DETERMINATION OF THE LO PHONON LIFETIME IN GaN

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The work presents results of experimental investigations of the heating and energy losses of hot electrons localized in the conduction channels of $Al_{0.33}Ga_{0.67}N/GaN$ heterostructures in carrier-heating electric fields up to 150 kV/cm. The results were obtained by means of the application of electric-field pulses lasting for 10–30 ns to the structures at a temperature of 4.2 K. The analysis of the results of transport measurements yielded the optical phonon energy for gallium nitride $\hbar\omega_{\rm LO} = 90$ meV, the time of its spontaneous emission $\tau_0 = 27$ fs, and the optical phonon lifetime $\tau_{\rm LO}$. The decay time of the optical phonon $\tau_{\rm LO} = 85$ fs obtained in the work is less by one order of magnitude as compared to the existing results of measuring $\tau_{\rm LO}$ with the help of optical research methods and theoretical calculations.

1. Introduction

In the last decade, one intensively investigates nitride semiconductor compounds, the most promising among which are GaN and AlGaN/GaN heterostructures. They are already used for the development and creation of numerous electronic and optoelectronic devices. Among them, we mention powerful sources of microwave radiation [1], laser diodes and light-emitting diodes [2], and radiation detectors insensitive to sunlight [3].

Theoretical investigations performed for today testify that one should expect the appearance of the Gunn effect in gallium nitride by analogy with gallium arsenide. This effect is related to the transition of hot electrons from the lower valley with a high mobility to the upper one, where the transition of carriers is essentially lower. Due to such a migration between valleys, there arise the conditions for the formation of a region of negative differential conduction on the current-voltage characteristic (CVC). In this region, we can expect the appearance of current oscillations in the microwave range with a high initial power. In gallium nitride, the energy distance between such valleys lies in the range 1.5–2 eV, which exceeds this energy interval for gallium arsenide more than by a factor of five. As follows from calculations, a significant migration between the valleys in GaN under such conditions must occur in the case of the electron heating in an external electric field of 140–200 kV/cm [3–6].

In addition, the drift velocities of carriers in GaN and structures on its basis must reach their maximal values of $3{\cdot}10^7$ cm/s in the indicated electric fields. It is the highest drift velocity among any semiconductors known up to now. From the practical point of view, so high velocities allow one to substantially extend the frequency range of devices of power microwave electronics.

Along with theoretical calculations, the kinetic transport phenomena in strong electric fields were investigated experimentally. The use of nanosecond electric pulses allowed one to investigate CVCs in GaN and AlGN/GaN heterostructures up to electric field intensities of 140-200 kV/cm [5–8]. It was found that no region of negative differential conduction expected from calculations was observed. Thus, not all factors and processes that essentially influence the character of the heating of carriers in strong electric fields were taken into account in the calculations. The most problem among them is the role of strongly nonequilibrium optical phonons, whose generation represents the dominant mechanism of energy losses by carriers in the course of their heating in external electric fields in the indicated intensity interval. It is considered that the accumulation of optical phonons in such fields can result in their reverse absorption. This process substantially influences the balance of energy losses by carriers and therefore results in their more intense heating, under which the conditions for the intervalley repopulation start to be fulfilled. On the other hand, such absorption processes must essentially affect the mobility of carriers, by decreasing it and consequently resulting in the negative differential conduction. The key moment in these processes is the lifetime of an optical phonon in GaN. The values of this important parameter available for today are obviously overrated, and this fact results in the discrepancy between the results of calculations and experiment.

The purpose of this work consists in the determination of the optical phonon lifetime from the results of

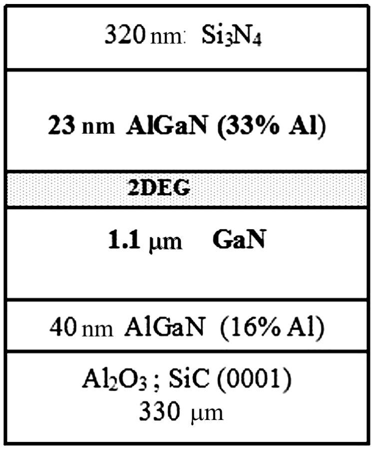

Fig. 1. Schematic diagram of the cross section of the investigated heterostructures

experimental investigations of the transport phenomena of hot carriers in strong electric fields. A substantial advantage of this work is the use of short pulses of the nanosecond range acting on AlGaN/GaN structures at the liquid-helium temperature. Such a technique allowed us to investigate the phenomena related to nonequilibrium optical phonons.

