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Maximum Power of Thin-Film Capacitive Electrostatic Micromotors Based on Nanogaps

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Abstract: This paper is devoted to the determination of the value of the maximum specific power of capacitive electrostatic micromotors based on nanometer working gaps. The motors under consideration were developed earlier. They have the following structure: a metal—thin crystalline ferroelectric layer with a high dielectric constant—a nanometer working gap—a movable electrode. The mechanism limiting the magnitude of the maximum field in the gap have also been determined in previous works. The mechanism is the stripping of atoms from the surface of the movable electrode under the action of electrostatic forces. It was shown that the maximum energy density in the working gap can be as high as 1.6×10^9 J/m^3. In the presented paper, a maximum frequency of electromechanical energy conversion as high as 10 MHz is estimated for these motors, with a maximum specific power of 5×10^8 W/kg. The application of the proposed motors for micromachines is discussed.

Keywords: energy converter; electrostatics; nanogap; ferroelectric; maximum power density

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1. Introduction

Currently, there is a need for a significant increase in the specific power (watts per kilogram) of electric motors, both for the creation of macrostructures (for example, for the creation of electric aircraft engines) and for micromechanical devices (for example, in the development of micro-flying vehicles).

To solve this problem, the three classes of electromechanical energy converters (motors and generators) most widely used are inductive, piezoelectric, and electrostatic electric machines, in which the direct and reverse transformation of the energy of the magnetic or electric field into mechanical energy is carried out. The specific and absolute powers of these energy converters are determined by the field energy density in the working gap and the conversion frequency.

In the best inductive converters, the energy density W_V of the magnetic field in the gap at the maximum possible values of magnetic induction B is of the order of 1–1.5 T. For magnetic circuits created on the basis of ferromagnets, it reaches $W_V = 1/2\ B^2/\mu_0 = 4 \times 10^5$–$10^6$ J/m^3 (μ_0—magnetic constant), with the minimum values of the gaps between the rotor and stator, determined by the production technology, being of the order of fractions of a millimeter but not less than 100–300 microns [1]. To maximize the power of such motors, the increased speed of the rotor with multi-section cores is used, due to which the maximum specific power of the electric motor reaches 10^4 W/kg. The frequency of inductive converters is limited by Coriolus forces, which can exceed the mechanical strength of the rotor material.

Piezoelectric energy converters, in terms of the field energy density, are comparable to electromagnetic ones; see, for example, devices based on PZT5H ceramics [2]. In such converters, the working gap is the piezoelectric material itself. Its energy density can be high due to the large value of its dielectric constant ε, as well as the large value of the electromechanical coupling coefficient, of the order of 0.5–0.8. However, for such converters, the value limiting the maximum density of the energy to be converted is not the maximum field that can be formed in the dielectric without violating its electrical strength, but rather the limit value of the mechanical stress of the material. When this value is exceeded, the irreversible deformation of the piezoelectric occurs: $\sigma = F_e/S$ (F_e is the elastic force, and S is the area of the converter): $W_V = 1/2\ \sigma^2/E_Y$ (E_Y—Young's modulus) [3]. For piezoelectric converters, the operating frequency is limited by the speed of sound in the piezoelectric and can reach tens of megahertz.

In capacitive electrostatic converters, as well as in inductive converters, the specific volume density of energy W_V is determined by the electric field strength in the working gap E_e.

$$W_V = \varepsilon_0 E_e^2/2 = \varepsilon_0\ V_e^2/2d_e^2 = C_e V_e^2/2d_e \quad (1)$$

where V_e is the voltage applied to the gap, d_e is its extent, $C_e = \varepsilon\varepsilon_0/d_e$ is the specific (per unit area) capacitance of the gap, and ε_0 is the dielectric constant of the vacuum. The energy per unit area of the structure W_S is equal to:

$$W_S = C_e V_e^2/2 = \varepsilon_0 V_e^2/2d_e \quad (2)$$

The operation of capacitive electrostatic energy converters is based on the shift of the movable electrode (ME) of an electric capacitor either under the action of electric field forces (motor [4,5]) or under the action of mechanical forces against electric field forces (generator [6]).

