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ATOMS, MOLECULES, OPTICS

# EELECTROMECHANICAL SELF-OSCILLATING SYSTEMS WITH FLEXIBLE FIELD ELECTRON EMITTERS


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**Abstract**. The paper presents the results of an experimental and theoretical study of electromechanical self-oscillations in systems consisting of a vacuum diode with a flexible field emission cathode, depending on its elastic properties and ability to deform. Self-oscillation regime experimentally demonstrated for field electron emitters based on carbon nanotubes and diamond microneedles. A mathematical model is developed to describe the electromechanical processes in the self-oscillating systems under consideration. Based on the analysis of the experimental data and simulation results, it is shown that the excitation of self-oscillations in a system with a flexible field emission cathode is determined by a combination of system parameters that result in a negative effective damping coefficient. The potential practical applications of self-oscillations of field emission cathodes in various micro- and nano-electromechanical systems are explored.

**Keywords**: *self-oscillations, field electron emission, microelectromechanical systems, carbon nanotubes, diamond*

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## 1. INTRODUCTION

Over the past two decades, considerable experimental evidence has been obtained for a phenomenon involving the emergence of stable undamped mechanical oscillations in field emission cathodes possessing certain mechanical flexibility and elasticity during electron emission under constant applied voltage [1–9]. This phenomenon was initially observed while studying field electron emission from individual carbon nanotubes (CNTs) and their yarns in an electron microscope chamber (see, for example, [1, 2]). However, in these first studies, the mechanism of such oscillations was not established. Later, mechanical oscillations occurring during electron emission were thoroughly investigated for silicon carbide nanowires [3, 4], individual multi-walled CNTs [5], microscale yarns twisted from CNTs [6], and field emission cathodes of macroscopic dimensions made from thin CNT membranes [7, 8]. These works demonstrated that this phenomenon represents electromechanical self-oscillations arising due to the fact that electric field that causes field emission current also leads to mechanical deformation of the elastic emitter.

Recently, it has been demonstrated that under certain conditions, self-oscillations can be observed not only for sufficiently flexible CNT-based cathodes or nanowires but also for diamond microscale emitters possessing high elastic modulus and relatively high rigidity [9]. Evidence has also been obtained that the self-oscillation effect can be one of the causes of degradation in CNT-based field emission cathodes [10, 11]. It was shown that during field electron emission from an array of aligned CNTs grown on a flat substrate, self-oscillations of individual nanotubes can occur, with amplitudes that can become sufficiently high and lead to partial or complete destruction of the nanotube.

In this work, based on characteristic experimental dependencies, we analyze the general properties of such systems and patterns determining the process of self-oscillation excitation, and discuss the prospects for practical application of this effect.

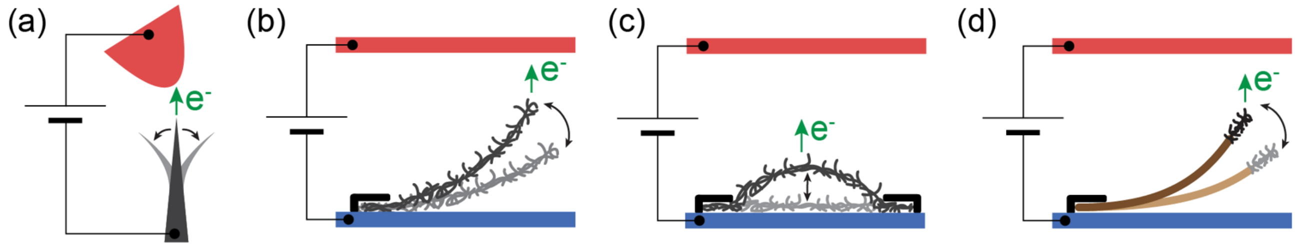


**Fig. 1.** Experimental setups in which electromechanical self-oscillations of various types of field electron emitters were observed. *a* - Individual nanoscale emitter. *b* - Emitter in the form of a CNT strip fixed at one end. *c* - Emitter in the form of a CNT yarn fixed at both ends. *d* - emitter based on metal elastic wire with CNT at the end

## 2. EXPERIMENTAL CONDITIONS AND RESULTS

### 2.1. Experimental Samples of Self-Oscillating Systems

As mentioned in the Introduction, electromechanical self-oscillations were experimentally observed for field electron emitters of various types. Moreover, the experimental geometry and measurement conditions could also differ significantly. Figure 1 shows diagrams of self-oscillating systems that were studied in works [3–9]. In the most general form, such systems represent a vacuum diode with a field electron emitter mounted on the cathode, possessing certain flexibility and elasticity. In the experiment, a constant voltage sufficient for observing field electron emission is applied between the cathode and anode of the diode.

