Ferroelectric Devices & Piezoelectric Actuators

Research Misconceptions and Rectifications

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Preface

ACTUATOR applications of piezoelectrics started in the late 1970s, which were followed in the next decade by major investments aimed at practical implementation, such as precision positioners with high-strain materials, multilayer device design, mass fabrication processes for portable electronic devices, ultrasonic motors for microrobotics, and smart structures. After the slump due to the worldwide recession, we are now experiencing a kind of "renaissance" of piezoelectric actuators, which are being put to use in sustainable environmental applications like energy-saving systems, as well as in emerging "active" biomedical devices.

To stimulate and challenge researchers in this area, I created a teaching tool originally titled the "Researchers' Misconceptions Top 10" list. This list of ideas and approaches was intended to encourage interdisciplinary thought and discussion among the materials, electrical and mechanical engineers working on piezoelectrics and actuators. I had discovered that certain misconceptions were creeping into teaching and instruction on these topics. Over time, as both an academic authority and an industry executive, I collected and codified these misconceptions, of which a number are spelled out in the box below—along with their sources. From reflection on these and similar ideas, the current book has grown.

As a starting point, the reader is invited to consider the following ten statements and indicate which are true and which are false. (In fact, all are false, and the reasons why are spelled out in the pages that follow.)

1. Electrostriction is caused by a slight displacement of ions in the crystal lattice under field. This displacement will accumulate throughout the bulk and result in an overall strain along the field (cited from a famous encyclopedia).
2. When 1 J electric energy is input to a piezoelectric with an electromechanical coupling factor k, we can expect k^2 J mechanical energy converted in this piezo-material. Thus, we can conclude that the efficiency of this device is k^2% (cited from a journal paper on mechanical engineering).
3. By applying 1 J electric energy on a piezoelectric with an electromechanical coupling factor k, we accumulated k^2 J mechanical energy in this piezo-material. Thus, this actuator can work mechanically up to k^2 J to the outside (cited from a journal paper on mechanical engineering).
4. Elastic compliances and sound velocity are the material's constants in a piezoelectric. Thus, the resonance frequencies are merely determined by the sample size.
5. PZT with the high electromechanical coupling factor k is the best piezoelectric material for heart beat monitoring sensors (from a conversation with an electrical engineering professor).
6. When a piezo-actuator generates unwelcome vibration ringing in a mechanical system, the best solution is to install a suitable mechanical damper in the system (from a conversation with a mechanical engineer).
7. The resonance mode is only the mechanical resonance, while the anti-resonance mode is not a mechanical resonance (from a conversation with a materials professor).
8. The resonance mode is the most efficient driving condition of the piezoelectric transducer.
9. Improving performance is the best way to discover a "best-selling" (i.e., commercially successful) device (most of the professors).
10. The device developer should focus solely on "component" development and purchase the driving circuit from outside, in order to reduce development costs and time (most industrial engineers).

These misconceptions are traceable to faulty ideas regarding the definitions of ionic displacement and strain, efficiency, the energy transmission coefficient, the constraint-dependency of piezo-materials' properties, impedance matching, piezoelectric dampers, resonance and anti-resonance, and system design principles. Part I of this text explains, and gives solutions for, the misconceptions.

Part II is devoted to the problem solving of "ferroelectric devices," which extends the book's coverage beyond piezoelectric actuators. The reason is this. In 2010 I authored *Ferroelectric Devices*, a textbook now used in classrooms worldwide and containing over one hundred educational problems. In the interim, I received a flood of requests from course instructors (and their students) for detailed answers to all the chapter problems, so they could teach (and take) the course with confidence. Thus, the latter part of the present volume presents clear and detailed solutions to problems in ferroelectrics.

It is assumed the reader has learned about ferroelectrics, either from the above-mentioned *Ferroelectric Devices* or an equivalent fundamental textbook. The present, more advanced volume, can be used to supplement the reader's knowledge by rectifying misconceptions and providing practice in ferroelectric problem solving.

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January, 2016

PART 1

Researchers' Misconceptions

BACKGROUND

ACTUATOR applications of piezoelectrics started in the late 1970s, and enormous investment was installed on practical developments during the 1980s aiming at consumer applications such as precision positioners with high strain materials, multilayer device designing, and mass-fabrication processes for portable electronic devices, ultrasonic motors for micro-robotics, and smart structures. After the slump due to the worldwide economic recession in the late 1990s, there is a sort of "renaissance" of piezoelectric actuators according to the social environmental changes for sustainability (i.e., energy saving, biomedical areas) and crisis technologies. Figure 1 shows the piezoelectric device market estimated from multiple sources [1]. The 2014 revenue around $25 billion will expand to $40 billion by 2017. Actuator/piezo-generator (energy harvesting) is the largest category, followed by transducer/sensor/accelerometer/piezo-transformer. Then, resonator/acoustic device/ultrasonic motor category chases.