Electromechanical energy converters with a metal–gap–metal structure (MGM) have not been widely used due to their low breakdown field strength and, accordingly, their low specific energy density. An increase in the field strength in the gap can be achieved by introducing an additional dielectric layer into the MGM with the use of metal–dielectric–gap–metal (MDGM) structures. The introduction of a dielectric layer that inhibits the development of breakdown makes it possible to increase the voltage applied to the structure to several hundred volts at small gap values of the order of 10–30 µm; see, for example, Ref. [7]. This structure is able to achieve an energy density comparable to that of large inductive converters. However, in such structures, when the gap width decreases to nanometer values, most of the applied voltage falls on the dielectric layer, which prevents a further increase in the bulk density of energy in the gap.

Previous Experiments and Formulation of the Problem

A new principle of electromechanical energy conversion, based on the use of a thin ferroelectric film in the metal–thin-ferroelectric-film–nanogap–movable metal film (MFGM) structures, has been developed in [8,9]. The nanogap is formed when the ME is pressed against the surface of the dielectric. The width of the nanogap, determined from measurements of the capacitance of the structure, is within the range of 5–50 nm [10]. It is limited by the roughness of the surface of the ferroelectric. It has been shown, both theoretically and experimentally [10], that when using a thin ferroelectric in these structures with a permittivity value ε exceeding 1000–5000, practically all of the voltage applied to the MFGM structure falls on the nanometer gap.

In [11], the maximum voltage value that could be applied to the MFGM structure, both without violating its electrical strength and without accumulating charge in the ferroelectric layer, was estimated. It has been shown that at atmospheric pressure and when changing the gap from values exceeding the impact ionization length of 3–7 µm to nanometer values, this voltage should not exceed a certain critical value, V_{cr} = 330 B. The maximum field value that can be reached in the gap $E_{cr} = 6 \times 10^{10}$ V/m and, accordingly, the maximum energy density in the working gap $W_{V,max} = 1.6 \times 10^9$ J/m^3 were determined. This value significantly exceeds the energy density achieved in powerful electromagnetic motors by up to 10^5 times. Estimates of $W_{V,max}$ for the vacuum mode of operation of electromechanical converters based on MFGM structures give values of the critical field and, accordingly, the maximum energy density that are close in order of magnitude to the previous mode. In this case, the mechanism limiting the value of the maximum field in the gap is no longer the impact ionization of the air in the gap, but rather the effect of pulling atoms from the surface of the movable electrode due to the action of a super-high field.

Thus, the maximum energy density that can be achieved in one conversion cycle has been estimated for MFGM structures, regardless of the specific device design. However, the question of the maximum specific power of such converters, or in fact, the maximum conversion frequency, remains open, which cannot be solved without analyzing the operation of a specific device design. Therefore, the solution to this problem was studied using the example of the design of film electrostatic motors developed in [12,13].

Earlier, in these papers, a new physical principle of electromechanical energy conversion, based on the gradual (section by section) pressing of a thin metal film to the ferroelectric surface under the action of electric field forces, was developed. Based on this effect, models of new capacitive electrostatic motors with high specific power were created. The principle of operation of these motors is given in Figure 1.

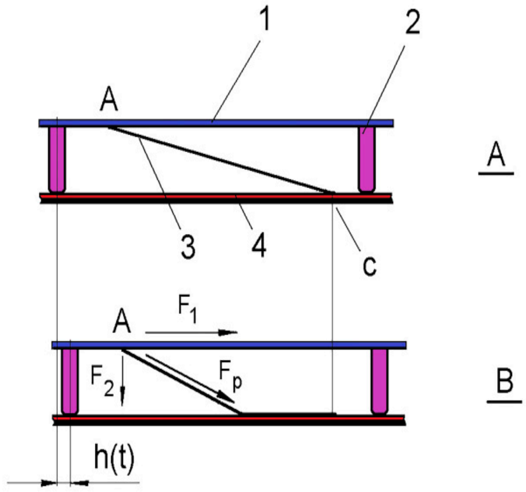

Figure 1. Schematic representation of the principle of electromechanical energy conversion under electrostatic rolling of a free metal film. 1—MP; 2—guides; 3—free metal film (movable electrode, ME); 4—FP. (**A**)—the initial state of ME; (**B**)—the position of MP and form of ME under action of voltage pulse. c is the place of pressing the ME to the surface of the ferroelectric. F_p is thrust force, F_1 and F_2—its tangential and normal components.