Figure 1a shows the measurement setup used to study nanoscale emitters, for example, in the form of a single CNT [5], CNT yarn [2], or silicon carbide nanowire [3]. In this case, a metal tip anode was used, positioned in close proximity to the emitter apex, at a distance not exceeding several micrometers.

For macroscopic emitters, such as narrow strips made from thin membranes or yarns twisted from a large number of CNTs, self-oscillations were studied in a flat vacuum diode configuration, as shown in Fig. 1 *b*, *c*. Moreover, self-oscillations were observed with point attachment of such flexible emitters on a flat base both at one end [7] (Fig. 1*b*) and at both ends [6] (Fig. 1*c*). The self-oscillating mode was also implemented for an emitter in the form of a metal wire segment with a CNT membrane fragment attached to its end [8] (Fig. 1*d*). The oscillation parameters and excitation conditions were determined in this case by a combination of the wire's elastic properties and field emission characteristics of CNTs.

This paper examines the results of experiments conducted on emitters made from two types of materials with significantly different mechanical properties. One of the studied emitters was a needle-like diamond crystallite (microneedle) with a single-crystal structure, 100 μm in length, approximately 1 μm thick near the base, and with a tip radius of about 10 nm (Fig. 2*a*). A detailed description of the manufacturing technique for diamond microneedles and their structural properties is presented in works [12,13]. The elastic modulus value of such microneedles corresponds to that characteristic of bulk single-crystal diamond, and the typical quality factor of oscillations for a microneedle fixed at its base is around 1000 [9]. The second type of emitters studied in this work was a strip 5 mm long and 0.5 mm wide, cut from a thin membrane, which consisted of intertwined single-walled CNTs (SWCNTs) and had a thickness of about 0.1 mm (Fig. 3*a*). The manufacturing technique and structure of such SWCNT membranes are described in detail in works [7, 14]. The SWCNT strip emitters had a much lower elastic modulus compared to diamond microneedles, and the quality factor of the oscillatory system made from such strips, fixed at one end, typically did not exceed 10.

### 2.2 Diamond-based emitters

The results of experiments with the diamond microneedle are presented in Fig. 2. In this case, the experiment was conducted according to the scheme shown in Fig. 1*a*, inside a scanning electron microscope chamber (SEM, model FEI Versa 3D) at a vacuum level of about Torr. A sharpened tungsten wire was used as the anode, with its tip positioned several micrometers away from the diamond microneedle apex.

When a constant voltage was applied to the diode, field electron emission was observed from the tip of