The "piezoelectric actuator" is really an interdisciplinary area to which materials and applied physics, electrical and mechanical engineers are primarily approaching. Because of narrow knowledge of junior professors, they occasionally instruct the students with a sort of misconception, reflecting the delay of innovative developments in the next generation. The top 10 among these misconceptions, which are primarily related with the misconceptions on the understanding of *ionic displacement and strain, efficiency, energy transmission coefficient,*

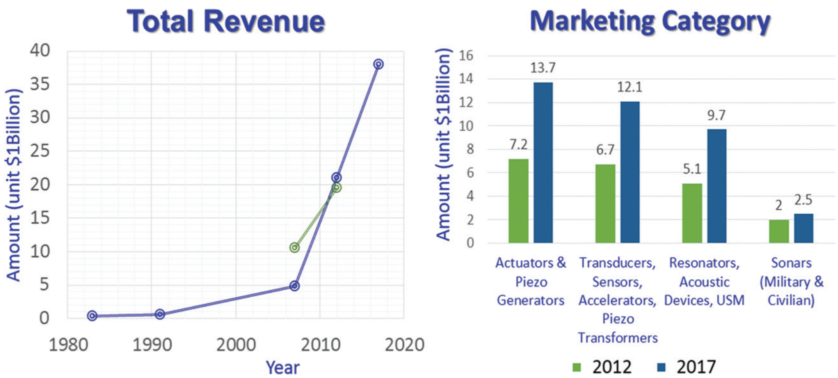

FIGURE 1. *Piezoelectric device market trends.*

constraint-dependency of piezo-materials' properties, mechanical impedance matching, piezoelectric damping mechanism, resonance and antiresonance, best-selling devices, and *system design principle* are reviewed. Table 1 summarizes the top 10 among these (all statements are actually false). If you do not find any "false" content in each question, you are a serious patient, and you should read this tutorial article further as a prescription for your successful future development. The author's philosophy: "Without a strong fundamental understanding, no breakthrough invention comes out."

STRAIN VERSUS IONIC DISPLACEMENT (Question 1)

The reason why a strain is induced by an electric field is explained in Question 1. For simplicity, let us consider an ionic crystal such as NaCl [2]. Figure 2 shows a one-dimensional rigid-ion spring model of the crystal lattice (Uchino's model, introduced in his thesis 1978). The springs represent equivalently the cohesive force resulting from the electrostatic Coulomb energy and the quantum mechanical repulsive energy. Figure 2(b) shows a centrosymmetric case (like NaCl), whereas Figure 2(a) shows a more general noncentrosymmetric case. In Figure 2(b), the springs joining the ions are all the same, whereas in Figure 2(a), the springs joining the ions are different for the longer and shorter ionic distances. In other words, hard and soft springs existing alternately are important. Next, consider the state of the crystal lattice in Figure 2(a) under an applied electric field. The cations are drawn in the direction of the electric field and the anions in the opposite direction, leading to the relative change in the interionic distance. Depending on the direction of the electric field, the soft spring expands or contracts more than the contraction or expansion of the hard spring, causing a strain x (a unit cell length change) in proportion to the electric field E. This is the *converse piezoelectric effect*. When expressed as:

$$x = dE \tag{1}$$

the proportionality constant d is called the piezoelectric constant.

On the other hand, in Figure 2(b), the amounts of extension and contraction of the spring are nearly the same [though ionic displacements are similar to Figure 2(a)], and the distance between the two cations (lattice parameter) remains almost the same, hence, there is no strain. However, more precisely, ions are not connected by such idealized

TABLE 1. Professors' Top 10 Piezoelectric Actuators Misconceptions.

