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ABSTRACT

Low-temperature dissipation of mechanical energy is studied in AlGaAs/GaAs-based nanomechanical resonators with a two-dimensional electron gas. It is experimentally shown that the temperature dependence of dissipation demonstrates a peak near 30 K. A short illumination leads to a persistent change in the quality factor, which can be compared with the persistent photoconductivity effect. In particular, the illumination persistently suppresses the dissipation peak. This suppression shows that the nature of the peak is not related to the thermoelastic and Akhiezer damping. A hypothesis associating the peak with DX-centers or similar low-symmetry and light-sensitive centers is proposed. The observed effects should be taken into account when studying the low-temperature dissipation using optical methods.

The quality factor $Q$ is one of the key parameters of micro- and nanomechanical resonators since it determines both their possible practical applications and the range of experimentally observable effects interesting for basic research.1–3 There is a series of physical mechanisms causing the energy dissipation in these systems, including clamping loss,4 air damping,5 thermoelastic6 and Akhiezer7 damping, Ohmic loss,8 interaction with two-level systems,9 etc. Despite the fact that these mechanisms are mostly well-studied, quantitative characterization of their relative contributions to dissipation at given conditions remains a complex task. Which mechanism is dominant depends on the resonator material and geometry, as well as on external conditions, such as temperature, pressure, and other properties of the surrounding medium. This task becomes even more complicated when the system dimensions are reduced to the submicron range. First, the classical dissipation mechanisms related to the phonon–phonon interaction are well described only in the model of diffusive phonon transport, which obviously breaks down when the phonon mean free path exceeds the system size.6,10 Second, besides the bulk dissipation, there is a surface contribution that strongly depends on the surface contents, roughness, morphology, and other microscopic properties.11

Typically, single-crystal micromechanical resonators demonstrate relatively high $Q$-factors. One of the examples of such resonators is the systems created from AlGaAs/GaAs heterostructures.8,12–20 These systems can sustain a two-dimensional electron gas, and, in this case, they represent a test site for studying the phenomena arising due to coupling of quantum electron transport and mechanical vibrations. Despite the fact that electron transport is experimentally shown13 to be traceable via the measurement of the $Q$-factor, the magnitude of these effects is usually small, and electron–phonon interaction only weakly contributes to dissipation.

There is a series of papers devoted to dissipation in GaAs-based resonators. In Refs. 14 and 15, a hypothesis about the role of metastable defects and impurities is proposed. In Ref. 16, the thermoelastic loss is considered as one of the main damping mechanisms. In Ref. 17, it is shown that, for high-frequency whispering mode resonators, the dissipation is determined by several mechanisms, including two-level systems and Akhiezer and thermoelastic damping.

In the present paper, we experimentally study the dissipation in AlGaAs/GaAs-based nanomechanical resonators with a two-dimensional electron gas at low (5–90 K) temperatures. We observe a peak near 30 K on the temperature dependence of dissipation. Comparison with the previous studies speaks in favor of the fact that the presence of similar peaks is a universal feature of AlGaAs/GaAs-based nanomechanical resonators. We show that a short illumination at low temperatures leads to a significant persistent $Q$-factor change, non-relaxing after turning the illumination off, similar to the persistent
photoconductivity. This fact demonstrates that (1) the dissipation peak is related to electrically charged centers whose state can be altered after illumination and (2) the low-temperature dissipation can be affected by the measurement procedure when studied using optical techniques.