The motor comprises a fixed plate (FP) (4), on which a silicon or sapphire substrate is fixed, with an electrode and a ferroelectric film applied on its surface, and a movable plate MP (slider) (1) with free elastic metal films (3) synthesized on its surface, fixed with one end on the surface of the MP moving relative to the FP along guides (2). The gap d_1 between the MP and the FP has a width of the order of 0.1 l, where l is the length of the movable electrode (ME).

The MP movement consists of several stages. When the first voltage pulse is applied between the ME (3) (having the initial form A) and the fixed electrode, electrostatic pressing of the end of the ME (3) to the surface of the ferroelectric (4) occurs. Then, the movement of the plate (1) starts due to the subsequent electrostatic rolling of the ME surface onto the ferroelectric surface (part by part), its bending, and its mechanical tension. This is how electromechanical energy conversion occurs. The rolling length $l_r(t)$ increases during the action of the voltage pulse t, and the shift $h(t)$ of the MP increases accordingly.

After the voltage pulse is switched off, the ME, under the action of elastic forces arising due to its bending and tension, comes either to the initial position in Figure 1A (under the action of a single voltage pulse) or to a new position characteristic of the continuous movement of the MP (when a series of pulses is applied to the sample). Then, when subsequent voltage pulses with frequency f arrive, the process is repeated. Thus, the continuous step-by-step movement of the MP is carried out.

On the basis of MFGM structures, we created an experimental model of a film capacitive motor, which was investigated and described in [12]. Since, in the studies given in [12], it was found that the conversion factor of electrical energy accumulated in the structure's capacitance into mechanical energy exceeds 80%, then in the first approximation, it can be assumed that the converted energy density is equal to the energy accumulated in the structure's capacitance: $W_V = C_V V^2/2$. The dependence of this energy (calculated from data on capacity C_V) on the amplitude of the applied voltage is shown in Figure 2. In particular, the W_V value at a voltage V = 90 V applied to the MFGM structure is 1.3×10^8 J/m^3. Extrapolating the W_V value according to the W_V~V^2 law to a maximum voltage V_{cr} = 330 V, we obtain the maximum value of the energy density, approximately equal to the theoretical estimate reported in [11].

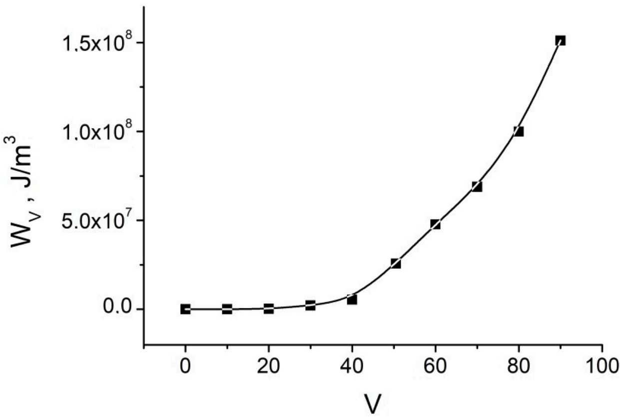

Figure 2. The energy density in the gap, measured for a thin-film capacitive motor.

Thus, the electrostatic energy converters developed by us based on MFGM structures with both ferroelectric films [12] and a layer of antiferroelectric ceramics [13] are promising for creating motors with high specific power. However, the question of the possible maximum operating frequency of such devices remains unclear.

Taking into account the above considerations, the purpose of the present work is to determine the values of this maximum frequency and the maximum specific power that can be achieved in a capacitive electrostatic motor.

2. Materials and Methods

As has been pointed out above, to determine the power of an electrostatic motor, it is necessary to take into account the particular construction of the device. The evaluation of the maximum specific power of capacitive motors is based on the mechanism of electromechanical energy conversion by means of electrostatic rolling, as mentioned above.

Since the determination of the maximum energy density in the working gap of the engines under consideration was carried out earlier in [11], to establish the maximum specific power $P_{V,max}$ of such devices, it is sufficient to determine the limit frequency f_{max} of the electromechanical energy conversion cycles:

$$P_{V,max} = W_{V,max} f_{max} \tag{3}$$

3. Results

3.1. Evaluation of Maximum Specific Power of Capacitive Motor

The operating frequency of the motor is inversely proportional to the duration of the conversion cycle, which consists of four stages: 1—the electrostatic capture of the ME; 2—the electrostatic pressing of the ME; 3—the separation of the ME and ferroelectric surfaces after the end of the voltage pulse; 4—the recovery of the shape of the ME necessary for subsequent rolling.