1. Electrostriction is caused by a slight displacement of ions in the crystal lattice under field. This displacement will accumulate throughout the bulk and result in an overall strain along the field (cited from a famous encyclopedia).
2. When 1 J electric energy is input to a piezoelectric with an electromechanical coupling factor k, we can expect k^2 J mechanical energy converted in this piezo-material. Thus, we can conclude that the efficiency of this device is k^2% (cited from a journal paper on mechanical engineering).
3. By applying 1 J electric energy on a piezoelectric with an electromechanical coupling factor k, we accumulated k^2 J mechanical energy in this piezo-material. Thus, this actuator can work mechanically up to k^2 J to the outside (cited from a journal paper on mechanical engineering).
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5. PZT with the high electromechanical coupling factor k is the best piezoelectric material for heart beat monitoring sensors (from a conversation with an electrical engineering professor).
6. When the piezo-actuator generates unwelcomed vibration ringing in the mechanical system, the best way is to install a suitable mechanical damper in the system (from a conversation with a mechanical engineer).
7. The resonance mode is only the mechanical resonance, while the antiresonance mode is not a mechanical resonance (from a conversation with a materials professor).
8. The resonance mode is the best efficient driving condition of the piezoelectric transducer.
9. Improving the performance is the best way for seeking for the successful "best-selling" device (most of the professors).
10. The device developer should focus merely on the "component" development by purchasing the driving circuit from the outside for reducing the development cost and period (most of industrial engineers).

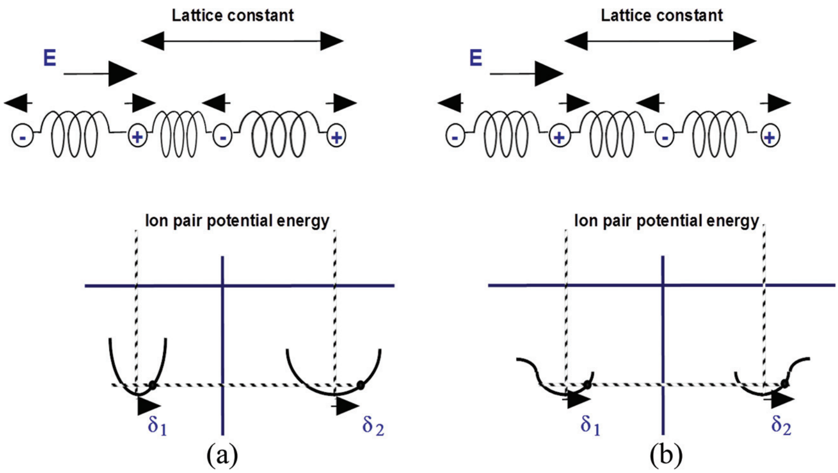

FIGURE 2. Piezoelectric device market trends: (a) Piezoelectric Strain and (b) Electrostriction.

springs [those are called harmonic springs, in which force (F) = spring constant (k) × displacement (δ) holds]. In most cases, the springs possess anharmonicity ($F = k_1\delta - k_2\delta^2$), that is, they are somewhat easy to extend but hard to contract. Such subtle differences in the displacement causes a change in the lattice parameter, producing a strain which is independent of the direction of the applied electric field (+E or –E), and hence is an even-function of the electric field. This is called the electrostrictive effect, and can be expressed as:

$$x = ME^2 \tag{2}$$

where M is the electrostrictive constant.

> ***Answer:*** Though the ionic displacements (δ) in Figure 2(a) and 2(b) are similar, the strain [*differentiation of the displacement* ($\partial\delta/\partial x$)] is very different.

EFFICIENCY (Question 2)

This is a typical misconception by mechanical engineering professors because they do not know how to recover the electrostatic energy from a piezoelectric.

First of all, remember the following constitutive equations:

$$D = \varepsilon^X E + dX \tag{3}$$

$$x = dE + s^E X \tag{4}$$

where d is the piezoelectric constant, s^E is the elastic compliance under short-circuit condition, and ε^X is the permittivity under stress-free condition. Then, the electromechanical coupling factor k is defined by:

$$k^2 = d^2 / s^E \varepsilon^X \tag{5}$$

The value k^2 has a meaning of *energy conversion rate*, that is,

$$k^2 = \text{(stored mechanical energy)/(input electrical energy)} \tag{6}$$

Taking an example value $k = 70\%$ for a piezoelectric pseudo DC device, $k^2 = 50\%$, then the input electrical energy 100 is converted into mechanical energy 50, by remaining 49 as stored electrical energy (in a capacitor). Because the loss factor (dielectric loss tan δ) is less than 1%, actual loss dissipated as heat is usually less than 1% (refer to Resonance and Antiresonance Modes: Efficiency). The energy conversion process is visualized in Figure 3(a). Thus, if we can collect the stored electrical energy back to the drive circuit, we can declare that the loss is only 1%. On the contrary, the efficiency η is defined by:

$$\eta = \text{(output mechanical energy)/(consumed electrical energy)} \tag{7}$$

If we can recover the mechanically unconsumed energy (stored in the piezoelectric elastic material, i.e., spring), we can consider that the actual consumed electric energy should be the sum of output mechanical energy (work to the outside) and heat loss, leading to 99% (very high).