Experimental samples are created from an AlGaAs/GaAs heterostructure grown using the method of molecular beam epitaxy. The heterostructure contains a two-dimensional electron gas (2DEG) in a 13 nm-wide GaAs rectangular quantum well placed 80 nm below the surface at the neutral plane of the nanomechanical resonator. This layer is sandwiched between Al0.33Ga0.67As layers δ-doped with Si. The distance between the dopants and the 2DEG is 33 nm. The heterostructure also contains a 400 nm-thick sacrificial Al0.8Ga0.2As layer at a depth of 166 nm under the surface. The heterostructure is described in detail elsewhere.18,19

Lateral geometry of the samples is defined using two-step electron-beam lithography. After the first step, reactive-ion etching is used to make 150 nm-wide and 80 nm-deep trenches electrically separating different areas of the 2DEG and defining its constrictions [see Fig. 1(a)]. After the second lithography step, geometry of the resonators and surrounding gates is defined by deep reactive-ion etching down to the sacrificial layer. After that, the sacrificial layer is selectively etched20 from-under the resonators to suspend them over the substrate. The resonators represent cross-like doubly clamped beams having a length of 6 μm, a width of 1.5 μm (near the clamps), and a thickness of 166 nm equal to the total thickness of the heterostructure layers above the sacrificial one. The beams are oriented along the [110] crystallographic direction. Side gates containing a 2DEG are placed on both sides of the resonators at the distance of 200 nm from them. Near both clamps of the beams, narrow (800 nm-wide) constrictions of the 2DEG are placed.

To drive the resonator vibrations, the electrostatic actuation scheme is used. A sum of dc and ac voltages is applied between the 2DEG incorporated into the resonator and that in the surrounding gates. A detailed study of the electrostatic actuation in 2DEG-containing systems with side gates can be found elsewhere.19–21

Speaking of the origin of the peak, some of the known dissipation mechanisms can be excluded from consideration in advance. We did not make any special effort to eliminate the clamping loss,4 and it can significantly contribute to dissipation in our experiment. However, this kind of damping is commonly considered as temperature-independent, and, thus, it cannot be responsible for the peak appearance. Air damping5 is negligible in our case since the resonator is placed into a pumped and cooled vacuum chamber during the experiment. Ohmic loss does not seem to contribute significantly to the

![FIG. 1. (a) Scanning-electron-microscope image of the studied nanomechanical resonator. The inset shows the etching depth in various regions. Dark red—deep (＞166 nm) etching; light blue—shallow (80 nm) etching. Notations: S—vsource, D—drain, and GND—grounded electrodes. Amplitude (b) and phase (c) dependences on the driving frequency measured at a temperature of 5K. Black squares show the experimental data, and red lines show the fits.](image)

![FIG. 2. Temperature dependences of dissipation (inverse quality factor) measured before and after a short illumination.](image)
damping since the change in dc gate voltage and, hence, the change of conductivity of the system do not lead to any prominent influence on the quality factor. Among other physical mechanisms, the effects related to thermoelastic damping, Akhiezer damping, and defects/impurities should be considered.

The thermoelastic damping\textsuperscript{26} originates from irreversible heat flow between the oppositely deformed regions having different temperatures, which are the top and bottom halves of the resonator in the case of flexural vibrations, due to a non-zero thermal expansion coefficient. The Akhiezer damping\textsuperscript{4,5} occurs due to the deformation-induced change in phonon dispersion relations, with the changes being different for different phonon branches. As a result of this, the deformation is accompanied by a thermodynamically irreversible redistribution of the phonons between the branches, leading to entropy growth and energy dissipation. For both cases, the dissipation can be expressed as follows:\textsuperscript{2,3}

\[ Q^{-1} = \Delta = \frac{\Omega \tau}{1 + (\Omega \tau)^2}, \]  

where \( \tau \) is the characteristic relaxation time equal to \( \tau_{TED} = \frac{\rho c_p}{E} \) and \( \tau_{Ak} = \frac{\Delta c_p}{c_p} \) for thermoelastic and Akhiezer damping, respectively. Here, \( t \) is the thickness of the resonator, \( \rho \) is the mass density, \( c_p \) is the heat capacity, \( \kappa \) is the thermal conductivity, and \( E \) is the Young modulus.