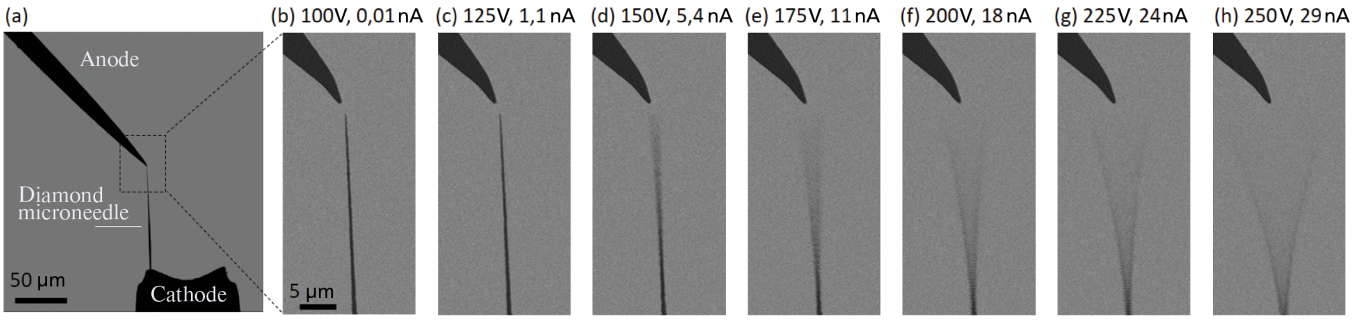


**Fig. 2.** a — SEM image showing the arrangement of elements during the field emission experiment with a diamond microneedle. b—h — SEM images of the diamond microneedle tip (cathode) and tungsten anode at various applied voltages and field emission currents

the diamond microneedle, with the current value measured using a picoammeter (Keithley 6487 model). When exceeding a certain threshold voltage value, stable undamped mechanical oscillations of the needle tip were observed with a frequency of about 1.4 MHz, close to the natural frequency of the microneedle. The oscillation amplitude increased with increasing voltage, which also led to an increase in field emission current, as shown in Fig. 2*b—h*. The threshold voltage for self-oscillations in the presented case was 150 V. At a voltage of 250 V, the maximum deviation of the needle tip from its axis was about 20°, which is close to the limit deformation at which there is a high probability of needle breaking at the point of maximum mechanical stress. It is important to note that the measured field emission current values did not change when the microscope electron beam was turned off. This means that the oscillations are not related to the electron beam action, as, for example, was observed in work [15]. Therefore, in the system under consideration, there are self-oscillations maintained by the applied constant voltage.

### 2.3. SWCNT-based emitters

The measurement results with an emitter in the form of a thin SWCNT strip are presented in Fig. 3. The experiments were conducted according to the scheme shown in Fig. 1*b*. The SWCNT strip was fixed on a flat metal base at one of its ends using conductive graphite tape. The base with the membrane strip was mounted on the cathode holder in the measuring vacuum cell parallel to the flat metal anode at a distance of 10 mm. The studies were conducted at a vacuum level in the cell of $10^{-6}$ Torr.

When a constant voltage was applied between the cathode and anode, the free end of the strip deflected towards the anode under the influence of electrostatic forces (Fig. 3 d). As the voltage increased, the membrane bending increased, and at 3000 V, field electron emission occurred from the CNTs located at the end of the strip. At 3300 V, the field emission current reached 25 μA, and the end of the strip began to oscillate, as shown in Fig. 3*c*. The time dependence of the field emission current, recorded using an oscilloscope, showed non-harmonic periodic oscillations (Fig. 3*c*, *b*). The oscillation frequency in this case was 140 Hz. The oscillation amplitude increased with increasing voltage; however, when exceeding a certain threshold voltage of about 3900 V, oscillations were

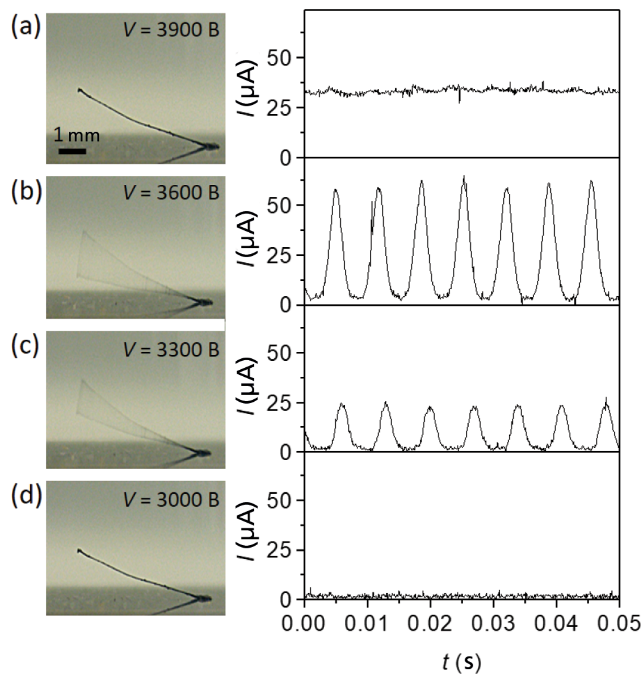


**Fig. 3.** *a-d* — Photographs of the emitter in the form of a CNT strip and corresponding dependencies of field emission current on time at various values of applied constant voltage. At the bottom of the photographs, the reflection of the CNT strip from the mirror surface of the metal base is visible (*a*)

