A new loss mechanism in graphene nanoresonators due to the synthetic electric fields caused by inherent out-of-plane membrane corrugations

2012 J. Phys. D: Appl. Phys. 45 435102

(http://iopscience.iop.org/0022-3727/45/43/435102)

IOP PUBLISHING JOURNAL OF PHYSICS D: APPLIED PHYSICS

J. Phys. D: Appl. Phys. **45** (2012) 435102 (7pp) doi:10.1088/0022-3727/45/43/435102

A new loss mechanism in graphene nanoresonators due to the synthetic electric fields caused by inherent out-of-plane membrane corrugations

N E Firsova[1] **and Yu A Firsov**[2]

[1] Institute for Problems of Mechanical Engineering, Russian Academy of Sciences, St Petersburg 199178, Russia

[2] A F Ioffe Physical-Technical Institute, Russian Academy of Sciences, St Petersburg, Russia

E-mail: nef2@mail.ru

Received 4 July 2012, in final form 2 September 2012
Published 6 October 2012
Online at stacks.iop.org/JPhysD/45/435102

Abstract

For the first time the influence of out-of-plane deformations, which always exist in graphene, on the non-stationary processes is considered for the case of a monolayer graphene nanoresonator. A new loss mechanism for this device caused by dissipative intra-valley currents stipulated by synthetic electric fields is studied. These fields are generated by time-dependent gauge fields arising in a graphene membrane due to its intrinsic out-of-plane distortions and the influence of the external periodic electromotive force. The corresponding formula for the quality factor has a quantum mechanical origin and includes quantum mechanical parameters. This loss mechanism accounts for an essential part (about 40%) of losses in a graphene nanoresonator and it is specific just for graphene. The ways of minimization of this kind of dissipation (an increase in the quality factor of the electromechanical system) are discussed. It is explained why one can enhance the quality factor by correctly choosing a combination of strains (by strain engineering). In addition, it is shown that the quality factor can be increased by switching on a magnetic field perpendicular to the graphene membrane.

1. Introduction

The recent successful preparation of one-atom layer of carbons, i.e. graphene [1–3], gave rise to the development of two-dimensional (2D) physics. However, the question whether a strictly 2D crystal can exist was first raised theoretically more than 70 years ago by Peierls [4, 5] and Landau [6, 7]. They showed that in the standard harmonic approximation, the thermal fluctuations should destroy a long-range order, essentially resulting in a 'melting' of the 2D lattice at any finite temperature. Mermin and Wagner proved that a magnetic long-range order could not exist in one and two dimensions [8] and, later, the proof was extended to the crystalline order in 2D [9]. In fact, all the observed mono-atomic graphene samples have inherent stable corrugations, i.e. out-of-plane deformations (ripples, bubbles, wrinkles, etc), see for instance [10], where it was discovered that '. . . .graphene sheets are not perfectly flat, but exhibit intrinsic microscopic roughening. . . ' and also '. . . the observed corrugations in the third dimension may shed light on the subtle reasons behind the stability of 2D-crystals'. In [11] it was theoretically shown that these 'dangerous' fluctuations can, however, be suppressed by the anharmonic coupling between bending and stretching modes.

As a result, a 2D membrane can exist, but strong height thermal fluctuations (about 7 nm) would be present and ripples spontaneously appear. So, considering a graphene membrane with distortions, we study not a specific case, but the general one. Therefore, it is very important to study the influence of these out-of-plane deformations on physical processes in graphene. It was shown that these corrugations lead to the appearance of a pseudo-magnetic field (gauge field) (see, for instance, [12]). These inevitably existing fields in graphene have a magnitude of about several teslas.

However, only in [14] it was pointed out that in graphene one should also take into account that the so-called synthetic electric fields, which arise if pseudo-magnetic gauge fields turn to be time-dependent. Having this idea in mind, the authors of [14] calculated the damping rate (see (14) in [14]) for flexural phonons. Comparing it with the Kubo formula for conductivity (see (13) in [14]), they were able to interpret the dissipation caused by the synthetic electric fields and the current associated with them as Joule-type losses.

It is interesting that such fields were artificially created not long ago in another nontrivial system. It was done in a rubidium Bose–Einstein condensate (BEC). This field was produced as a time-dependent one which led to the appearance of the so-called synthetic electric fields [13]. In [13], the effective time-dependent vector potential for neutral atoms was created via the interaction with laser light generating a synthetic electric field simulating a charged condensed matter system in the array of neutral atoms.

Unlike the authors of [14] we consider a problem that enables application to devices. Namely, we investigate below the influence of ripples on the performance of graphene nanoresonators. As is well known, these devices have proven to be very useful in a large number of applications in different spheres of activities. In the series of new small-sized devices named nanoelectromechanical systems (NEMS) (see [15, 16]) the nanoresonators seem to be especially prospective.