The corresponding damping amplitudes \( \Delta \) can be estimated as:

\[ \Delta_{TED} = \frac{E^2 c_p}{\rho c_p}, \quad \Delta_{Ak} = \frac{\kappa^2 c_p \rho T}{E}. \]  

Here, \( \alpha \) is the thermal expansion coefficient and \( \gamma \) is the variance of the Gruneisen parameter for different phonon branches. Due to specific temperature dependences of \( \alpha \) and \( \gamma \) in GaAs and AlGaAs, both mechanisms predict dissipation peaks at temperatures on the order of 30 K.\textsuperscript{26,27} Note that these peaks arise from the \( \Delta(T) \) dependence are not the Debye peaks, i.e., \( \Omega \neq \frac{1}{\tau} \) at the corresponding temperatures. Substitution of the listed parameters into Eq. (1) gives estimates \( Q_{TED}^{-1} \approx 3 \times 10^{-11} \) and \( Q_{Ak}^{-1} \approx 3.5 \times 10^{-8} \) (upper estimate), both being far below the experimentally observed magnitude of the peak. Despite this, the thermoelastic and Akhiezer damping cannot be completely excluded from consideration in advance. First, it is highly likely that the bulk values of \( c_p \) and \( \kappa \) used in the estimates cannot be used to describe the phonon transport in our resonator since the specific heat can be increased due to the abundance of local phonon modes near the surface defects\textsuperscript{2} or due to the modified phonon spectrum,\textsuperscript{2} and the thermal conductivity can be largely decreased due to surface scattering.\textsuperscript{2} Second, at low temperatures, the bulk phonon mean free path far exceeds the resonator thickness of 166 nm, and the picture of diffusive transport cannot be used when describing the dissipation processes.\textsuperscript{9} Finally, there is no reliable reference data on \( \kappa \) in Al\textsubscript{1-x}Ga\textsubscript{x}As at low temperatures.

The effect of defects and impurities\textsuperscript{9} originates from the thermally activated or tunneling transitions between different states. The vibrational energy of a nanomechanical resonator can be transferred to them, provided that the mechanical deformation leads to different shifts of the energy levels corresponding to different states. In previous papers,\textsuperscript{14} it was shown that dissipation in GaAs resonators quadratically depends on the applied magnetic field, speaking in favor of the fact that the dissipative centers are charged, and an idea about the role of DX-centers was proposed.

Despite the fact that several hypotheses are suggested to explain the dissipation peak at temperatures close to 30 K, their experimental confirmations are lacking. To determine whether the peak is associated with pure phonon processes or with charged states, we use a short illumination. It is well known that illumination leads to the effect of persistent photoconductivity\textsuperscript{25} (PPC) lasting for hours and days after the light turn-off. On the other hand, a direct persistent influence of illumination on the system of thermal phonons is unlikely.

We used a commercial white light-emitting diode for illumination. The sample was illuminated for 1 s at 30 K, and after that, the Q-factor was measured as a function of temperature gradually decreasing to 5 K. The obtained dependence is shown by the black curve in Fig. 2. The illumination causes a decrease in the resonant frequency by 5 kHz (0.06%). This frequency shift can be explained by the increased effect of electrostatic softening.\textsuperscript{19} Indeed, the illumination contracts the electron-depleted areas near the lateral edges, thus leading to an increase in the capacitance between the resonator and the gate. For the illuminated sample, temperature rise (sweeping) to 35 K leads to a temperature-induced relaxation of the resonant frequency toward the pre-illumination value, with the relaxation being fast (50–100 Hz/min) enough to prevent reliable Q-factor measurements at higher temperatures since Q is obtained from the frequency dependences each measured for at least several minutes. However, at lower temperatures, both the resonant frequency and the quality factor remain stable for hours, and at 5 K, the relaxation is on the order of several days, as well as that of the PPC. It can be seen that the illumination reduces dissipation at 27 K by almost half. At the same time, at 5 K, dissipation increases. The peak observed before the illumination at 27 K becomes strongly suppressed, but a small feature arises at \( T \approx 15 \) K. Thus, the observed Q-factor change is similar to the PPC effect. We believe that the suppression of the peak after illumination speaks in favor of its nature being related to defects or impurities whose charge state is changed after illumination, rather than to the interaction between phonons (Akhiezer or thermoelastic damping). In this context, the feature arising at 15 K after the illumination can be interpreted as a consequence of redistribution of electrons to different dissipative centers (probably, located near the surface) activated when charged. The experimental data obtained are insufficient to establish a specific center responsible for the dissipation peak, but some testable hypotheses can be proposed.