Because the mechanical engineering professor did not know how to recover the electrostatic energy stored in the actuator/capacitor, he released it by shorting the drive circuit in order to move to the next operation. Of course, in this worst scenario, the efficiency less than 50% (equal to k^2) is true in his paper.

Now, how can we recover the electrostatic energy from the piezoelectric? Let us consider dot-matrix/ink-jet printer and diesel injection valve control applications, where multilayer actuators are driven at < 1 kHz, much lower than the resonance frequency. Refer to an equivalent circuit (k_{31} mode) shown in Figure 3(b). In this equivalent circuit,

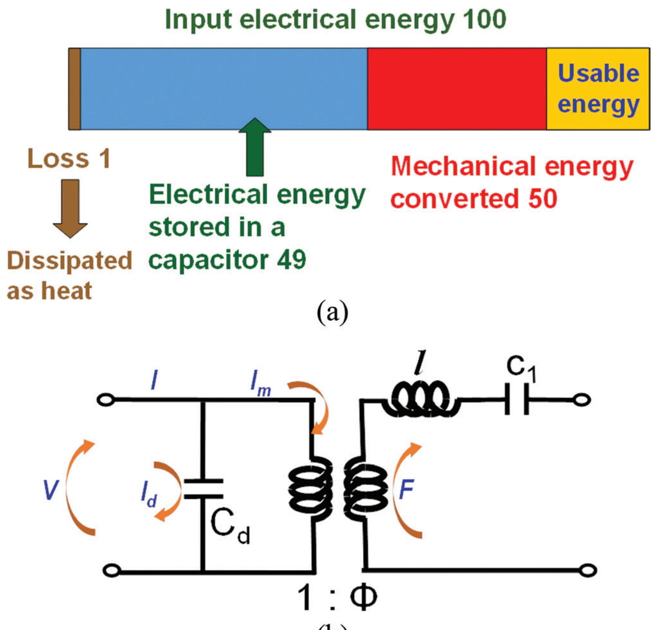

FIGURE 3. (a) Energy conversion rate in a typical piezoelectric. (b) Equivalent circuit (k_{31} mode).

motional current and damped current [$C_d = (1 - k^2)C_0$] should have $k^2 : (1 - k^2)$ ratio under an off-resonance condition. If we insert the inductance L in the driving system so as to create a resonance circuit of L and C_d under the condition of $\omega^2 = 1/LC_d$ (ω: operation cycle such as 1 kHz), the electric energy stored in the damped capacitance C_d starts flip-flopping with L, without losing this energy. A negative capacitance usage is an alternative solution recently.

> ***Answer:*** The efficiency of the piezoelectric devices is high around 99%, if we recover the stored electric energy with a suitably selected inductance or a negative capacitance.

ENERGY TRANSMISSION COEFFICIENT (Question 3)

Not all the mechanically stored energy can actually be used, and the actual work done depends on the mechanical load [Figure 3(a)]. With zero mechanical load or complete clamp condition (i.e., no strain), no output work is done or no energy is spent to the outside. The *energy transmission coefficient* is defined by:

$$\lambda_{max} = (\text{output mechanical energy/input electrical energy})_{max} \qquad (8)$$

or equivalently,

$$\lambda_{max} = (\text{output electrical energy/input mechanical energy})_{max}$$

The difference of the above from Equations (6) and (8) is "stored" or "output/spent."

Let us consider the simplest case where an electric field E is applied to a piezoelectric under constant external stress X (< 0, compressive stress). This corresponds to the situation that a mass is put suddenly on the actuator, as shown in Figure 4(a) [2]. Figure 4(b) shows two electric-field versus induced-strain curves, corresponding to two condi-