As was shown in [14], the time of the electrostatic capture of the ME and, accordingly, the beginning of MP movement is only a small part of the conversion cycle. With a ME length of about 1–4 mm, it was experimentally established that the duration of the cycle is 10^{-4}–10^{-3} s, while the capture time is 1–3 µs. The separation time of the ME and ferroelectric surfaces is equal to (1–3) $\times$ 10^{-7} s: this process is determined by the action of elastic forces in the ME pressed to microspikes on the ferroelectric surface [15]. Thus, the duration of the cycle is determined by two processes: the electrostatic pressing of the ME (2) and the restoration of the shape of the ME after the separation of surfaces (4).

The electrostatic pressing time of the ME is a small fraction of the energy conversion cycle. To illustrate this statement, Figure 3 shows the ME pressing process from a distance of 1 µm, with a ME length of about 10 µm. The duration of this process in this case is 5×10^{-8} s.

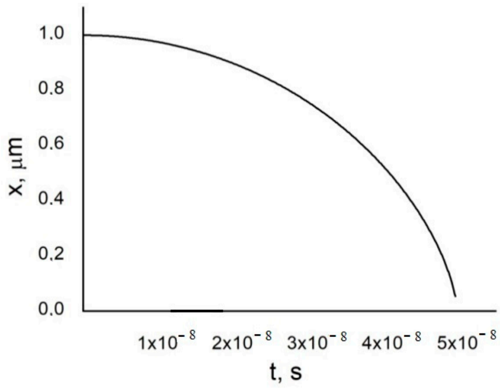

Figure 3. The process of pressing ME weighing 2×10^{-13} kg from a distance of 1 µm. V = 300 V; ferroelectric material parameters: ε = 1000 and d = 1 µm.

With the ME being a beam fixed at one end, the duration of the ME shape recovery process is inversely proportional to the natural frequency of the ME, f_0, which was confirmed experimentally. It was shown that the speed of the motor slider is limited by the frequency f_0: the maximum speed and output power are in the region of f_0 (see Figure 4 in [12]).

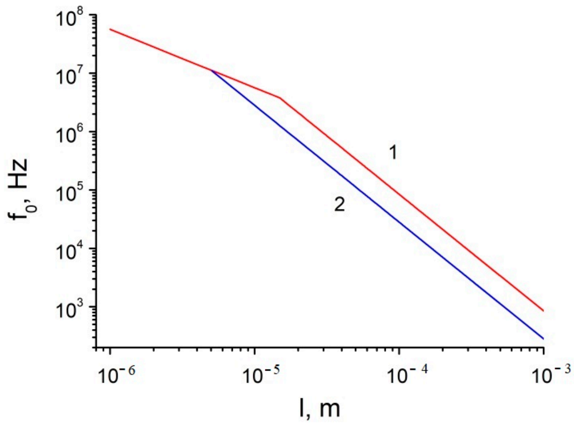

Figure 4. Dependence of ME natural oscillation frequency on its length at ME thicknesses (1) of 1.5 µm and (2) 0.5 µm.

The natural frequency of ME oscillations is calculated using the following equation:

$$f_0 = 0.162\, d_p / l^2 (E_Y/\rho)^{1/2} \quad (4)$$

Here, dp is the thickness of the ME, E_Y= 10^{11} N/m^2 is Young's modulus, and ρ = 8.25 $\times$ 10^3 kg/m^3 is the specific weight of the ME material.

The natural frequency of ME oscillations with thicknesses of 0.5 and 1.5 µm, depending on its length, is presented in Figure 4: when the ME length is comparable to its thickness, a dimensional effect manifests itself; therefore, in this case, a restriction is introduced to estimate the natural frequency: d_P = 0.1 l. With a ME length of about 10 µm, the initial state recovery time is 10^{-7} s (see Figure 4), while the pressing time is 10^{-8} s.

Thus, with a ME length of 10 µm, the natural frequency of ME oscillations reaches 10 MHz. In this case, according to our previous estimates of the maximum energy of the capacitive converter ($W_{S,max}$ = 80 J/m^2), we have $P_{S,max} = W_{S,max}\, f_0 = 8 \times 10^8$ W/m^2, or 8×10^2 W/mm^2, and $P_{V,max} = 1.6 \times 10^{17}$ W/m^3.

