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СТРОЕНИЕ И СВОЙСТВА НАНОРАЗМЕРНЫХ И МЕЗОСКОПИЧЕСКИХ МАТЕРИАЛОВ

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On the Frequencies of Collective Electron Oscillations in Conductive Nanofibers

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The resonant frequency of the collective electron oscillations in a conductive nanofiber is calculated. The friction force acting on the oscillating collective electrons from the side of the ions is taken into account. Due to the action of this force, the phase shift between the phase of the applied external homogeneous alternative electric field and the phase of the oscillating movement of the collective electrons appears. This phase shift is also calculated. Measured resonant frequency, phase shift, and/or resonant amplitude could be used to calculate the relaxation time τ responsible for the friction.

Рассчитана резонансная частота коллективных электронных колебаний в проводящем нановолокне. Учтена сила трения, действующая на коллективно колеблющиеся электроны со стороны ионов. Благодаря действию этой силы появляется фазовый сдвиг между фазой приложенного внешнего однородного переменного электрического поля и фазой колебательного движения коллективных электронов. Этот фазовый сдвиг также рассчитан. Измеренная резонансная частота, фазовый сдвиг и/или амплитуда резонанса могут использоваться для расчёта времени релаксации τ, ответственного за трение.

Розраховано резонансну частоту колективних електронних коливань у провідному нановолокні. Враховано силу тертя, яка діє з боку йонів на електрони, що колективно коливаються. Завдяки дії цієї сили з'являється фазовий зсув між фазою прикладеного зовнішнього однорідного змінного електричного поля та фазою коливного руху колективних електронів. Цей фазовий зсув також розраховано. Вимірювані резонансна частота, фазовий зсув і/або амплітуда резонансу можуть використовуватися для розрахунку часу релаксації τ, відповідального за тертя.

Key words: collective electron oscillations, phase shift, nanofibers.

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1. INTRODUCTION

Collective oscillations are the most prominent features of the excitation spectrum of all the many particle systems, from macroscopic bodies like metal samples, to clusters, molecules, atoms, and nuclei.

Collective electron oscillations determine, to a large extent, the cross-sections of interaction of all the above-mentioned objects with electromagnetic radiation and fast charged particles.

Langmuir or plasma frequency of the collective electron oscillations in bulk conductors is presented by the following relation [1]:

$$\omega_L = 4\pi e^2 n/(\varepsilon m). \quad (1)$$

Here, $e > 0$ is the elementary charge, m is the electron effective mass, n is the number of the electrons per unit volume of a sample (the electron density), and ε is the dielectric constant of a material. Langmuir oscillations are the oscillations of the collective electrons as a whole body without changes in the electron density, which remains a homogeneous one throughout a sample. Langmuir oscillations are the lowest energy oscillations. Higher energy oscillations correspond to plasma waves with wave vector of the oscillations $\mathbf{k}$, their frequency $\omega(\mathbf{k}) = \omega_L + \alpha|\mathbf{k}|^2$ (here, α is a constant) (see, *e.g.*, Ref. [2]).

Oscillations of the collective electrons as a whole body, without changes in the electron density in a carbon nanotube are studied in Ref. [2]. In this work, the homogeneous longitudinal collective electron oscillations with angular frequency inversely proportional to the square root of its length are found in a carbon nanotube.

Here, we shall consider the same type of the oscillations in a conductive nanofiber, taking into account the friction force acting on the collective electrons from the side of the ions. Due to the action of this force, the phase shift between the phase of the applied external homogeneous alternative electric field and the phase of the oscillating movement of the collective electrons appears. The relationship between this phase shift and the relaxation time τ responsible for the friction is found.

2. MODEL FOR NANOFIBER

Let us consider a conductive nanofiber of a length l, which is assumed to be essentially larger than the nanofiber diameter $2R$. The nanofiber is placed in a dielectric media with dielectric constant ε. We assume also that the nanofiber diameter is essentially smaller than the screen-

ing radius and the skin-effect penetration depth. This allows us to assume that the collective electrons move as a whole without deformation along the axis of a nanofiber relative to the ions in an oscillatory fashion.