The PPC in AlGaAs/GaAs heterostructures is usually attributed to deep electron traps with a large energy barrier preventing recapture of the photoexcited charge carriers.\textsuperscript{22,23} Since we observe a dissipation peak persistently suppressed by illumination, the hypothesis about the dissipative role of these traps should be considered. The most known of the traps causing the PPC is the so-called Si-related DX-center. The hypothesis of dissipative DX-like centers in GaAs nanomechanical resonators was mentioned in previous studies.\textsuperscript{14} Moreover, attenuation of ballistic phonons caused by Sn- and Te-related DX-centers was demonstrated at a temperature of 1.5 K,\textsuperscript{27} and the persistent photoinduced change in attenuation was also observed. The need to consider the DX-centers as a source of dissipation in our case is further enhanced by the fact that Si donors are placed in Al\textsubscript{0.33}Ga\textsubscript{0.67}As alloy, and according to previous papers,\textsuperscript{28} most of them should be incorporated.
as DX-centers rather than as shallow donors for this alloy composition.

At certain conditions, DX-centers can contribute to dissipation via reorientation to the most energetically favorable direction that depends on the vibrations-induced mechanical stress.\(^\text{19}\) Note that, at low temperatures, we can neglect the electron emission and capture by the DX-centers since the corresponding time is on the order of the PPC relaxation time, i.e., it equals hours and days. According to the existing theories,\(^\text{17}\) the DX-center represents a negatively charged Si donor (DX\(^{-}\)), for which the substitutional (III-group) position becomes metastable, leading to its spatial shift lowering the defect symmetry. Note that the dissipation due to continuous transitions of such a kind is unlikely because of their low rate characterized by the time constants on the order of the PPC relaxation time. However, there are several equivalent positions for the Si atom to occupy after leaving the lattice site, and if the potential barriers separating these positions are low enough, then thermally activated or tunneling transitions between them can occur. The mechanical stress induced by flexural vibrations changes the energies corresponding to differently oriented positions, and it can lead to reorientation of DX-centers according to the thermally equilibrium distribution. According to the model of Chadi and Chang,\(^\text{29}\) to form the DX-center, the Si atom shifts to one of the four nearest interstitials. Our experimental results do not contradict the above-described mechanism. First, illumination leads to electron emission from the DX-center with subsequent return of the Si atom to the highly symmetric substitutional site. In this case, the reorientation-induced dissipation should be suppressed after illumination, in agreement with the experiment. Second, the flexural vibrations of the resonator induce mechanical stress in the [110] crystallographic direction (along the resonator), and this stress should actually lift the degeneracy of the interstitial positions in an AlGaAs crystal.

A weak point of the proposed hypothesis is the need for the rate of transitions of a Si atom between the equivalent positions to be high (of order of \(\Omega \approx 55\) MHz at 27 K). According to Ref. 29, the shift from the lattice site is accompanied by rupture of a bond with one of the nearest As atoms. To jump between the nearest interstitials, the Si atom needs to break one more such bond and create a new bond with other As anion, and one could expect the thermal barrier between different interstitials to have a height of hundreds meV. On the other hand, calculations of this height are lacking, and previous studies do not contradict the rapid reorientation of the DX-centers. In Ref. 30, it is argued that the thermal equilibration takes no more time than the filling pulse of deep-level-transient spectroscopy (on the order of 500 \(\mu s\) at 190 K\(^\text{1}\)). The existence of other rapidly reorienting (during time less than 1 ns at 4.2 K) defects in the GaAs crystal is known.\(^\text{1}\) Moreover, the reorientation of Te- and Sn-associated DX-centers was considered as a mechanism of attenuation of ballistic phonons at 1.6 K.\(^\text{1}\)