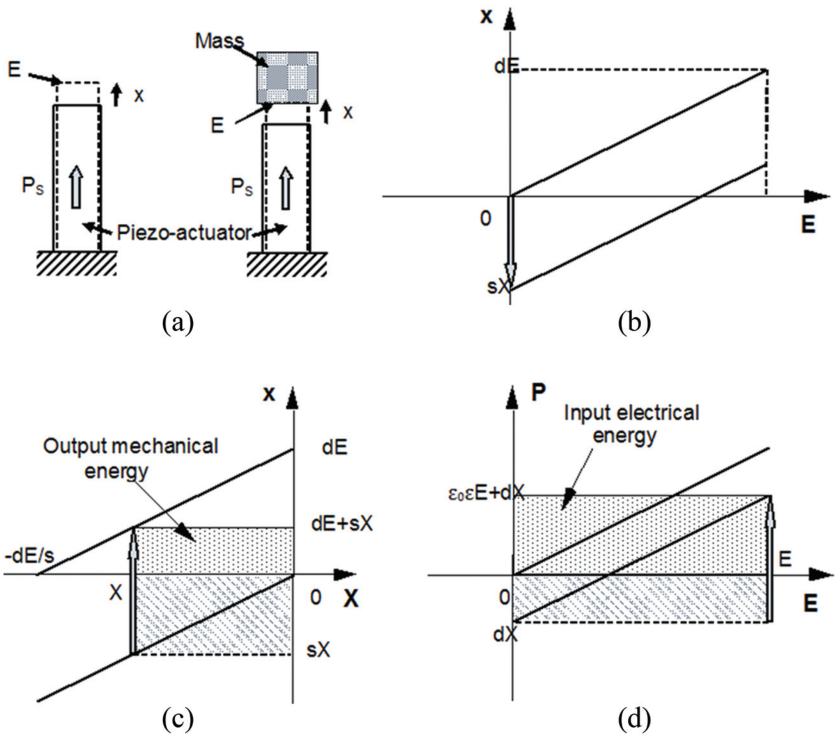

FIGURE 4. Calculation of the input electrical and output mechanical energy: (a) load mass model for the calculation; (b) electric field versus induced strain curve; (c) stress versus strain curve; and (d) electric field versus polarization curve.

tions; under the mass load and no mass. Because the area on the field-strain domain does not mean the energy, we should use the stress-strain and field-polarization domains in order to discuss the mechanical and electrical energy, respectively. Figure 4(c) illustrates how to calculate the mechanical energy. Note that the mass shrinks the actuator first by sX (s: piezo-material's compliance, and $X < 0$). This mechanical energy sX^2 is a sort of "loan" of the actuator credited from the mass, which should be subtracted later. This energy corresponds to the hatched area in Figure 4(c). By applying the step electric field, the actuator expands by the strain level dE under a constant stress condition. This is the mechanical energy provided from the actuator to the mass, which corresponds to $|dEX|$. Like paying back the initial "loan," the output work (from the actuator to the mass) can be calculated as the area subtraction [shown by the dotted area in Figure 4(c)]:

$$\int(-X)dx = -(dE + sX)X \tag{9}$$

Figure 4(d) illustrates how to calculate the electrical energy. The mass load X generates the "loan" electrical energy by inducing $P = dX$ [see the hatched area in Figure 4(d)]. By applying a sudden electric field E, the actuator (like a capacitor) receives the electrical energy of $\varepsilon_0\varepsilon E^2$. Thus, the total energy is given by the area subtraction [shown by the dotted area in Figure 4(d)]:

$$\int(E)dP = (\varepsilon_0\varepsilon E + dX)E \tag{10}$$

Now, we need to choose a proper load to maximize the *energy transmission coefficient*. From the maximum condition of:

$$\lambda = (dE + sX)X/(\varepsilon_0\varepsilon E + dX)E \tag{11}$$

we can obtain:

$$\lambda_{max} = [(1/k) - \sqrt{(1/k^2) - 1}]^2 = [(1/k) + \sqrt{(1/k^2) - 1}]^{-2}$$

We can verify from Equation (11) that:

$$k^2/4 < \lambda_{max} < k^2/2$$

depending on the k value. For a small k, $\lambda_{max} = k^2/4$, and for a large k, $\lambda_{max} = k^2/2$. It is also worth noting that the maximum condition stated above does not agree precisely with the condition which provides the