2. Experimental Procedure and Samples

The investigations were performed with the use of heterostructures produced by the technology of metal-organic chemical vapor deposition (MOCVD). The structures were grown on (0001) surfaces of the sapphire or silicon carbide substrate. A nucleating AlGaN layer with 16% of Al grown on the substrate was mainly intended to decrease of the inconsistency between the lattices of the basic 1.1-μm GaN layer and the substrate. A barrier AlGaN layer (33% of Al) of 23 nm in thickness was grown over the GaN layer. The former was covered by a Si_3N_4 layer of 320 nm in thickness for the stabilization of the surface. The schematic diagram of the cross section of these structures is depicted in Fig. 1.

A conductive channel of two-dimensional carriers 2DEG is formed at the boundary of the AlGaN and GaN layers. At the AlGaN–GaN boundary of such structures, the two-dimensional electron gas is formed as a result of the appearance of positive ion charges there both due to the spontaneous polarization of gallium nitride and the piezoelectric polarization as a result of the mechanical stresses arising due to the inconsistency of the AlGaN and GaN lattices. The calculations performed for such structures demonstrate that conduction electrons are localized in the direction normal to the heteroboundary at a distance of ~10 nm. Thus, the conduction channel is formed by the gas of two-dimensional electrons, 2DEG. According to the results of measuring the Hall effect, the concentration of carriers in this channel was $n_{2\mathrm{DEG}} = 1 \times 10^{13}$ cm^{-2} and did not change in the temperature range 4.2–300 K.

In the experiments, we used samples with two ohmic contacts of 100 μm in width, and a distance between them was equal to 5-10 μm. The contacts for the structures were produced using the standard technology by means of the deposition of Ti/Al/Ti/Au layers over the structure and their 40-second annealing at a temperature of 800 °C. Electric investigations of the transport phenomena of hot carriers in such samples were performed by means of the application of electric field pulses lasting for 10–30 ns. Such short pulses with a low repetition rate (~50 Hz) were used in order to prevent the destruction of the structures on their heating by Joule heat.

Pulsed field investigations were carried out at the liquid-helium temperature. In the course of additional measurements, we determined the conduction of the structures in low (non-heating) electric fields as a function of the temperature in the range 4.2–375 K.

3. Results of Studies

The CVCs for the heterostructures grown on the sapphire and silicon carbide substrates obtained in pulsed investigations are depicted in Fig. 2, scale 1.One can see that, in small electric fields, a linear dependence is observed for the both samples, which corresponds to the constant conductivity. At a voltage higher than 3 V, that corresponds to the electric field strength equal to 6 kV/cm with regard for a distance between the contacts equal to $5\cdot 10^{-4}$ cm, the linear dependence is changed to a sublinear one with an evident tendency to the saturation in fields higher than 20 kV/cm. The saturation current amounts to 0.15-0.17 A, which corresponds to a density of 15-17 A/cm at a width of the conducting channel of 100 μm. The mobility of carriers in the structures produced on the SiC substrate was somewhat higher than that on the sapphire one. As a result, the current in the SiC-based structures in low fields was larger as compared to that in the sapphire-based ones.