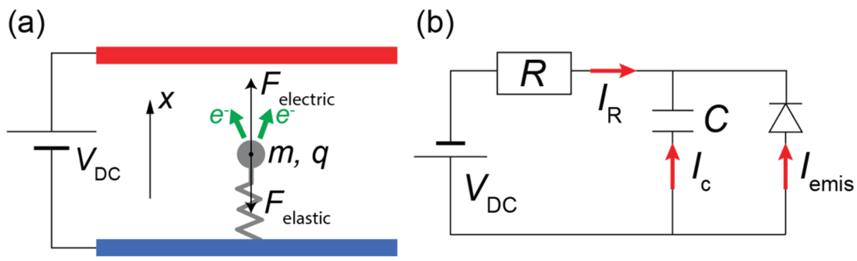


**Fig. 4.** *a* — Empirical representation of the system with a flexible field electron emitter. *b* — Equivalent electrical circuit of the system

not observed (Fig. 3*a*). Thus, in this case, self-oscillations in the system occurred only within a specific voltage range.

## 3. MODEL OF SELF-OSCILLATING SYSTEM

An empirical model describing electromechanical processes in a system with a flexible field electron emitter was previously proposed in works [4, 7]. In the present work, this model is used to analyze experimental data and determine the necessary general conditions for implementing the self-oscillating regime.

To describe the general patterns in the studied self-oscillating systems, let us consider a one-dimensional case of a material point motion under the influence of an electric field (Fig.4*a*). The equation of motion for a particle with effective mass and coordinate can be written in general form

$$mx = F_{electric} + F_{elastic} + F_{friction}.$$

Here

$$F_{elastic} = m\omega_0^2 x$$

is the elastic force determined by the natural frequency $f_0 = \omega_0 / 2\pi$;

$$F_{friction} = m(\omega_0 / Q)x$$

is the velocity-proportional internal friction force determined by the quality factor $Q$;

$$F_{electric} = dW / dx$$

is the electrostatic force (Coulomb force), which is related to the electrostatic energy $W = C(x)V^2/2$, determined by the voltage on the emitter $V$ and its effective capacitance $C(x)$, depending on the coordinate $x$. The voltage on the emitter $V$ is related to the voltage $V_{DC}$, which is applied to the capacitor plates, by Kirchhoff's equation

$$I_{emis} + I_C = I_R$$

for the equivalent electrical circuit of the system shown in Fig. 4*b*. Here $I_{emis}$ is the field emission current

$$I_C = \frac{d(C(x)V)}{dt}$$

is the capacitive current,

$$I_R = \frac{V_{DC} - V}{R}$$

is the current through the emitter body with resistance $R$. Analysis of the equation of motion when substituting small harmonic oscillations of the coordinate

$$x(t) = X_0 + X\cos(\omega_0 t)$$

and voltage near the equilibrium position

$$V(t) = V_0 + V\cos(\omega_0 t + \varphi_0)$$

shows that the effective damping coefficient in the system can be written as

$$\gamma = \gamma_0 - \Delta\gamma(V) = \frac{\omega_0}{Q} - const\frac{\partial I / \partial x}{1 + (\omega_0 \tau)^{-2}}V. \quad (1)$$