First, materials such as piezoelectrics, silicon, metallic nanowires and carbon nanotubes were used for fabrication of nanoresonators. The best dynamic characteristics may be achieved as the resonator size and the mass scale down (which is assumed in the classical linear elastic Bernoulli–Euler beam theory). The resonance frequency may be essentially increased, while the quality factor Q will not become significantly worse (see [17, 18], for instance). This allows the sensitive detection of many microscopic physical phenomena and the measurement of parameters such as spin, force and molecular mass. These possibilities opened way for new investigations in biology: virus, protein, DNA detection, the detection of enzymatic activity, etc.

New opportunities arise if we come to materials such as graphene—the one carbon atom layer. For instance, recently a new especially precise method has been suggested for mass detection (with *zg* sensitivity) based on an NEM mass spectrometer [19] exploiting the advantage of graphene membranes.

Different modifications of graphene nanoresonators were studied, for instance, in [20–22]. It was shown that the damping rate increases linearly with resonance frequency. Different kinds of loss mechanisms are discussed in [20–25]. Some of them are common to all experimental setups: attachment losses, thermoelastic dissipation, etc. The others depend on the actuation scheme, for instance, the magnetomotive actuation scheme, capacitive coupling, etc. The surface-relative losses usually can be modelled by the distribution of effective two-level systems. All these possibilities were considered in detail in [24]. The authors of [24] pointed out that in the dissipation of graphene nanoresonators the essential part is due to the electrostatically coupled graphene layer and a doped metallic backgate, the energy being dissipated by increasing the electron–hole excitations and due to the interaction of a charge fluctuation with lower energy flexural phonons. Moreover, the authors of [26] investigated intrinsic loss mechanisms of monolayer graphene nanoresonators undergoing flexural oscillations. They found that spurious edge modes of vibrations, which arose intrinsically due to the different properties of edge atoms, were the dominant intrinsic loss mechanism that reduced the Q-factors. In [27] the authors studied two effects from the free edges on graphene nanoresonators, which are both responsible for reducing the quality factors. They are the imaginary edge vibration effect and the so-called artificial effect. It is shown that the armchair edges in graphene nanoresonators lead to higher values of Q-factors than the zigzag edges.

However, as was mentioned above, such approaches do not take into account very specific properties of 2D systems. It is well known that in graphene a significant role is played by gauge pseudo-magnetic fields [12] created due to the spontaneous generation of large-scale stable distortions of the 2D graphene surface (ripples, wrinkles, etc) responsible for its high bending rigidity. There exist expectations that these pseudo-magnetic fields can be used for the creation of new graphene nanoelectromechanics. Later it was discovered that these gauge fields might be varied by applying external strains [28–30] (strain engineering).

Note that in all the papers where graphene nanoresonators are investigated the authors consider a purely flat 2D model without taking into account the inevitably existing ripples. Also a major part of them did not analyse the microphysical reasons underlying the macrophenomena. In this paper we investigate the influence of ripples, which leads to a new dissipation mechanism in graphene nanoresonators. We call this new mechanism the Joule-type losses and we describe its quantum origin. We consider the synthetic electric fields, which inevitably arise during nanoresonator vibrations driven by an external time-dependent electromotive force. Our problem essentially differs from the one analysed in [14]. While in [14] the amplitude of vibrations in the long wave limit tends to zero, in our case of the external time-dependent electromotive force it is not so. Therefore, formula (14) from [14] cannot be directly used in our case of the long wave limit ($q \approx 1/L$, L is the characteristic length scale of a membrane). Nevertheless, the necessary procedures demonstrating that the physics of damping is of Joule type can be performed in our case as well. To analyse the Joule-type losses in our problem we use the analytical formulae for pseudo-vector potential $\vec{A}$ for a monolayer graphene sheet obtained by the authors of [31].

Below we also estimate the resonator intrinsic losses (quality factor Q) caused by the synthetic electric fields. We show that the corresponding contribution to $1/Q$ is very essential and leads to rather large Joule-type losses in graphene nanoresonators.

Of course, the role of synthetic electric fields in other NEMS may also be important.

In the last section of our paper we discuss the methods for the reduction of Joule-type losses in graphene nanoresonators.

2. The Model

We consider a graphene nanoresonator (see for instance figure 1 in [21] or figure 1 in [22]). For a monolayer graphene membrane described by the equation of surface $z = h(x, y)$, for any atom the vectors directed to three nearest neighbours have the form (see for instance [31])

$$\vec{u}_1 = a(\sqrt{3}/2, 1/2), \qquad \vec{u}_2 = a(-\sqrt{3}/2, 1/2),$$
$$\vec{u}_3 = a(0, -1).$$

Here $a = 2.5$ Å is the distance between nearest atoms in the lattice; $h = h(x, y)$ is the distance from a point on a membrane to its projection (x, y) in the XOY-plane.

