The photoacoustoelectric effect of the SAW amplification in the structure of Graphene-Piezocrystal LiNbO$_3$

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Abstract
The work presents and analyzes the results of detecting the photoacoustoelectric effect of surface acoustic waves amplification by illumination of a hybrid graphene-LiNbO$_3$ structure. This SAW photoamplification effect is associated with the appearance of an additional photoacoustoelectric current and a decrease of collisional scattering of photoinduced electrons under the action of the SAW electric field. Possible mechanisms of SAW amplification based on the analysis of modern data are discussed. This SAW photoamplification effect can be used to create optoacoustoelectronic devices on a graphene-piezoelectric structures for collecting, amplifying, and detecting superweak sources of THz-radiation photons.

Introduction
The acoustoelectric (AE) effect of amplifying of the surface acoustic wave (SAW) amplitude in graphene-piezoelectric crystal SAW-structure [1, 2] can be used to collect, amplify, and register ultra-weak photon-sources in a wide range of the radiation spectrum, including the terahertz (THz) range. First of all, it is possible due to the unique electrical and optical properties of graphene high electrical conductivity and ambipolarity of monolayer graphene, broadband absorption of electromagnetic radiation in the entire optical range from UV to further terahertz IR-radiation [3] and strong nonlinear interaction with the 2D electronic subsystem graphene [4], which are leads to strong electromagnetic response [5] at room temperature [6] and the possibility of registering it. Second of all, in the ability of the electric field of SAW to generate constant acoustoelectric current (I$_{AC}$) in graphene [7], to redistribute the charge carriers in graphene over the potentials of the electric field of the SAW (in accordance with the distribution of the electric potential at the maximum and minimum SAW and transfer them to macroscopic distance [8–10]). And thirdly, these are the photoresponse [11] and the amplification of the I$_{AC}$ when illuminating the graphene-piezoelectric crystal structure, depending on the frequency and power of the SAW [12, 13]. This is not a complete list of the features of the interaction of SAW with graphene [14, 15], which makes it promising to use the AE of the SAW amplification in the creation of an optoacoustoelectric device based on a hybrid SAW-structure graphene-piezoelectric crystal [13].

However, it is still difficult to understand the dynamic properties of the I$_{AC}$ graphene-piezo crystal SAW structure, which depend on the intensity and frequency of the SAW [8], the magnitude and the sign of bias voltage ($V_{bias}$) [2, 8, 11, 15], illumination [11–13], and the properties of graphene [8, 12, 13] as well as piezoelectric crystal [1, 13, 15, 16] and the interface between the graphene and the piezoelectric crystal surface.

In this work, we analyze the results of changes in the amplitude SAW of the hybrid SAW-structure graphene-piezoelectric LiNbO$_3$ depending on the effect of an external electric field, $V_{bias}$, and the illumination at light wavelength $\lambda_{iv} = 555$ nm.

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Experimental technique

In the experiment, we used bilayer graphene (BG) from Sigma Aldrich, grown by the CVD method on copper. Raman spectra of the SAW structure graphene - LiNbO₃ (YZ-128) show the presence of 2 monolayer of graphene, figure 1.

We studied SAW-structures with resonance frequencies \( f_{\text{SAW}} = 34 \text{ MHz} \) (SAW-1 it is the structure with a SAW wavelength \( \lambda_{\text{SAW}} = 100 \mu m \)), \( f_{\text{SAW}} = 57 \text{ MHz} \) (SAW-2 - with \( \lambda_{\text{SAW}} = 50 \mu m \)) and \( f_{\text{SAW}} = 124.5 \text{ MHz} \) (SAW-3 - with \( \lambda_{\text{SAW}} = 30 \mu m \)). The procedure for the formation of SAW-structures is described in articles [9, 11].

The scheme for measuring the amplitude-frequency characteristics (AFC) of SAW-structures is shown in figure 2 [2].

Results and discussion

The SAW was excited at the input IDT-1 of the piezoelectric crystal from high-frequency generator ANR-2140 at the power of the output RF signal \( P_{\text{RF}} = 3 \text{ W} \) (1.78 dBm). The SAW output signal at the second IDT-2 was measured with a high-frequency analyzer Network Analyzer 1.3 GHz OBZOR TR1300 / 1. An external longitudinal bias voltage \( V_{\text{bias}} \) is applied between graphene electrodes, one of which, like IDT1, is grounded through the device circuit, figure 2(a). When the transverse gate voltage \( V_{\text{gate}} \) is applied between the graphene contact and the piezoelectric surface, the energy levels of doping of graphene are shifted relative to the piezoelectric crystal. The gate voltage value is determined by the voltage \( V_{\text{CNP}} \) of the cut-off point at which the current is zero. The AFCs of the SAW-1 and SAW-2 structures are shown in figure 3.