The following notations are introduced in this formula $\gamma_0$ is the damping coefficient of natural mechanical oscillations, $\Delta\gamma(V)$ is the change in damping coefficient due to the presence of field emission current. The constant

$$const = C'(m\omega_0^2 C)^{-1},$$

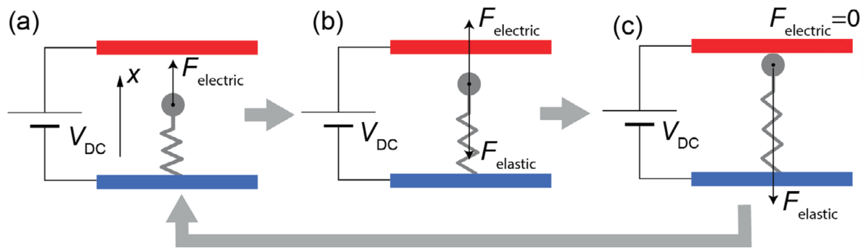


**Fig. 5.** *a-c* — Diagram of particle motion under the influence of electrostatic and elastic forces.

included in the expression for $\Delta\gamma$, includes parameters independent of voltage. The time constant

$$\tau = R_\Sigma C = \left(\frac{\partial I}{\partial V} + \frac{1}{R}\right)^{-1} C$$

is determined by both the emitter resistance $R$, and the differential resistance $(\partial I / \partial V)^{-1}$, i.e., the slope of the current-voltage characteristic of field emission.

From formula (1), it can be seen that at certain values of system parameters, the friction coefficient can take negative values. In this case, self-excitation of the system occurs and the oscillations become increasing in amplitude. Due to the presence of nonlinear terms in the original equation of motion, amplitude stabilization can occur, and as a result, self-oscillations will be observed, i.e., stable oscillations in a system with dissipation, maintained by an external energy source (DC voltage source) [16].

The role of field emission current can be clearly demonstrated using a model system shown in Fig. 5, where during the motion of a material point under electrostatic and elastic forces, its direct contact with the anode is possible. Fig. 5 a-c shows diagrams corresponding to the material point's movement towards the anode. At the moment of contact, the electrostatic force becomes zero, as all the charge of the material point instantly "flows" to the anode. After contact, the material point will move in the opposite direction under the force arising from elastic deformation until its charge is restored, after which the process repeats again. The return motion time and, consequently, the oscillation period in such a system will be determined by the time constant $RC$, i.e., the characteristic charging time of the system's capacitance.

In a system with a field emission cathode, when instead of anode contact, field electron emission occurs at a certain voltage value, the emitter charge also begins to "flow" to the anode, but not instantly, rather according to the emission current value determined by the current-voltage characteristic $I(V)$. The charge drainage due to field emission current, by reducing the voltage on the emitter and, consequently, the electrostatic force magnitude, effectively "pushes" the material point away from the anode, thereby implementing positive feedback in the system. Thus, the field emission current plays the role of a nonlinear element, which is an integral part of any self-oscillating system [16]. Moreover, as will be shown in the next section, the determining factor for the emergence of self-oscillations is the relationship between the time constant $\tau = R_\Sigma C$ and the natural oscillation period of the flexible cathode $2\pi\omega_0^{-1}$.

## 4. CONDITIONS FOR SELF-OSCILLATION EXCITATION

As discussed above, self-oscillations occur when the effective damping coefficient becomes negative. The obtained formula (1) allows formulating the physical causes of self-oscillations, i.e., the conditions under which the change in the damping coefficient $\Delta\gamma$, arising due to the presence of field emission current, exceeds the damping coefficient of mechanical oscillations of the emitter $\gamma_0 = \omega_0/Q$. A typical form of the function $\Delta\gamma$ $(V_{DC})$ is shown in Fig. 6 for parameters corresponding to experiments with CNT strips.

At the quality factor value $Q = 10$, obtained in the experiment, the curve $\Delta\gamma$ intersects the level $\gamma_0$ at points $V_{min}$ and $V_{max}$, which are the boundaries of the range where self-oscillations occur. The quality factor characterizes internal friction in the system, and at lower values of $Q$ (for example, at $Q = 5$ in Fig. 6*a*) the damping coefficient is positive everywhere and self-oscillations do not occur. At the same time, in the case of low friction (for example, at $Q = 50$ in Fig. 6*a*) self-oscillations are observed in the entire voltage range exceeding the threshold voltage. The latter case corresponds to the experiment with a diamond microneedle, where the quality factor was significantly higher than for the SWCNT strip, and self-oscillations did not disappear with increasing voltage up to the limiting values of field emission current and oscillation amplitude.

