A SIMPLE DEVICE FOR HEAT TO ELECTRICAL ENERGY CONVERSION BY MEANS OF FERROELECTRICS

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Introduction

A few years ago, Zaev [1, 2] demonstrated experimentally the possibility of heat to electrical energy conversion by means of ferroelectrics. A capacitor filled with a ferroelectric material was charged and discharged periodically at a temperature just a little lower than the Curie point. According to Zaev, the capacitor must have a nonlinear capacitance $dC/dV > 0$, which means the capacitance increases with rising voltage. Besides these experimental results, it was proven by a theoretical calculation that the electrical energy obtained during discharging can reach up to 1.35 of the energy introduced to charge the capacitor. The present paper presents an inexpensive and simple electric circuit which can be used to prove heat to electricity conversion experimentally. Moreover, the physical mechanism of heat to electricity conversion is explained in the form of a thermodynamic cycle.

Thermodynamic cycle for energy conversion

The following thermodynamic cycle is composed of four reversible steps. It works only at a temperature just a little lower than the Curie point, where the dielectric constant is highly temperature dependent. Fig. 1 shows the relative dielectric constant of a representative ferroelectric ceramic as a function of temperature.

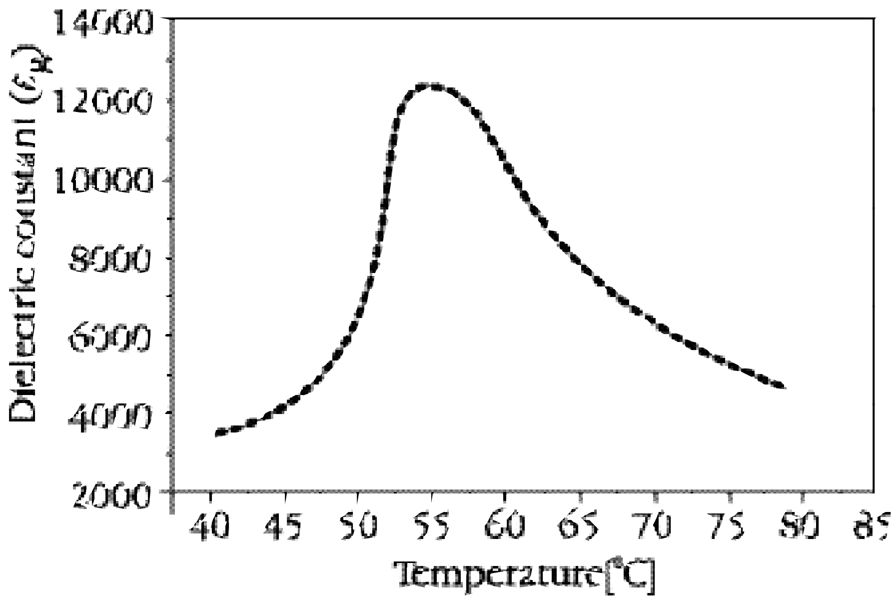

Fig. 1
Relative dielectric constant versus temperature for a barium strontium titanate ceramic (80% Ba, 20% Sr) prepared by the author. Curie point = 55^0 C.

As it can be seen, just below the Curie point in the range from 50 to 55^0C, small changes of the temperature cause high changes of the dielectric constant.

Furthermore, to understand the conversion mechanism, it is necessary to understand the electrocaloric effect. When an electric field is applied to a dielectric medium, the latter is polarized. For ferroelectric materials, the parallel domain alignment is the most important part of the total polarization. During the successive alignment of the domains, some material parameters in particular entropy, heat capacity and temperature change. Since the material possesses less degrees of freedom in the polarized state, its entropy and heat capacity are reduced. As a consequence, provided that no heat exchange with the environment is possible (adiabatic conditions), the temperature increases. It is very important to understand that the energy for warming of the dielectric is not taken from the polarizing electric field. The increase in temperature is a result of the decreased heat capacity only.

From this, it can be derived easily what means "nonlinear capacitance".