The latter estimate determines the specific power in the interelectrode gap, and it does not take into account the parameters of the engine elements, such as the thickness and specific weight of the stator and slider (or rotor), which depend on its specific design. Naturally, there may be several engine designs, and the particular design depends on the field of application.

3.2. Example of High-Power Capacitive Motor Design

Based on the described principle of energy conversion, it is possible to build both linear motors and capacitive rotation motors. An example of one of the structures of a capacitive rotation motor is schematically shown in Figure 5. It consists of two cylinders separated by a gap d_1: movable (rotating) and stationary. The surface of the first cylinder is covered with a thin layer of ferroelectric material. Free metal films, fixed at one end on the surface of the fixed cylinder, are attracted to the surface of the first cylinder.

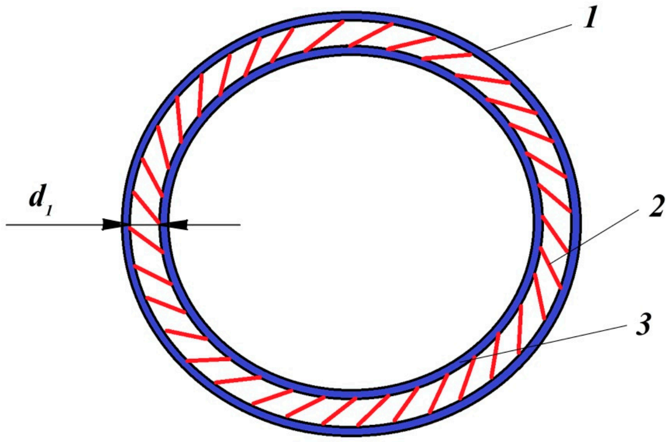

Figure 5. Schematic view of capacitive rotation motor. *1*—Stator: ferroelectric–metal structure on a substrate; *2*—free metal films ("petals"), fixed at one end on the stator surface; *3*—rotor.

The specific power of such an engine is significantly higher than the power of inductive rotation motors. By neglecting the weight of auxiliary structural elements (such as guides and current collectors), it can be evaluated as:

$$P_m = W_{S,max} h k \rho_S f_0 \quad (5)$$

where f_0 is determined by Equation (4), ρ_s is the specific weight of the cylinder wall material, h is the wall thickness and k is the surface filling factor by working elements (metal MEs). Assuming k = 0.8, l = 10 µm and h = 0.1 mm and considering that the MEs are made of beryllium bronze and the cylinders are made of steel, we obtain $f_0 \approx 10$ MHz and $P_m = 5 \times 10^8$ W/kg. This value of specific power exceeds the analogous characteristic of inductive motors by 5 orders of magnitude.

4. Discussion

In conclusion, it should be noted that for most designs of electro-mechanical energy converters, it is essential to have a gap between the fixed (stator) and moving (rotor or slider) parts of the device. The energy generated by such converters increases with a decrease in the gap. It was shown that in MFGM structures with a ferroelectric layer with a high electrical capacitance, when the gap size is reduced to a few nanometers, it is possible to achieve the limiting values of the energy density [11]. In this work, using the example of electrostatic motors based on MFGM structures [12], the maximum frequency of energy conversion in such motors is estimated, and the maximum specific power is determined.

The obtained estimates of the ultimate power of capacitive electrostatic motors based on nanogaps and thin films of ferroelectrics show broad prospects for their application, both for the creation of high-power electric motors with a wide field of applications and for the production of electric motors for micro- and macromachines. For example, a micromotor weighing 1 mg can develop a peak power of the order of 100 W.

In conclusion, it should be noted that for the long-term operation of capacitive film motors, they need effective forced cooling using liquid nitrogen. Naturally, taking into account the weight of the cooling systems the value of the specific power (watts per kilogram) will be reduced. To solve this problem, it is necessary to develop a specific engine design and evaluate it in an experimental study; it cannot be analyzed from general physical considerations. Therefore, the solution to this problem is beyond the scope of this article and will be the subject of further research.

However, engine operation modes for which forced cooling is not required are possible: e.g., the short-term activation of the forced mode with the subsequent transition to moderate power consumption by reducing the operating frequency.

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