The following formulae for the gauge field vector potential $\vec{A}$ were obtained in [31] (see also [32]):

$$A_x(\vec{r}) + \mathrm{i}A_y(\vec{r}) = -\sum_j \delta t_j(\vec{r})\mathrm{e}^{\mathrm{i}\vec{u}_j\vec{K}}$$
$$= -\frac{\varepsilon_{\pi\pi}}{2}\sum_j [(\vec{u}_j\cdot\nabla)\nabla h]^2\mathrm{e}^{\mathrm{i}\vec{u}_j\vec{K}}, \tag{1}$$

$$A_x = -\tfrac{1}{2}A^0[(h_{xx})^2 - (h_{yy})^2]a^2,$$
$$A_y = A^0[h_{xy}(h_{xx} + h_{yy})]a^2, \tag{2}$$

$$A^0 = \frac{3}{4}\cdot\frac{\varepsilon_{\pi\pi}}{e}\cdot\frac{c}{V_\mathrm{F}}. \tag{3}$$

Here V_F is the Fermi velocity, the energy $\varepsilon_{\pi\pi}$ characterizes the strength of valence bonds, $\varepsilon_{\pi\pi} = 2.89$ eV $\vec{K} = a^{-1}(4\pi/3\sqrt{3}, 0)$ is the Dirac point position, t_j is the exchange integral with the jth nearest neighbour, $j = 1, 2, 3$ (we consider the tight binding approximation), and A^0 has the same dimension as the vector potential. The products of the expressions in square brackets in the formulae for A_x, A_y in (2) by a^2 are dimensionless, i.e. they are numerical coefficients, their magnitudes being dependent on the deflection depth of the graphene membrane (we take into consideration large-scale deformations such as ripples, wrinkles, etc) and also on the lattice constant value for the current moment of time. Note that in [33, 34] (see also [12]) a different formula for pseudo-magnetic vector potential was considered. The difference between these two formulae is discussed in [12, 32].

When alternating electromotive field directed along the OZ-axis is switched on, the vectors $\vec{u}_j$ should get the time-dependent variation $\Delta\vec{u}_j(t)$, which is proportional to $E_0\sin\omega t$, i.e. we have in the linear approximation

$$a(t) = a_0 + \Delta a(t), \tag{4}$$

where $a_0 = 2.5$ Å is the initial value of the parameter a at $t = 0$ and

$$\Delta a(t) = \eta_1 E_0\sin\omega t = a_{00}\sin\omega t. \tag{5}$$

Here the coefficient η_1 has dimensionality (cm^2 V^{-1}).

Similarly we assume

$$h(x, y, t) = h_0(x, y) + \Delta h(t), \tag{6}$$

$$\Delta h(t) = \eta_2 E_0\sin\omega t\cdot\cos\left(\frac{\pi x}{2L}\right) = h_{00}\sin\omega t\cdot\cos\left(\frac{\pi x}{2L}\right), \tag{7}$$

where $z = h_0(x, y)$ is the equation of the initial membrane surface form and η_2 has the same dimensionality as η_1. Both of them describe an interaction with actuating field on the microscopic level. The coefficients η_1, η_2 may, generally speaking, depend on x, y, but they do not essentially influence the main results of our paper. The last factor in (7) is connected with the clumping of the opposite membrane edges by $x = \pm L$ (doubly clumped).

Note that, as is shown in [21], the linear approximation is reasonable if the deflection amplitude of the graphene nanoresonator vibrations does not exceed 1.1 nm. As we assume in our calculations below, it equals 1 nm really. Therefore, our assumption about linearity is quite reasonable. The nonlinear problem was studied in a number of works (see [35] and references therein) as well. However, we restrict ourselves here to the linear case.

In the presence of the external actuating periodic electric field $E_0\sin\omega t$ the gauge field vector potential $\vec{A}$ will depend on time, i.e. in the monolayer graphene membrane the so-called synthetic electric field arises:

$$\vec{E}_\mathrm{syn} = -c^{-1}\vec{A}_t. \tag{8}$$

Let $\omega \approx \omega_\mathrm{res}$, where ω_res is the eigenfrequency of our nanoresonator. Then substituting (2)–(7) into (8) we find

$$(\vec{E}_\mathrm{syn})_x = -c^{-1}(\vec{A}_x)_t$$
$$= \frac{A^0}{c}\cdot\{[(h_{xx}^2 - h_{yy}^2)(\Delta a)_t + ah_{xx}(\Delta h)_{xxt}]a\}, \tag{9}$$

$$(\vec{E}_\mathrm{syn})_y = -c^{-1}(\vec{A}_y)_t$$
$$= -\frac{A^0}{c}\cdot\{h_{xy}[2(h_{xx} + h_{yy})(\Delta a)_t + a(\Delta h)_{xxt}]a\}. \tag{10}$$