Figure 3 shows the frequency response for the SAW-1 and SAW-2 structures at the input IDT1 S11 (a), (c) and at the output IDT2 S21 (b), (d). The passband of the IDT SAW structure is 10% within the excitation frequency (33–36 MHz), the resonance frequency is \( f_{\text{SAW}} \approx 34 \text{ MHz} \), for SAW-1 and (54–60 MHz) for SAW-2, \( f_{\text{SAW}} \approx 57 \text{ MHz} \).

The measurements of the acoustoelectric current \( I_{\text{AC}} \) depending on the voltage applied to the graphene to the surface \( V_{\text{gate}} \) were made at SAW frequencies \( f_{\text{SAW}} = 34 \text{ MHz} \) and \( f_{\text{SAW}} = 57 \text{ MHz} \). In some cases, a change in the SAW amplitude was recorded when exposed to green light (\( \lambda_{\text{hv}} = 555 \text{ nm} \)) from a LED-light-emitting diode to a SAW-transformed graphene-piezoelectric crystal.

In figure 4 shows the frequency response of the SAW-2 structure with \( f_{\text{SAW}} = 57 \text{ MHz} \) at different signs \( \pm V_{\text{bias}} \). It is seen that with a positive + \( V_{\text{bias}} \) an increase in SAW is observed, with a negative - \( V_{\text{bias}} \), a

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**Figure 1.** Raman spectra: (a) piezoelectric crystal LiNbO₃, (b) graphene piezoelectric crystal LiNbO₃, c) graphene minus the Raman spectrum of piezoelectric crystal LiNbO₃. The full width at half maximum (FWHM) parameters of characteristic peaks of FLG-graphene: G (FWHM) = (11–12) cm⁻¹; 2D (FWHM) = (30–32) cm⁻¹; \( l_{2D}/l_G = 1.95–3.00 \).

**Figure 2.** Scheme for generating a SAW signal on the surface of a piezoelectric crystal and measuring of the \( I_{\text{ac}} \) and EMF at open circuit on graphene – (a), the sample view – (b). Reprinted from [2] with the permission of AIP Publishing.
decrease in SAW occurs. In the case of a negative voltage \((-V_{\text{bias}})\), the amplitude SAW decreases to greater extent than it increases with a positive \((+V_{\text{bias}})\) of the same magnitude.

Amplification SAW occurs due to the high speed of movement of graphene electrons near the piezoelectric crystal, which is much higher than the speed of the SAW [1]. This takes place at high densities $I_{\text{AC}}$ and powers $P(\text{RF})$ of SAW generation [8], at high voltages with damage to $V_{\text{bias}}$ [14], and increases with increasing frequency and intensity of SAW [15]. For these parameters, a giant $I_{\text{AC}}$ oscillation is observed [16], caused by interband transitions in graphene, and was shown earlier for 2D electronic structures [17]. At low SAW powers and low voltages $V_{\text{bias}}$, a linear increase in $I_{\text{AC}}$ is observed in the graphene [14] due to intraband conduction mechanism [16].

An increase in the SAW amplitude at positive $V_{\text{bias}} = +10 \text{ V}$ of (3–4) layers graphene was observed by us earlier [2] from the diffraction deformation spectra of the surface of a $\text{Ca}_3\text{NbGa}_3\text{Si}_3\text{O}_{14}$ piezoelectric crystal.

Figure 3. AFC of the delay lines of SAW-structures at the resonance frequencies $f_{\text{SAW}} \approx 34 \text{ MHz}$ (a), (b) and $f_{\text{SAW}} \approx 57 \text{ MHz}$ (c), (d). S11 - for IDT-1 (a), (c) and S21 for IDT-2 (b), (d).

Figure 4. AFC of a SAW structure with $f_{\text{SAW}} = 57 \text{ MHz}$ at $V_{\text{bias}} = 0 \text{ V}$ (black), $V_{\text{bias}} = +10 \text{ V}$ (red), $V_{\text{bias}} = -10 \text{ V}$ (blue line).
upon passage of a SAW with frequency of $f_{\text{SAW}} = 471$ MHz ($\lambda_{\text{SAW}} = 6$ $\mu$m) at the power of input RF signal $P_{RF} = 3$ W (15 V). In this experiment, the SAW enhancement is observed in the SAW structure bilayer graphene-piezoelectric crystal LiNbO$_3$ also at high $P_{RF} = 3$ W and $V_{bias} = +10$ V.