When a capacitor is charged adiabatically which means its voltage increases faster than any heat exchange with the environment is possible, due to the electrocaloric effect, the temperature of the dielectric must also increase. As it can be seen from Fig.1, below the Curie point, an increasing temperature leads to a higher dielectric constant. Assuming that both temperatures, the one before charging and the other after charging are still below the Curie point, one can say that the dielectric constant increases with an increase in voltage.

Since the capacitance is proportional to the dielectric constant, the capacitor has a nonlinear characteristic $dC/dV > 0$. In the same way it can be concluded that adiabatic charging just a little above the Curie point reveals a nonlinear capacitor characteristic with $dC/dV < 0$.

Quantitative experimental measurements on the electrocaloric effect in some representative ferroelectric and antiferroelectric materials were published by Thacher [3].

STEP 1: Adiabatic charging of the capacitor

We consider a capacitor filled with a ferroelectric medium at an environmental temperature a little lower than the Curie point.

An adiabatic charging of a capacitor (no heat exchange) effects an increase in temperature and capacitance due to the electrocaloric effect. We assume that this increase in temperature is so small that the temperature remains below the Curie point. Finally, the capacitor is completely charged while the dielectric medium has a higher dielectric constant and therefore a higher capacitance than it posseses at the environmental temperature.

To go further to step 2, the capacitor is hold under conditions where no discharge is possible, e.g. it is disconnected from the power supply.

STEP 2: Thermal equilibration

After a short time, the charged capacitor has cooled down to the environmental temperature. While cooling down, the dielectric constant and capacitance decrease. But the charges of the capacitor plates remain constant. As a consequence, the voltage and the electrical energy increase. This can be readily recognized from the general capacitor equation $q = C V$ (q = charge, C = capacitance, V = voltage):

$$q = \text{constant} = C_1 V_1 = C_2 V_2$$

STEP 3: Adiabatic discharging of the capacitor

While discharging the capacitor the temperature and capacitance decrease (again heat capacity changes) due to the electrocaloric effect, leading to a further increase in the available electrical energy. The ferroelectric medium posseses now a final temperature below the temperature of the environment.

STEP 4: Thermal equilibration

In order to proceed with step 1, it is necessary to reach the environmental temperature. An inflow of heat from the environment to the dielectric material is required.

Electric circuit to observe energy conversion

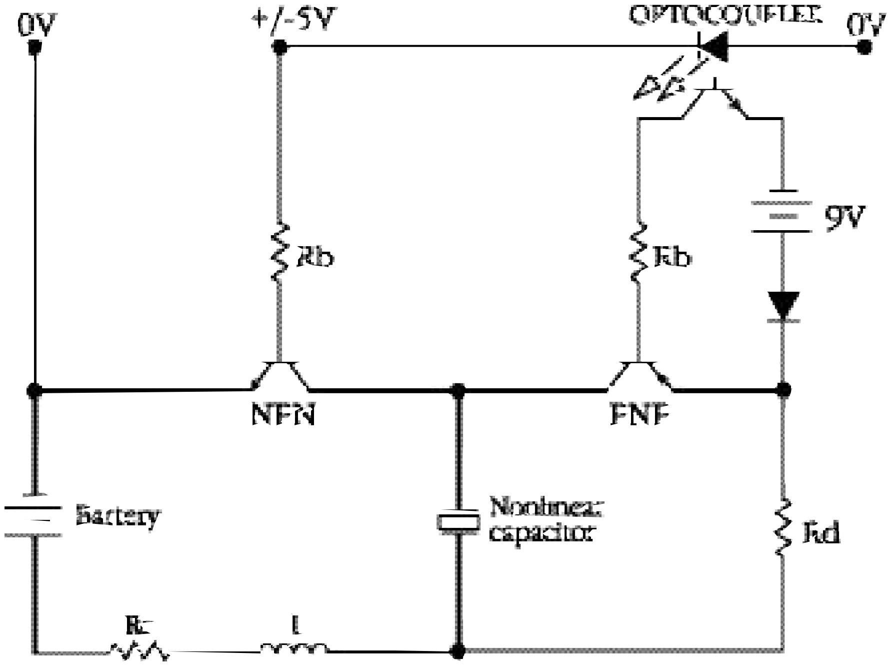

Fig. 2
Electric circuit for testing the energy conversion effect. The connections to the square wave generator are labeled with 0V and +/- 5V, the resistors Rb are to adjust the maximum base current of the transistors.

