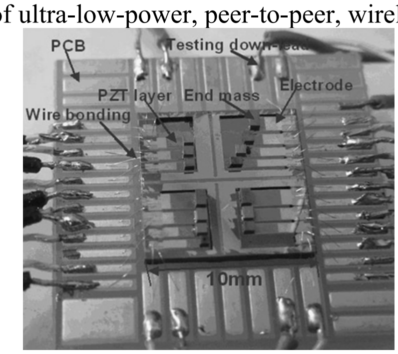

Figure 9. Picture of power generator array prototype [11].

C. Sensor network

Energy-harvesting can enable a new mode of operation, namely, the energy-neutral mode in which the system uses only as much energy as is available from the environment [12].

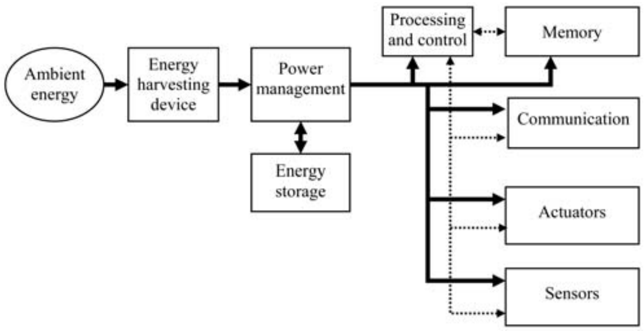

Figure 10. A generic sensor network node with energy harvesting device [13].

The power consumed by a network node can be split between the various functions. A structure of a general sensor network node is described by Benini et. al. [13], with the key elements shown in Figure 10. The power requirement of each element depends on the particular application.

D. Energy harvesting piezoelectric circuitry

Piezoelectric generators are appropriate to convert the smallest mechanical deformations directly into electrical energy. This solid state effect is free of degradation in a wide operation range. A vibrating piezoelectric device differs from a typical electrical power source in that it has capacitive rather than inductive source impedance, and may be driven by mechanical vibrations of varying amplitude. Figure 11 describes a PZT element generator with diodes and parallel capacitor.

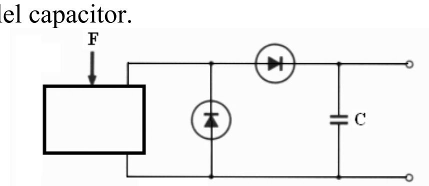

Figure 11. PZT element generator with diodes and parallel capacitor.

The principle of charge generation by a PZT disc to an electronic circuit performance are the shape of the PZT transducer, the manner in which the transducer is mounted and, of course, the nature of the electrical load (Figure 12).

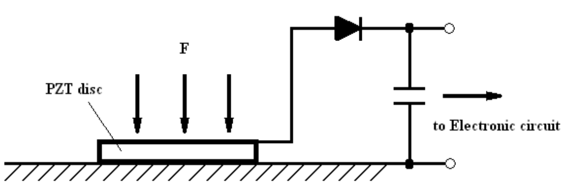

Figure 12. Mechanical force applied to a PZT disc followed by an energy converter.

A PZT disc compressed between two metal surfaces will expand in the radial direction less than a thin cylinder. So the way in which the material is mounted will directly affect the energy conversion per unit volume. The general rule therefore is to allow the PZT body some freedom to expand radially since charge generation is directly coupled to deformation.

Typical energy harvesting circuitry consists of voltage rectifier, converter and storage (Figure 13).

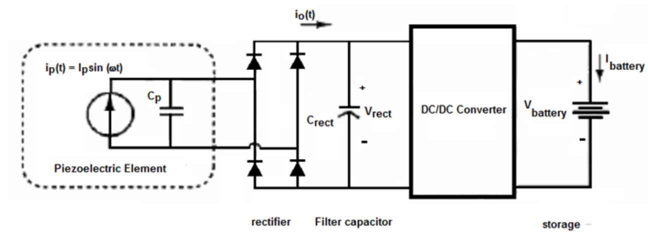

Figure 13. Typical energy harvesting circuitry.

Generally, the device will include an appropriate transducer, converter of mechanical energy to electrical one, chopper, dc-cc converter and high performance microcontroller which will control the performances, and stability of the all system.