Fig. 6*b* shows the dependence of $\omega_0\tau$ on the applied voltage. It can be seen that self-oscillations occur under the condition $\omega_0\tau \approx\sim 1$, i.e., when the characteristic charging time of the system capacity is of the same order as the natural oscillation period of the flexible field emission cathode. In the low voltage region, the value of $\tau$ is constant, since $R_\Sigma \approx R$, and takes the maximum value $\tau = RC$. With increasing voltage, field emission current appears and decreases, as the system capacity recharging process accelerates due to the decrease in the differential resistance value $(\partial I / \partial V)^{-1}$. In the limit at high voltages $R_\Sigma = (\partial I / \partial V)^{-1}$, so tends $R_\Sigma$ to zero. Therefore, the condition $\omega_0\tau \sim 1$ is met when the emitter resistance $R$ and differential resistance $(\partial I / \partial V)^{-1}$ are of the same order of magnitude.

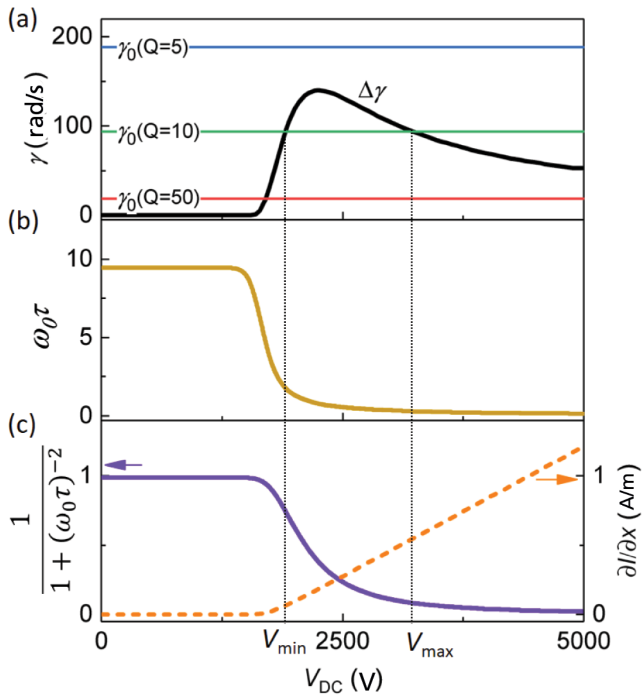


**Fig. 6.** *a-c* — Dependencies of various terms included in formula (1) on the applied voltage at model parameter values corresponding to the experiment with CNT strip.

The value $\Delta\gamma$ in formula (1) is determined by the product of functions $1/[1 + (\omega_0\tau)^{-2}]$ and $\partial I/\partial x$, typical graphs of which are shown in Fig. 6 c. It can be seen that that expression $1/[1 + (\omega_0\tau)^{-2}]$, like $\omega_0\tau$, tends to zero with increasing voltage. The current derivative $\partial I/\partial x$, on the contrary, increases with increasing voltage. Therefore, the product of these two functions reaches its maximum in a certain voltage range, where self-oscillations become possible.

It is important to note that the large value of the derivative $\partial I/\partial x$, which characterizes the degree of field emission current change when the emitter deviates from the equilibrium position, can enable the observation of self-oscillations for samples with relatively high rigidity, as is the case with the diamond microneedle (Fig. 2). Indeed, due to the chosen geometry of the anode, made in the form of a tip, a relatively small deviation of the diamond microneedle from the equilibrium position leads to a significant change in the field emission current due to the change in distance between its end and the anode. Also, the large value of $\partial I/\partial x$ provides higher efficiency in converting the applied DC voltage into AC voltage, which may be important for practical applications of the considered self-oscillating systems.