We can write formulae (9) and (10) in the form

$$(\vec{E}_\mathrm{syn})_x = E^0(\omega)h_{00}I_x\cos\omega t,$$
$$(\vec{E}_\mathrm{syn})_y = E^0(\omega)h_{00}I_y\cos\omega t, \tag{11}$$

where $h_{00} = (E_0\eta_2)$ is the resonator oscillation amplitude (deflection) and

$$I_x = \left\{\left[\left(\frac{\eta_1}{\eta_2}\right)(h_{xx}^2 - h_{yy}^2) - ah_{xx}\left(\frac{\pi}{2L}\right)^2\cos\left(\frac{\pi x}{2L}\right)\right]a\right\}, \tag{12}$$

$$I_y = \left\{h_{xy}\left[2\left(\frac{\eta_1}{\eta_2}\right)(h_{xx} + h_{yy}) - a\left(\frac{\pi}{2L}\right)^2\cos\left(\frac{\pi x}{2L}\right)\right]a\right\}, \tag{13}$$

$$E^0(\omega) = \frac{3}{4}\cdot\frac{\varepsilon_{\pi\pi}}{e}\cdot\frac{\omega}{V_\mathrm{F}}. \tag{14}$$

It is worth noting that the dimensionless quantities I_x, I_y do not turn to zero even by zero deflection because of the presence of deformations such as ripples and wrinkles in graphene. It follows from (11)–(14) that after time averaging we have

$$(\vec{E}_\mathrm{syn})^2 = (\vec{E}_\mathrm{syn})_x^2 + (\vec{E}_\mathrm{syn})_y^2 = (E^0(\omega))^2h_{00}^2(I_x^2 + I_y^2)/2. \tag{15}$$

Note that our problem differs very much from the one considered in [14]. In particular, in [14], where the damping rate of flexural phonons due to the Joule-type losses is calculated, their vibrational amplitude tends to zero in the long wave limit. However, in our case the amplitude of the membrane vibration does not tend to zero because of the external electromotive force. Nevertheless, the corresponding procedure can be carried out in our case as well. As was explained, the dissipation mechanism in a monolayer graphene resonator driven by a time-dependent electromotive force may be considered as Joule-type losses (like the problem of finding flexural phonon damping rate in [14]). So we can write in our problem the Joule-type losses $\Delta\varepsilon_J$ for the period $T = 2\pi/\omega$ in the form

$$\Delta\varepsilon_J \approx 2\pi(\vec{E}_{\rm syn})^2\sigma\frac{L_xL_y}{\omega}, \tag{16}$$

where L_x, L_y are membrane sizes and σ is the 2D conductivity (for more details see below). From (15) and (16) we obtain

$$\Delta\varepsilon_J \approx \pi(E^0(\omega))^2h_{00}^2(I_x^2+I_y^2)\sigma\frac{L_xL_y}{\omega}. \tag{17}$$

Note that in (16) and (17) we took into consideration the contribution from only one Dirac cone K (from only one valley, i.e. from only one sublattice). We discuss the correction connected with the role of another valley K^* in summary and conclusions.

From formulae (14) and (17), we see that the damping rate linearly depends on frequency. It is interesting that in nanoresonators, on the basis of carbon nanotubes, the dissipation mechanism connected with electron tunnelling through a vibrating nanotube also causes the damping rate to linearly depend on frequency [25].

The general losses of graphene nanoresonators include parts of different nature:

$$Q^{-1} = Q_0^{-1} + Q_J^{-1}. \tag{18}$$

Here Q_0^{-1} is connected to the dissipation mechanisms studied earlier by the other authors (see for instance [20–25]), and Q_J^{-1} is connected to the mechanism considered and analysed for the first time in this paper.

We introduce a quality factor Q_J connected to the Joule-type losses as follows:

$$Q_J^{-1} = \frac{\Delta\varepsilon_J}{\varepsilon_{\rm total}}. \tag{19}$$

Here $\Delta\varepsilon_J$ is found from (17), and the total energy is defined as follows:

$$\varepsilon_{\rm total} = N\cdot m_{\rm at}\cdot\omega^2\cdot h_{00}^2, \qquad N = L_xL_y/(a^2 3\sqrt{3}/2),$$

where N is the number of atoms in the graphene membrane, $m_{\rm at}$ is the atom mass and h_{00} is the oscillation amplitude of the membrane. So we obtain

$$Q_J^{-1} = \pi\frac{3\sqrt{3}}{2}\cdot\frac{(E^0(\omega))^2\cdot\sigma[a^2(I_x^2+I_y^2)]}{\omega^3 m_{\rm at}}. \tag{20}$$

Note that using equation (13) for $E^0(\omega)$ and the general formula of the form $\sigma \cong \frac{e^2}{h}\frac{\varepsilon_{\rm F}\tau}{h} \cong \frac{e^2}{h}k_{\rm F}l$ for conductivity, we see that the quality factor (20) does not depend on the electron charge e. It is connected to the fact that the synthetic fields are chargeless ($\mathrm{div}\vec{E}_{\rm syn} = \mathrm{div}\vec{A}_t = 0$). The fact that there is no electric charge associated with the 'electric' and 'magnetic' fields created by structural deformations was mentioned in [32]. We see that their 'structural electrodynamics' generated by external time-dependent activating forces is also chargeless.