Let us shift the electrons in the layer by a distance s along the axis of a cylinder. As a result of the shift, we have opposite charges on the bases of the cylinder, $q = \pm esN/l$ (here, N is the number of the collective electrons in the nanofiber). The two bases are situated rather far away from each other; so, they should be treated as two separate charged disks. A disk is a limiting case of flattened ellipsoid of revolution (ovoid), with half-axes $a < b = c$. Therefore, the capacitance of a disk is that of the ovoid at $a = 0$ and $b = c = R$, that is the capacitance of a disk situated in a vacuum $C = 2R/\pi$ [3]. The electrostatic energy of the two charged disks is $U_d = 2q^2/(2\varepsilon C)$ [4]. Taking into account that $q = \pm esN/l$, we have $U_d = \pi e^2 s^2 N^2/(2\varepsilon l^2 R)$. The interaction energy of the two charges, $e^2 s^2 N^2/(\varepsilon l^3)$, is $2R/(\pi l)$ times smaller than U_d and could be neglected. So, the force acting on all the collective electrons oscillating as a whole body (the lowest energy oscillations) could be approximated as $f_r = -\partial U_d/\partial s = -\pi e^2 s N^2/(\varepsilon l^2 R)$. This force is a restoring one. The restoring force can be presented as $f_r = -\omega_0^2 Nms$, where

$$\omega_0 = \sqrt{\frac{\pi N}{\varepsilon m R}}\,\frac{e}{l} = \sqrt{\frac{\pi R}{4l}}\,\omega_L \tag{2}$$

is the intrinsic frequency of the longitudinal oscillations of collective electrons in the nanofiber or the carbon nanotube [2].

3. FORCES ACTING ON COLLECTIVE ELECTRONS

We shall take into account the force acting from the side of the alternative homogeneous external electric field, applied along the axis of a nanofiber E, $-eNE$, the restoring force mentioned above, and a friction force, $-kN(\partial s/\partial t)$, a standard expression for the friction force. Here, $\partial s/\partial t$ is the velocity of the collective electrons. To calculate the k coefficient, let us consider stationary case with homogeneous external electric field, E_0, being applied along the axis of the nanofiber. In this case, $\partial s/\partial t = -(e\tau/m)E_0$, where $e\tau/m$ is the mobility of the collective electrons [5], τ is the corresponding relaxation time. As a friction force, $k(e\tau/m)NE_0$, together with the force arising from the external electric field, $-eNE_0$, comprise zero, we have $k = m/\tau$. Therefore, the total force acting on collective electrons is

$$f = -eNE - \omega_0^2 Nms - \frac{m}{\tau} N \frac{\partial s}{\partial t}. \tag{3}$$

We shall further consider a case when $E = E_0 \sin\omega t$.

4. NEWTON EQUATION AND ITS SOLUTION

Newton equation is $mN(\partial^2 s/\partial t^2) = f$. Let us look for the solution in the following form: $s = s_0 \sin(\omega t - \varphi)$, where φ is the phase shift. Then, the equation of motion yields:

$$\mathrm{tg}\varphi = \omega/[\tau(\omega_0{}^2 - \omega^2)] \text{ or } \tau = \omega \mathrm{ctg}\varphi/(\omega_0{}^2 - \omega^2). \tag{4}$$

It should be noted here that the phase shift φ is positive when $\omega_0{}^2 > \omega^2$. When $\omega_0{}^2 < \omega^2$ the phase shift φ is negative.

Newton equation also yields

$$s_0 = -(e\tau/m)E_0[\tau^2(\omega_0{}^2 - \omega^2)^2 + \omega^2]^{-1/2}. \tag{5}$$

According to Eq. (5), the amplitude s_0 has a maximum at $\omega = \omega_r$, where

$$\omega_r = \sqrt{\omega_0^2 - \frac{1}{2\tau^2}}. \tag{6}$$

It follows from Eq. (6) that the resonant frequency ω_r is shifted to lower value due to the friction. The maximum amplitude at the resonance is

$$s_{0m} = E_0 e\tau/(m\omega_0). \tag{7}$$

At $\omega_0\tau$ much larger than one, the resonant frequency tends to ω_0 and the maximum amplitude is very large, as should be.

5. DISCUSSION

The friction force acting on the oscillating collective electrons from the side of the ions has been taken into account. Due to the action of this force, the phase shift between the phase of the applied external homogeneous alternative electric field and the phase of the oscillating movement of the collective electrons appears. This phase shift has been calculated. The shift of the resonant frequency is calculated too, as well as the maximum amplitude.

Results of the measurements of the phase shift, the shift of the resonant frequency, and the maximum amplitude could be applied to calculate the relaxation time τ responsible for the friction. If the friction is not strong ($\tau^2\omega_0{}^2$ is essentially larger than unity), the resonant frequency tends to the intrinsic one, the phase shift is negligible and Eq. (5) yields as follows:

$$s_0 = eE_0/[m(\omega_0{}^2 - \omega^2)]. \tag{8}$$

Equation (8) shows also that in this limit ω_0 is really the intrinsic frequency of the longitudinal oscillations of collective electrons in a nanofiber or a carbon nanotube [2].

It should be noted here that the same calculations are also relevant for the dipole oscillations of the collective electrons in a fullerene molecule [6]. In this case, ω_0 is the intrinsic frequency of the dipole oscillations of the collective electrons in the fullerene molecule (see Eq. (9) in Ref. [6]).

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