E. Low energy harvesting power source

A self-powered autonomous wireless sensor system composed of a power source and a wireless sensing communication system (Figure 14) was realized by Marsic et. al. [14].

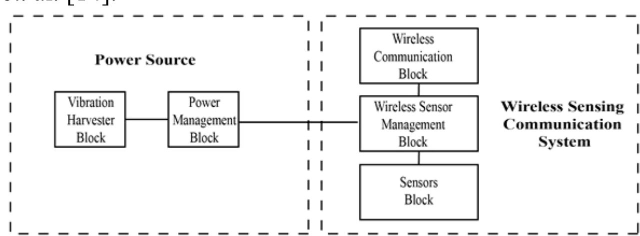

Figure 14. Block diagram of a wireless sensor node powered by a vibration energy harvester. [14]

The design optimization [14] for low power consumption minimization ensures the system's energy autonomous capability.

V. CONCLUSIONS AND FUTURE WORKS

Several techniques have been proposed and developed to extract energy from the environment. In general, "*vibration energy*" could be converted into electrical energy by three techniques: electrostatic charge, magnetic fields and piezoelectric.

Piezoelectric materials like PZT and PVDF embedded in different electronic configurations are suitable for applications, such as: unimorph, bimorph and multilayers transducers, energy harvesting circuitry, sensor network nodes with energy harvesting devices, multilayer devices generated for low frequency vibration energy harvesting, micromachining PZT cantilever, micro-power generator array, energy harvesting sensor networks, networks of ultra-low-power, peer-to-peer, wireless nodes, etc.

Mechanical resonance frequency of piezoelectric bimorph transducers depends on geometric size (length, width, and thickness of each layer), and the piezoelectric coefficients (d_{31} and s_{11}) of the piezoelectric material.

In future work we will study the influence of mechanical impacts (shocks) on the behavior of piezoelectric elements function of the piezoelectric elements characteristics (material type, size, volume, thickness, impact value, etc.); in order to increase the values of generated electrical charges and device efficiency.

ACKNOWLEDGMENT

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TABLE I. THE ELECTRIC, PIEZOELECTRIC AND DIELECTRIC CHARACTERISTICS OF SOME PIEZOCERAMIC MATERIALS

Material property	**Type of Piezoceramic Material**								
	$BaTiO_3$	*PZT - 4*	*PZT - 8*	*PXE - 4*	*PZT - 5A*	*PZT - 6*	*Piezolan*	*PXE - 7*	*PXE-11*
ρ [10^3 kg·m^{-3}]	-	7.5	7.6	7.5	7.45	7.45	7.4	7.75	4.50
K_p	0.354	0.58	0.50	0.55	0.60	0.42	0.35	0.52	0.43
K_{31}	0.208	0.33	0.295	0.32	0.34	0.25	0.21	0.31	0.25
K_{33}	0.493	0.70	0.62	0.68	0.705	0.54	0.48	0.70	0.55
K_t	-	0.51	0.44	-	0.49	0.39	0.42	-	-
ε	-	1300	1000	1500	1700	1050	950	700	400
d_{33} [10^{-12} m/V]	191	289	218	265	374	189	210	220	100
d_{31} [10^{-12} m/V]	-79	-123	-93	-141	-170	-80	-78	-86	-44.5
g_{33} [10^{-3}V·m/N]	11.4	26.1	24.5	20.0	24.8	20.4	2.0	35.4	28.2
g_{31} [10^{-3}V·m/N]	-4.7	-11.1	-10.5	-9.4	-11.4	-8.6	-7.3	-14	-11.2
s_{11E} [10^{-12} m^2/V]	8.55	12.3	11.1	13.0	16.4	10.7	12.1	12.5	8.1
s_{33E} [10^{-12} m^2/V]	8.93	15.5	1.39	12.7	18.8	13.3	17.3	15.8	9.5
s_{11S} [10^{-12} m^2/V]	8.18	10.9	10.1	11.7	14.4	10.1	11.6	-	-
s_{33S} [10^{-12} m^2/V]	6.76	7.9	8.5	6.8	9.46	9.2	13.3	-	-
Q		500	1000	500	75	450	450	80	270
$10^3 \cdot$ tg δ		4	4	6	20	20	15	20	25
T_c [^{0}C]		328	300	265	365	335	290	320	400 (195)