Note also that our formula (20) for the Joule-type loss quality factor contains the Planck constant h and the energy $\varepsilon_{\pi\pi}$ characterizing the strength of the valence bonds. So the considered loss mechanism due to the intrinsic synthetic fields has a quantum origin. In addition, it was shown in [14] (see formula (45) and a discussion thereabout) that the 2D conductivity σ does not (or weakly) depend on the activating field frequency in graphene. But for estimating the approximate value of the Joule-type losses in the next section we shall take the measured value of σ using experimental data [37].

Note that in experimental work [26] the authors wrote that 'it was determined that the intrinsic loss mechanism in graphene can nearly be eliminated through applied tensile mechanical strain'. As the applied tensile mechanical strain decreases the values I_x, I_y it is clear from our formula (20) that the quality factor should increase. So the loss mechanism considered in our paper explains these experimental results.

3. The Joule-type losses estimate and the ways of their minimization

Let us estimate the value of the Joule-type losses using formula (20) and compare the calculated value with experimental data. We consider the graphene nanoresonator with frequency $\omega_{\rm res} \approx 130\,\mathrm{MHz}$ investigated in [21]. For our case $m_{\rm at} = 12\,1.67\times10^{-24}\mathrm{g}$ and we have $m_{\rm at}\cdot\omega^3 \approx 42\,\mathrm{g\,s^{-3}}$.

From formula (14) we obtain

$$E^0(\omega) = \frac{3}{4}\cdot\frac{\varepsilon_{\pi\pi}}{e}\cdot\frac{\omega}{V_{\rm F}} \approx 3/4\times3\times\frac{1.3}{3}\,\mathrm{V\,cm^{-1}} = 3.9/4\times\frac{1}{300}\mathrm{CGSE}. \tag{21}$$

The conductivity for our case was not written in [21] for the graphene sample mentioned above. So we take it from another paper [35] where the parameters of the experiment are close to the ones in [21]. From [35], for the concentration value $n = 2.5\times10^{11}\,\mathrm{cm^{-2}}$ we find in figure 1 that $\sigma \approx 1.2\times10^9\,\mathrm{cm\,s^{-1}}$ (for a sample of good quality).

Estimate now the factor $a^2(I_x^2+I_y^2)$ in (20). In [21] it is demonstrated that the membrane oscillation critical amplitude after which the nonlinearity becomes essential is equal to 1.5 nm. We assume it to be $h_{00} \approx 1\,\mathrm{nm}$. It is naturally to think that $\Delta a/a \approx h_{00}/h \approx 0.1$ i.e.

$$\eta_1/\eta_2 \approx \Delta a/h_{00} \approx (\Delta a/a)\cdot(a/h_{00}) \approx 2.5\times10^{-2}.$$

Let us estimate the first term in the expression for $a^2(I_x^2+I_y^2)$, using formulae (12) and (13). Taking into consideration that a graphene membrane surface has corrugations

and assuming for simplicity the deformation height (depth) and the basis (length, width) to have close sizes we find $a^2 \cdot I_x^2 \approx (6.25 \times 10^{-4} a^4 \cdot (h_{xx}^2)^2 + \cdots) \approx (6.25/81) \times 10^{-8}$. When estimating, we assumed the deformation radius to be $\delta_x \approx 15\,\text{nm}$, and $\delta h/\delta_x \approx 2$. Other terms in the formula for $a^2(I_x^2 + I_y^2)$ can be estimated similarly. Therefore, we obtain $a^2(I_x^2 + I_y^2) \approx 0.7 \times 10^{-8}$. Hence, we find from (20) and (21) the approximate theoretical numerical value for the Joule-type losses in the sample mentioned above $Q_J^{-1} = \Delta\varepsilon_J/\varepsilon_{\text{total}} \approx 3 \times 10^{-5}$. Since the experiment in [21] gives the result $Q \approx 14\,000$ we see that the Joule-type losses are responsible for about 40% of the total losses and our model gives a reasonable magnitude of the damping rate.

It is interesting that in [22] for the sample with about the same resonance frequency the authors obtained the quality factor $Q \approx 100\,000$. The measured increase in the quality factor to our point of view was obtained by the authors because they used tension. From our formula (20) it is clearly seen that in this case the factor $(I_x^2 + I_y^2)$ decreases, which enhances the quality factor, i.e. the measured increase in quality factor is in accordance with our theory.