A decrease of the SAW intensity at negative $V_{bias} = -10$ V is due to the current of graphene electrons directed towards the $I_{\text{AC}}$ current, which leads to a decrease in their speed of movement and, accordingly, to a decrease in SAW [2]. A decrease in the SAW amplitude shows that with $-V_{bias}$ a larger acoustoelectric current $I_{\text{AC}}$ is induced than with $+V_{bias}$. This indicates a different shift in the doping level at different signs of $V_{bias}$ and, accordingly, different levels of $I_{\text{AC}}$ current generation under the action of SAW.

The dependences of the $I_{\text{AC}}$ on the bias voltage $V_{bias}$ for the SAW-1 and SAW-2 structures show different doping levels, figure 5. The I–V characteristic has characteristic bends, which indicate doping levels at which $I_{\text{AC}}$ does not change or changes only slightly with a change in $V_{bias}$ at cut-off voltages $V_{\text{CNP}}$, where the current density $I_{\text{AC}}$ is zero [13].

The I–V characteristic of SAW-1 with $f_{\text{SAW}} = 34$ MHz shows one level with the cut-off voltage or voltage of the charge neutrality point $V_{\text{CNP}}$ (the voltage at which $I_{\text{AC}} = 0$) is in the range (1.0–1.5) V, approximately at the level $V_{\text{CNP}} \approx 1.2$ V, $I_{\text{AC}} \approx 100$ nA, figure 5(a).

The I–V characteristic of SAW-2 with $f_{\text{SAW}} = 57$ MHz shows two levels with cut-off voltages $V_{\text{CNP}} \approx 0.1$ V and $V_{\text{CNP}} \approx 1.0$ V, figure 5(B). One level at $V_{\text{CNP}} \approx 1.0$ V with a large signal $I_{\text{AC}} \approx 10,000$ nA and the second level at $V_{\text{CNP}} \approx 0.1$ V with a weak signal $I_{\text{AC}}$ about several units of nA, which is not recorded by us due to the smallness of the signal.

As predicted in [8], the I–V characteristic of SAW-1 with $f_{\text{SAW}} = 34$ MHz to several tens thousands nA (tens microamperes mA) for SAW-2 with $f_{\text{SAW}} = 57$ MHz, figure 3. And the fact that on the SAW-1, in contrast to the SAW-2, the level is not observed at $V_{\text{CNP}} \approx 0.1$ V, although graphene with the same characteristics was used on all SAW structures, figure 1, cut from one initial a sample of commercial graphene, is explained by the insufficient level of registration of low currents $I_{\text{AC}}$, induced by SAWs with $f_{\text{SAW}} = 34.0$ MHz at low $V_{bias}$, figure 3(a).

This is evidenced by the results of [15], where the level at $V_{\text{CNP}} \approx 0.4$ V ($I_{\text{AC}} = 0$) is observed on the parameters of the SAW structure identical to those of SAW-1, and an increase in $I_{\text{AC}}$ with the frequency of the SAW [8]. And where for the first time the change in the sign of $I_{\text{AC}} \approx \pm 10$ nA is directly shown when the $V_{\text{gate}}$ is gated from 0.33 V to 0.42 V.

Thus, by changing of the external $V_{bias}$ become is possible to change not only the doping level, but the type of conductivity from n-type to p-type, and thus the direction of the acoustoelectric current.

And the fact that the change in the level of doping of graphene from the $V_{bias}$ is clearly manifested in the change in the amplitude SAW according to the measurements of the frequency response of the SAW- structure of the graphene-piezoelectric than the measurement of the I–V characteristic of this structure, once again indicates that the frequency method is a more sensitive method for monitoring the parameters of the SAW-structure than registration of electrical parameters.

In figure 6 shows the AFC of the graphene-piezoelectric crystal SAW- structure under the illumination of graphene with green light at wavelength $\lambda = 555$ nm. Illumination of the graphene-free surface of the piezoelectric crystal does not lead to any changes, i.e., the photoresponse is associated with the illumination of graphene. In what follows, the term SAW- structure illumination will be used, implying illumination of graphene on the surface of a piezo crystal.

It can be seen that a slight increase in the amplitude SAW is observed under illumination. In all cases of recording the change in SAW under illumination using other SAW- structures with resonant frequencies of 34

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**Figure 5.1** - V characteristics of structures SAW-1 with $f_{\text{SAW}} = 34$ MHz (a) and SAW-2 with $f_{\text{SAW}} = 57$ MHz (b). $P_{RF} = 3$ W. Blue points in figure 5 means reverse I–V characteristic.
MHz, 57 MHz, and 114.5 MHz at the maximum output power of the RF signal $P_{\text{RF}} = 3W$, a steady increase was also observed amplitudes SAW are small.