Thus, the analysis of formula (1) shows that to achieve a negative value of the effective damping coefficient, it is preferable to meet the condition $(\partial I/\partial V)^{-1} \sim R$ and $\omega_0\tau \sim 1$, while the parameters $\partial I/\partial x$, $Q$, $C'$ should have the maximum possible value, and the values of parameters $\omega_0$, $m$, $C$ should be minimal. With a negative damping coefficient, the oscillation amplitude increases with time, so the oscillations cease to be small, and further system behavior can be determined by solving the original nonlinear equation of motion. Over time, due to the presence of nonlinear terms, the oscillation amplitude stabilizes. The characteristics of the established self-oscillations are determined by the specific form of the system parameters' dependencies (capacitance, field strength, etc.) on coordinate and voltage. In general, the frequency of self-oscillations turns out to be slightly higher than the natural frequency of the flexible field emission cathode due to additional mechanical stress created as a result of its deformation under electrostatic force. Both the amplitude and frequency of self-oscillations increase with increasing electrical voltage and are largely determined by the dependence of the field emission current on coordinate.

The presented model adequately describes the experimentally observed dependencies for both macroscopic emitters based on membranes and CNT yarns, as well as micro- and nanoscale emitters in the form of a single diamond needle, carbon nanotube, or semiconductor nanowire. Thus, the phenomenon of electromechanical self-oscillations in systems with flexible field emission cathodes is of a general nature and can be observed for field emission cathodes of any type and size, provided certain conditions and system parameters ensure a negative value of the effective damping coefficient.

## 5. PROSPECTS FOR PRACTICAL APPLICATION OF SELF-OSCILLATING SYSTEMS

The practical use of self-oscillations of flexible field emitters in various micro- and nanoelectromechanical systems may be of significant interest. Such devices will not require an external AC source and can be used similarly to active microelectronic elements. First of all, this interest is related to the potential possibility of creating generator devices directly at the micro level. Furthermore, examples of electromechanical devices based on the considered effect can be DC to AC voltage converters, clock pulse generators, etc. Moreover, when using nanoscale emitters, the frequencies of electromechanical oscillations can reach values corresponding to the microwave range of electromagnetic radiation. Indeed, in experiments with diamond microneedles with characteristic transverse dimensions of about 1 μm, oscillation frequencies ranged from 100 kHz to several MHz. The oscillation frequency is inversely proportional to the characteristic size of the system in the first approximation, so for a single emitter with a diameter of 1 nm (for example, for a single carbon nanotube), the self-oscillation frequency will be in the range from 100 MHz to several GHz. This estimate coincides with the resonant frequencies values for individual nanotubes that are typically registered experimentally when excited by an external alternating electric field [17]. In the case of self-oscillations excitation during field electron emission from a single nanotube, the charge at its end will generate a high-frequency electromagnetic field in the surrounding space. The electron motion creating the electromagnetic wave in this case will be mainly due to the mechanical movement of the emitter tip, rather than electric current, as occurs in a standard transmitting antenna. Thus, when using self-oscillating electromechanical systems, it is potentially possible to create nanoscale electromagnetic wave sources and transmitting antennas based on them, which can be fully integrated into various microelectronic devices. Additionally, the availability of such sources also allows the integration of various nanoelectromechanical devices based on individual carbon nanotubes that use external macroscopic high-frequency oscillation generators in their operation. Such devices include, for example, ultra-sensitive mass or force sensors created based on individual oscillating carbon nanotubes or graphene films [18,19], devices for transmitting and receiving radio signals at the nanoscale [20,21], clock generators [22], electronic logic elements [23], and others.

## 6. CONCLUSION

The paper investigates the effect of electromechanical self-oscillations occurring in systems with flexible field electron emitters. The main types of systems exhibiting this effect are considered, and experimental results are presented for two representative types of emitters based on CNTs and diamond microtips, which had significant differences in mechanical properties. Using the developed mathematical model of the considered self-oscillating systems, requirements for mechanical (quality factor, natural frequency) and electronic (capacitance, resistance, current-voltage characteristic) system parameters necessary for the emergence of negative effective damping coefficient, at which the self-oscillating regime is realized, are determined. In particular, it is shown that the time constant, which determines the characteristic charging time of the system capacitance and is related to the electrical resistance of the emitter and the steepness of the current-voltage characteristic, should be of the same order of magnitude as the period of natural oscillations of the elastic field emission cathode. From a practical perspective, the self-oscillation effect may be of considerable interest due to the possibility of creating microelectromechanical generator devices based on it, such as DC-to-AC voltage converters, clock pulse generators, transmitting antennas, etc.

## FUNDING

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