Now consider the question, how can one minimize the Joule-type losses Q_J^{-1}? It is clear that the expressions I_x, I_y in (12), (13), and consequently the losses (20) can be reduced by varying the form of the function $h(x, y)$ with the help of strains of different kinds. The fact that one can increase the quality factor by such actions was studied experimentally. From formula (20) this experimental result is absolutely understandable.

One can decrease Joule-type losses also by switching on a magnetic field perpendicular to the graphene membrane plane. In fact, in [38], figure 4, we see that for temperature $T = 300\,\text{K}$ the magnetic fields less than 8 T are not quantizing (they are classical) and longitudinal resistivity is an increasing function of field (in [39], figure 3(a), $T = 5\,\text{K}$, a nonquantizing magnetic field is much less and resistivity is again an increasing function). So, for example for $H = 6\,\text{T}$ we have ([38], figure 4) that the Joule losses Q_J^{-1} are about six times less. We saw above that the percentage of these losses is about 40%. Consequently, the quality factor would be one and a half times more if the magnetic field $H = 6\,\text{T}$ were switched on.

Since the graphene membrane surface has corrugations external magnetic field components parallel to the vibrating membrane can arise. These components play the role of magnetomotive force. Hence, as is shown in [40, 41], we can obtain an extra damping and the increase in Q may be less.

Note that the formulae obtained using the Boltzmann equation stops to be correct when a quantization in magnetic field of Landau-type starts. Nevertheless, the tendency of the losses decreasing remains valid though the form of the dependence may be different. The experimental investigation of the dependence $Q(H_\perp)$ appeared just now (see [42], figure 3(c)) for the temperature $T = 5\,\text{K}$ (i.e. the fields about 6 T are quantizing). However, for the magnetic field 6 T they measured an increase in Q of about 30%. The role of the synthetic fields was not discussed in [42].

4. Summary and conclusions

In this paper, for the first time, the influence of the inevitably existing out-of-plane deformations on the graphene nanoresonator quality factor was taken into account. As a result, a new quantum dissipation mechanism for graphene nanoresonators, i.e. 'Joule-type' losses caused by synthetic electric fields was considered. For the linear case (i.e. electromotive alternating force is rather weak and temperature is not very low) the formulae for Joule-type losses were obtained. However, though a graphene lattice consists of two sublattices in formula (20) for quality factor derivation we took into consideration the contribution from only one valley K (one sublattice). Note that in the ideal case, i.e. if there is time-reversal symmetry, [36], the gauge fields in K and K^* have opposite directions and equal magnitudes, and the two valley currents compensate for each other. However, this question was analysed in [14], where it was shown that the two corresponding valley currents do not compensate for each other if we take into account an inter-valley Coulomb drag effect and inter-valley scattering on short-range impurities. So, in fact additionally we should also have in (20) a dimensionless factor, which depends on the relaxation times τ_D and τ_v, where τ_D^{-1} is the inter-valley Coulomb drag responsible for the drag effect and τ_v^{-1} is the inter-valley scattering rate due to the short-range impurities. But such a theory is beyond the scope of this paper.

We would like to stress especially that while in majority of papers dedicated to nanoresonators the phenomenological approach within the framework of the continuum nonlinear elastic model (see [43] and last review-like paper [35]) was used (nonlinear Duffing oscillator), our results for Joule-type losses are obtained on the basis of microscopic theory taking into account the specific features of graphene. Although the membrane vibration is supposed to be classical, the mechanism of losses in graphene nanoresonator is described within the framework of quantum solid-state physics. In particular, our main formula for Joule losses and quality factor includes quantum mechanical parameters $\varepsilon_{\pi\pi}$, V_F.

Using the formula obtained for the Joule-type losses, we calculated their magnitudes approximately. This estimate shows that their contribution to the general dissipation appears to be about 40%.

The possible methods of reduction of the Joule-type losses are as follows.

- The application of strain engineering methods to minimize quantities I_x, I_y and consequently to enhance Q.
- Switching on a magnetic field perpendicular to the graphene membrane.

Note that just now a paper [44] has appeared where it was stated that in polycrystalline graphene sheets of multilayer graphene nanoresonators measured losses proved to be much larger than that calculated for monolayer graphene. The authors in [44] mentioned that it could have been due to angle misorientations of grain boundaries, which generate out-of-plane buckling (see figure 2 in [44]). These types of corrugations also should cause artificial gauge fields and lead to the microscopic mechanism

of losses suggested in our paper. In [44] it was also mentioned the significant Q-factor increasing with reduction in height of out-of-plane buckling under a tensile strain. This strain-engineering method to reduce losses was theoretically found by us for the first time in [45]. It would also be interesting to study Q-factor increasing in CVP-grown graphene, when the external perpendicular magnetic field is switched on, its magnitude and temperature being varied.