Transitions of Si atoms between interstitials can be considered as a thermally activated process or as a result of tunneling similar to two-level systems.\(^\text{2,3}\) In the present paper, we limit ourselves to the former approach. If we would assume that the peak observed at 27 K before illumination is caused by identical centers characterized by the same activation energy \(E_a\) and relaxation time \(\tau\), then the peak shape could be analyzed using the Zener model of anelastic solid\(^\text{1}\) as that of a Debye peak [see Eq. (1)] with the Arrhenius dependence of the relaxation time,

\[
\tau = \tau_0 \exp \left(\frac{E_a}{kT}\right).
\]

However, we can expect a significant dispersion of both \(E_a\) and \(\tau_0\) values, because these parameters should strongly depend at least on the number of Al atoms near the interstitials, which can be varied from 0 to 4. The experimentally observed peak should be considered as a convolution of narrower peaks, like in the case of a DLTS signal.\(^\text{33}\)

This complicates analysis of the peak shape and makes Eqs. (1) and (3) unsuitable for a direct extraction of \(E_a\) and \(\tau_0\) values as fitting parameters. It can be supposed that \(\tau_0\) is close to the period of the local vibrational mode associated with Si DX-centers (approximately 8.5 \(\times\) 10\(^{-14}\) s\(^\text{1}\)). In this case, to observe the peak in our experimental conditions at a temperature of 27 K, the activation energy should be on the order of \(E_a = kT \ln \frac{\tau_0}{\tau} \approx 30\) meV. If the resonant frequencies were 250 kHz and 1 MHz (like in Refs. 14 and 16), the dissipation peaks would be expected at temperatures of 21 and 23 K, respectively. Thus, the considered value of activation energy is in agreement with a small dispersion of the experimentally observed peak positions. The peaks are observed at 30 K in Refs. 14 and 16, but the small variations of the peak positions can be material-dependent.

Note that our experimental data do not prove that the dissipation is related to Si dopants. For example, similar persistent photoinduced effects were also observed earlier when studying the propagation of surface acoustic waves in GaAs crystals; however, in these works, they were explained by EL-2 defects rather than by DX-centers.\(^\text{15}\) Finally, the surface can also contain deep electron traps with low symmetry, whose motion can lead to dissipation, despite in this case a broader dissipation peak can be expected.\(^\text{15}\) Identification of the dissipative centers will make it possible to increase the \(Q\)-factor by their elimination or proper placing. Moreover, providing that the observed effects are due to the DX-centers, the study of the related nanomechanical dissipation can be used as a tool for their investigation.

Further studies can clarify the role of Si dopants in dissipation processes by comparing the results obtained on different samples with various distances between a resonator neutral plane and the Si \(\delta\)-layer. It would be also useful to compare the damping at various resonant frequencies and in different vibrational modes, as well as to study the dependence of the photo-induced effects on the illumination wavelength, intensity, and duration.

To conclude, we experimentally show that AlGaAs/GaAs-based nanomechanical resonators containing Si \(\delta\)-layers demonstrate a dissipation peak at temperatures close to 30 K. Short illumination leads to a prominent persistent change in the dissipation, which does not relax after turning off the light and, thus, resembles the persistent photoconductivity effect. The illumination suppresses the dissipation peak, showing that its nature is related to neither thermoelastic nor Akhiezer damping. The photosensitivity of the peak speaks in favor of the fact that it is associated with deep electron traps whose state is changed after illumination. A hypothesis about the microscopic origin of the dissipation due to DX-centers is proposed. The observed effect of the persistent photoinduced change in the dissipation can be used to increase the \(Q\)-factor at certain temperatures. Besides, it should be taken into account when studying the low-temperature dissipation mechanisms using optical methods.

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