It should be noted that a direct increase in the SAW amplitude in the AFC spectrum under illumination was recorded for the first time. Earlier in [18], a decrease in the amplitude SAW in the AFC spectrum was observed when the SAW structure of a graphene-piezoelectric crystal LiNbO3 was illuminated with laser light with a wavelength of $\lambda = 633$ nm, which the authors explained by heating graphene under illumination.

Illumination of a SAW structure in the absence of a SAW causes a slight increase in the conductivity of graphene, in fact, a photoresponse. Exposure to a SAW causes a strong increase in the $I_{\text{AC}}$ photocurrent in graphene, by a factor of about 8 [11], which is much higher than the initial photocurrent and higher than the dark acoustic $I_{\text{AC}}$ current without illumination [12]. However, in [11], an increase in the positive and negative acoustoelectric photoresponse is observed depending on the polarity of the electric potential applied to graphene, while the direction of propagation of the SAW remains unchanged. And at the same time, the same $I_{\text{AC}}$ values are observed at different signs of the bias voltage $V_{\text{gate}}$. This indicates that, in both cases, the number of photoinduced carriers $I_{\text{AC}}$ in graphene is the same and does not depend on the direction of external $E$.

The effect of an external electric field applied to graphene a SAW-structure influence on the character of changes in the resistance $R$ and $I_{\text{AC}}$ under illumination and exposure to SAW has been well studied [12–15]. They showed that a sharp increase in the photoresponse under the action of a SAW occurs due to an increase in the mobility of charge carriers $I_{\text{AC}}$ current due to a decrease in collisional processes of scattering of hot photoelectrons [14] during their redistribution in the minima and maxima of the acoustic wave potential [15], which, accordingly, leads to an increase in the collection charges in a graphene film and their photoresponse efficiency [12]. An external applied voltage $V_{\text{bias}}$ can change the doping level and conductivity of graphene from n- to p- type [15]. In this case, a weakening of the SAW amplitude is observed due to the appearance of negative dynamic conductivity with a change in the conductivity type of graphene [1], and the influence of the role of the surface of the piezoelectric crystal [19].

In our case, an increase in the SAW amplitude is observed when the SAW-structure is illuminated without the application of an external electric potential. This fact an SAW increasing under illumination, as well as an increase in the photo $I_{\text{AC}}$ under the action of a SAW, is most likely associated with a decrease in collisional scattering of hot photoelectrons [14]. In the case of plasmons [20], there will be no such dependences due to the fast (picosecond) processes of their thermalization [21, 22].

**Conclusions**

1. The first time the direct photoacoustoelectric effect of SAW amplification by illumination of the hybrid structure graphene-LiNbO3 was recorded. The illumination of the graphene-free surface of the piezoelectric crystal LiNbO3 does not lead to the SAW any changes.

![SAW, dB](image)

**Figure 6.** AFC of the SAW-structure of a graphene-piezoelectric crystal with $f_c = 124.5$ MHz before (initial - black) and after (red) illumination with green light ($\lambda \approx 555$ nm), $P_{\text{RF}} = 3W$. The visible oscillation in the AFC spectra of the SAW is caused by the processes of SAW reflection from the second IDT due to insignificant SAW distortions during reflection from the second IDT.
2. An increase in the SAW amplitude by illumination is associated with the generation of additional photoinduced $I_{AC}$ in graphene and with a decrease of collisional scattering of photoinduced electrons in graphene due to the ordering action of the electric field of the surface acoustic wave E(SAW).

3. The SAW amplitude is controlled by applying an external bias voltage $V_{bias}$ to graphene in both directions, both during amplification and decreasing. The SAW amplification occurs when the directions of the $I_{AC}$ and the SAW coincide. The reason for this is the high velocity of graphene electrons near the surface of the piezoelectric crystal, which is much higher than the SAW velocity. For opposite directions of $I_{AC}$ and SAW, the SAW amplitude decreases due to the appearance of negative dynamic conductivity of graphene.

4. A linear increase of the acoustoelectric current $I_{AC}$ is observed at low $V_{bias}$ due to intraband interlevel transitions at small shifts of the graphene doping level inside the conduction band. A nonlinear increase in $I_{AC}$ is observed at large $V_{bias}$ caused by interband transitions in graphene due to a strong distortion of the energy levels of graphene.

This photoacoustoelectric effect of SAW amplification can be used to create optoacoustoelectronic devices based on a graphene-piezocrystalline structure for collecting, amplifying, and detecting superweak sources of THz radiation photons.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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