Although the prediction of quality factor increase due to the magnetic field switch on perpendicular to the membrane was first published in [45] by us, the experimental investigation of the dependence of Q on $B_\perp$ is done just now (see figure 3(c) in [42]) in the quantum limit for the temperature $T = 5$ K. The increase in Q in the quantizing magnetic field $B_\perp$ was really observed and its value was proved to be about 30%. Note that authors of [42] think that in the standard 2D model of graphene (without out-of-plane corrugations) this effect may be due to the magnetization of graphene in the quantum Hall limit which changes electromechanics.

Note also that the synthetic electric currents we considered in this paper lead not only to Joule-type losses but cause dissipation due to their interaction with currents arising on a gate. Recently, in [46] the current-induced force theory was developed for the purely flat 2D case. This theory can be applied for the investigation of many dissipation mechanisms enumerated in section 1 in a purely 2D case. We hope to analyse in the next paper the above-mentioned current–current losses mechanism modifying the methods proposed in [46] to take into consideration the out-of-plane deformations.

In this paper we found that taking into account the various corrugations inevitably existing in graphene membranes gives an essential contribution to the magnitude of the graphene nanoresonator quality factor in the megahertz and gigahertz frequency ranges. Obviously, this mechanism should also influence the nonlinear electromagnetic response of graphene in the terahertz and optical frequency ranges. In transport phenomena we should also take it into consideration. So for exact estimates of losses when constructing different kinds of devices where graphene is used in the non-stationary regime in branches such as photonics and optoelectronics, we should also take into account the generation of synthetic electric fields and investigate their influence. Some ideas to minimize its negative action were also outlined.

References

[1] Novoselov K S, Geim A K, Morozov S V, Jiang D, Zhang Y, Dubonos S V, Grigorieva I V and Firsov A A 2004 Electric field effect in atomically thin carbon films *Science* **306** 666

[2] Novoselov K S, Geim A K, Morozov S V, Jiang D, Katsenelson M I, Grigorieva I V, Dubonos S V and Firsov A A 2005 Two-dimensional gas of massless Dirac fermions in graphene *Nature* **438** 197

[3] Zhang Y *et al* 2005 Experimental observation of quantum Hall effect and Berry's phase in graphene *Nature* **438** 201

[4] Peierls R E 1934 Bemerkungen uber Umwandlungstemperaturen *Helv. Phys. Acta* **7** 81–3

[5] Peierls R E 1935 Quelques proprietes typiques des corpes solides *Ann. I. H. Poincare* **5** 177–222

[6] Landau L D 1937 Zur Theorie der Phasenumwandlungen II *Phys. Z. Sowjetunion* **11** 26–35

[7] Landau L D and Lifshitz E M 1980 *Statistical Physics* part I (Oxford: Pergamon)

[8] Mermin N D and Wagner H 1966 Absence of ferromagnetism or antiferromagnetism in one- or two-dimensional isotropic Heisenberg models *Phys. Rev. Lett.* **17** 1133–6

[9] Mermin N D 1968 Crystalline order in two dimensions *Phys. Rev.* **176** 250–4

[10] Meyer Jannic C, Geim A K, Katsnelson M I, Novoselov K S, Booth T J and Roth S 2007 The structure of suspended graphene sheets *Nature* **446** 60–3 (arXiv:cond-mat/0701379)

[11] Fasolino A, Los J H and Katsnelson M I 2007 Intrinsic ripples in graphene *Nature Mater.* **6** 858–61

[12] Vozmediano M A H, Katsnelson M I and Guinea F 2011 Gauge fields in graphene *Phys. Rep.* **496** 109

[13] von Oppen F, Francisko G and Eros M 2009 Synthetic electric fields and phonon damping in carbon nanotubes and graphene *Phys. Rev.* B **80** 075420

[14] Lin Y-J, Compton R L, Jimenez-Garcia K, Phillips W D and Spielman I B 2010 A synthetic electric force acting on neutral atoms, arXiv:1008.4864v1 [cond-mat-quant-gas]

[15] Cleland Andrew N 2003 *Foundation of Nanomechanics* (Berlin: Springer)

[16] Ekinci K L and Roukes M L 2005 Nanoelectromechanical systems *Rev. Sci. Instrum.* **76** 061101

[17] Gaidarzhy A 2007 High quality gigahertz frequencies in nanomechanical diamond resonators, arXiv:0710.2613 [cond-mat]

[18] Eom K, Park H S, Sung E D and Kwon T 2011 Nanomechanical resonators and their applications in biological/chemical detection: nanomechanics principles *Phys. Rep.* **503** 115

[19] Atalaya J, Kinaret J M and Isacsson A 2010 Nanomechanical mass measurement using nonlinear response of a graphene membrane *Europhys. Lett.* **91** 48001 (arXiv:0911.0953.v2 [cond-mat])