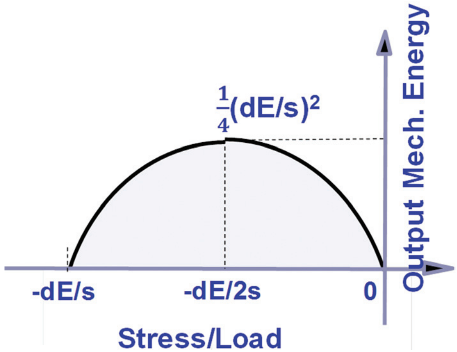

FIGURE 5. *Calculation of the maximum output energy.*

maximum output mechanical energy. The maximum output energy can be obtained when the dotted area in Figure 4(c) becomes maximum under the constraint of the rectangular corner point tracing on the line (from dE on the vertical axis to $-dE/s$ on the horizontal axis). Therefore, as pictured in Figure 5, the load should be a half of the maximum generative stress and the mechanical energy: $-[dE - s(dE/2s)](-dE/2s) = (dE)^2/4s$. In this case, since the input electrical energy is given by $[\varepsilon_0\varepsilon E + d(-dE/2s)]E$,

$$\lambda = 1/2[(2/k^2) - 1]$$

which is close to the value λ_{max} when k is small, but has a different value when k is large, that is predicted theoretically.

> ***Answer:*** Among the stored mechanical energy k^2, usable mechanical energy is one-quarter to one-half of the stored energy [Figure 3(a)].

CONSTRAINT-DEPENDENCY OF PIEZO-PROPERTIES (Question 4)

It is important to consider the conditions under which a material is operated when characterizing the dielectric constant and elastic compliance of a piezoelectric material, which reflect to its sound velocity [3]. When a constant electric field is applied to a piezoelectric sample as illustrated in Figure 6(a), the input electrical energy will be different for two distinct mechanical conditions that may be applied to the material:

(1) the *mechanically clamped state*, where a constant strain is maintained and the specimen cannot deform (pure electrostatic energy), and (2) the *mechanically free state*, in which the material is not constrained and is free to deform. We expect then that the total input electrical energy under the free condition will be the sum of the energies associated with pure electrostatic energy (without deformation) and the pure mechanical energy under a short-circuit condition. This can be expressed by:

$$\frac{1}{2}K^X\varepsilon_o E_o^2 = \frac{1}{2}K^x\varepsilon_o E_o^2 + \frac{1}{2}\frac{d^2}{s^E}E_o^2 \tag{12a}$$

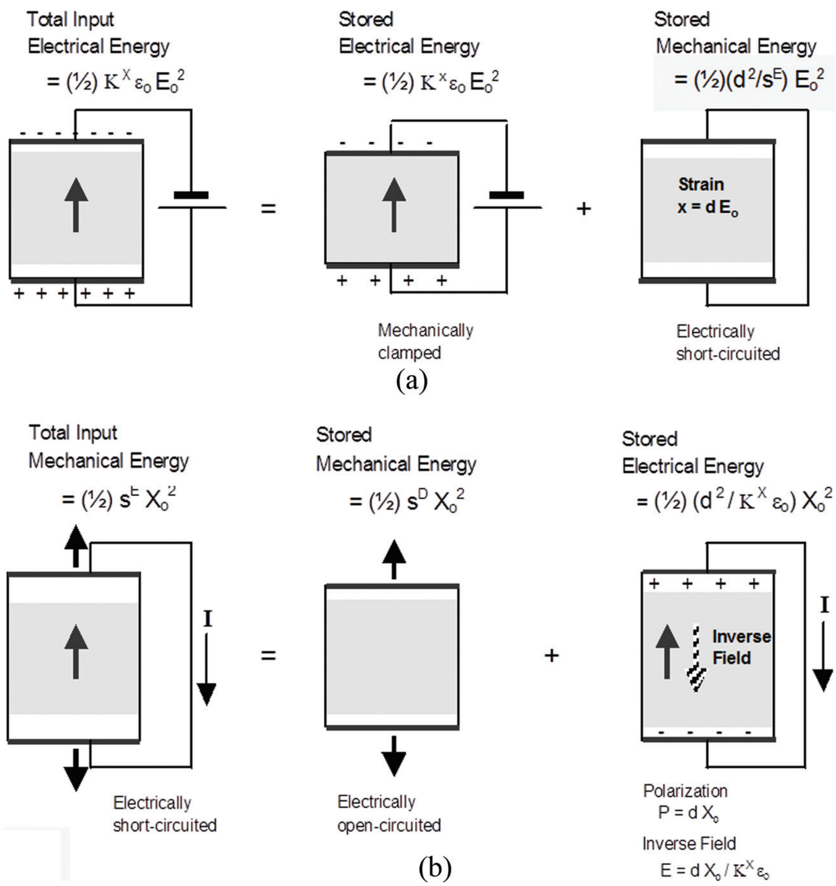

FIGURE 6. Schematic representation of the response of a piezoelectric material under (a) constant applied electric field and (b) constant applied stress conditions.

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