Assuming the experimenter has a nonlinear capacitor, the set-up shown schematically in Fig. 2 is proposed as a possible conversion device. The circuit contains two different types of transistors (NPN and PNP) which fulfill here the function of a switch.

The NPN junction transistor consists of two n-type semiconductors (called the emitter and collector) separated by a thin layer of p-type semiconductor (called the base). On the other hand the PNP junction transistor consists of a thin layer of n-type semiconductor lying between two p-type semiconductors. The base is the ON/OFF switch for the transistors. If a current flows to the base, there is a path from the collector to the emitter, where a current can flow (switch is ON). If there is no current flowing to the base, then no current can flow from the collector to the emitter (switch is OFF).

The charging-discharging process is controlled by a square wave generator which produces an output signal switching from +5V to -5V. The switching frequency is adjustable from 0.1 Hz up to at least 10 kHz. This output signal is applied to the bases of both transistors.

During the time the square wave generator output signal is +5V, a base current flows through the base-emitter junction of the NPN transistor which creates a low resistance path between the collector and the emitter. As a consequence, the capacitor is charged by the battery. The collector-emitter junction of the PNP transistor has a very high resistance, because here no base current flows. Therefore the capacitor is not discharged at the same time. When the output signal switches to -5V, a current flows to the base of the PNP transistor and not to the base of the

NPN transistor. Now the capacitor is discharged.

In order to understand the function of the inductance in Fig. 2, we analyze the thermodynamics of the charging process.

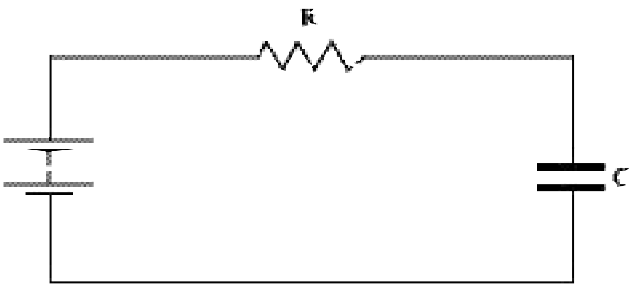

Fig. 3
Simple circuit for charging a capacitor

If a linear capacitor of capacitance C is charged to a voltage V through the load R according to Fig. 3, the energy $W = 0.5\ C V^2$ is stored in the capacitor. During the charging process, a time-dependent current I(t) flows:

$$I(t) = V/R \exp(-t/RC)$$

This current develops the heat Q in the load:

$$2Q = R \int I^2(t)dt = 0{,}5CV^2$$

Here the integration limits are from zero to infinity. This calculation shows, that the energy taken from the battery is the energy stored in the capacitor after charging plus the heat produced in the load, also 2•C V2. One can see that the heat Q is not dependent on the resistance value R.

The above used equations are only valid in case of a one-step charging process.

If the capacitor is charged stepwise to the final voltage V, e.g. using a ramp generator, and each voltage step effects a voltage increase , the total heat produced in the load is (N = number of voltage steps):

$$Q = N\ 0{,}5\ C\ (V/N)^2 = 0{,}5\ C/N\ V^2$$

Now the energy taken from the source is:

$$W = 0{,}5 \cdot (1 + 1/N) 1/2\ CV^2$$

If the number of steps N tends to infinity, the heat Q tends to zero.

This energy loss in the load dramatically influences the efficiency of any conversion device and must be taken into account, otherwise all experimental attempts to observe energy conversion would fail.

A more detailed discussion on charging a capacitor and the unavoidable energy losses was given by Heinrich [4] and Gupta et al. [5].

The inductance in the circuit (Fig. 2) effects a slower rising of the current during the charging process (due to self induction) and can reduce the heat generated in the load dramatically.

Acknowledgments

Financial support of this work was provided by the Brazilian agency FAPESP (www.fapesp.br) and the German Academic Exchange Service (DAAD), (www.daad.de).

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