[20] Bunch J *et al* 2007 Electromechanical resonators from graphene sheets *Science* **315** 490–3

[21] Chen C *et al* 2009 Performance of monolayer graphene nanomechanical resonators with electrical readout *Nature Nanotechnol.* **4** 861

[22] Eichler A *et al* 2011 Nonlinear damping in mechanical resonators based on graphene and carbon nanotubes *Nature Nanotechnol.* **6** 339

[23] Sazonova V *et al* 2004 A tunable carbon nanotube electromechanical oscillator *Nature* **431** 284

[24] Seoanez C, Guinea F and Castro Neto A N 2007 Dissipation in graphene and nanotube resonators *Phys. Rev.* B **76** 125427

[25] Lassagne B, Tarakanov Y, Kinaret J, Sanchez D-G and Bachtold A 2009 Coupling mechanics to charge transport in carbon nanotube mechanical resonators *Science* **325** 1107

[26] Kim S Y and Park Harold S 2009 The importance of edge effects on the intrinsic loss mechanisms of graphene nanoresonators *Nano. Lett.* **9** 969

[27] Jiang J W and Wang J S 2012 Why edge effects are important on the intrinsic loss mechanisms of graphene nanoresonators *J. Appl. Phys.* **111** 054314

[28] Pereira V P and Castro Neto A N 2009 All-graphene integrated circuits via strain engineering *Phys. Rev. Lett.* **103** 046801

[29] Low T and Guinea F 2010 Strain-induced pseudo-magnetic field for novel graphene electronics *Nano. Lett.* **10** 3551

[30] Guinea F, Katsnelson M I and Geim A K 2010 Energy gaps, topological insulator state and zero-field quantum Hall effect in graphene by strain engineering *Nature Phys.* **6** 30–3 (arXiv:0909.1787 [cond-mat])

[31] Kim E-A and Castro Neto A N 2008 Graphene as an electronic membrane *Europhys. Lett.* **84** 57007
[32] Castro Neto Antonio H 2009 Les Houches *Notes on Graphene Les Houchs School on Modern Theory of Correlated Electron Systems (11–29 May)* (arXiv:1004.3682)
[33] Morozov S V, Novoselov K S, Katsnelson M I, Schedin F, Jiang D and Geim A K 2006 Strong suppression of weak localization in graphene *Phys. Rev. Lett.* **97** 016801
[34] Katsnelson M I and Novoselov K S 2007 Graphene: new bridge between condensed matter physics and quantum electrodynamics *Solid State Commun.* **143** 3
[35] Moser J *et al* 2011 Dissipative and conservative nonlinearity in carbon nanotube and graphene mechanical resonators, to appear in *Fluctuating Nonlinear Oscillators* ed Mark Dykman arXiv:1110.1234v1 [cond-mat. Mes-nan]
[36] Morpurgo A F and Guinea F 2006 Intervalley scattering, long-range disorder, and effective time reversal symmetry breaking in graphene *Phys. Rev. Lett.* **97** 196804
[37] Bolotin Kirill I *et al* 2008 Temperature dependent transport in suspended graphene *Phys. Rev. Lett.* **101** 096802
[38] Cho S and Fuhrer Michael S 2008 Charge transport and inhomogeneity near the charge neutrality point in graphene *Phys. Rev.* B **77** 081402
[39] Bolotin Kirill I *et al* 2008 Ultrahigh electron mobility in suspended graphene *Solid State Commun.* **146** 351
[40] Cleland A N and Roukes M L 1999 External control of dissipation in a nanometer-scale radiofrequency mechanical resonator *Sensors Actuators* **72** 256–61
[41] Feng X L *et al* 2007 Dissipation in single-crystal 3C-SIC ultra-high frequency nanomechanical resonators *Nano Lett.* **7** 1953
[42] Singh V *et al* 2012 Coupling between quantum Hall state and electromechanics in suspended graphene resonator *Appl. Phys. Lett.* **100** 233103 (arXiv:1202.0669v1)
[43] Landau L D and Lifshitz E M 1986 *Theory of Elasticity* vol 7 3rd edn (Oxford: Butterworth-Heinemann)
[44] Qi Z and Park Harold S 2012 Intrinsic energy dissipation in CVD-grown graphene nanoresonators *Nanoscale* **4** 3460–5
[45] Firsova Natalie E and Firsov Yuriy A 2011 Losses in monolayer graphene nanoresonators due to Joule dissipation caused by synthetic electric fields and the ways of Joule losses minimizations, arXiv:1110.5742v1
[46] Bode N, Kusminskiy S V, Egger R and von Oppen F 2012 Current-induced forces in mesoscopic systems: a scattering matrix approach *Belstein J. Nanotechnol.* **3** 144–62