Based on the obtained CVCs, we constructed the dependence of the electric power applied to the structures during the action of the voltage pulse, Fig. 2,

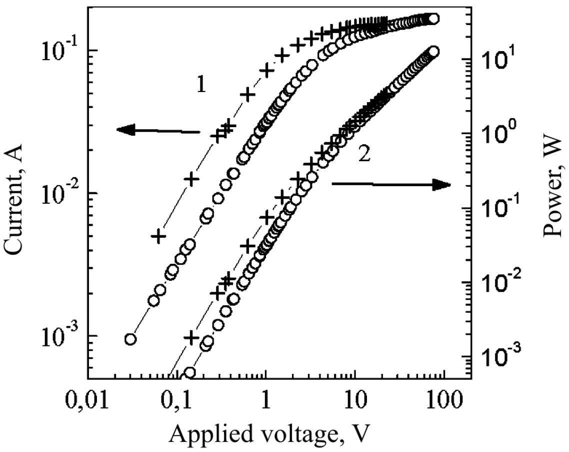

Fig. 2. Current-voltage characteristics (1 – left scale) for AlGaN/GaN heterostructures produced on SiC (+) and sapphire (○) substrates and the corresponding powers of the carrier-heating electric field (2 – right scale). Duration of a field pulse is 11 ns, measurements were performed at 4.2 K

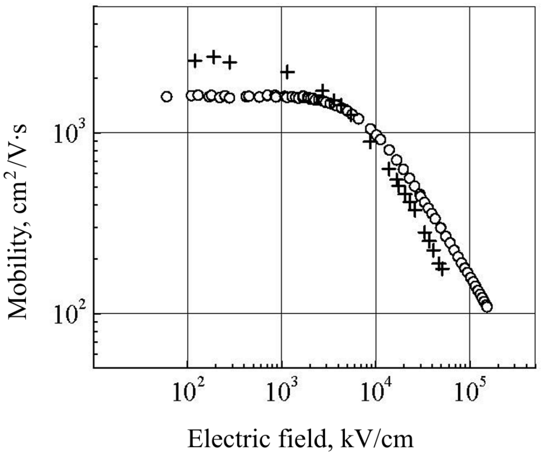

Fig. 3. Dependences of the carrier mobilities in the conduction channels of AlGaN/GaN heterostructures produced on SiC (+) and sapphire (○) substrates

scale 2. The power was determined from the obtained CVCs:

$$P = I \cdot U, \tag{1}$$

where I is the current running in the structure, and U is the voltage applied to the latter. The highest absolute value of the power was observed for the structure with the sapphire substrate and amounted to 12.7 W. From the results of measurements of the CVCs presented in Fig. 2, scale 1, one can obtain the mobilities of carriers in the channel of heterostructures depending on the electric field intensity.

For this purpose, we used the relation

$$\mu(E) = \frac{J}{n \cdot e \cdot E}, \tag{2}$$

where μ denotes the carrier mobility, J is the linear current density (A/cm), E is the electric field strength (V/cm), n stands for the concentration of a two-dimensional electron gas (1/cm^2), and e is the elementary charge. It could be assumed in the calculations that the carrier concentration in a conduction channel remained constant, i.e. the concentration was not changed in the whole range of applied electric fields. The obtained dependences for two types of the investigated heterostructures are presented in Fig. 3.

One can see that, for the both structures, the mobility remains constant in low electric fields. Starting from fields of several kilovolts per centimeter, the heating of carriers in the external electric fields becomes substantial, which results in a decrease of the mobility with increase in the heating field. In fields of 50–150 kV/cm, the mobility falls more than by an order of magnitude.

The further analysis of the obtained results becomes possible after another series of experimental investigations was carried out. These investigations consisted in the measurement of the temperature dependence of the conduction of the structures in low electric fields, where the effect of the field heating of carriers can be neglected. Such measurements in constant electric fields in the temperature range 4.2–400 K yielded the mobilities of carriers in a channel depending on the equilibrium temperature.

The obtained dependences for the both types of the structures were similar, therefore, we present only the results for the sapphire-based structure in Fig. 4. This structure is more important, as it is exactly the one where the CVC was investigated up to the electric field intensities of 150 kV/cm which are extremely high for heterostructures.

The comparison of the obtained experimental data with theoretical estimates [9] demonstrates that the dependences of the mobility on the inverse temperature are of similar character in the range of temperatures higher than 250 K. In this region, the mobility changes proportionally to $\exp\left(\frac{\hbar\omega_{\mathrm{opt}}}{kT}\right)$, where $\hbar\omega_{\mathrm{opt}}$ is the energy of the optical phonon in GaN which is equal to 92 meV according to the data of independent optical

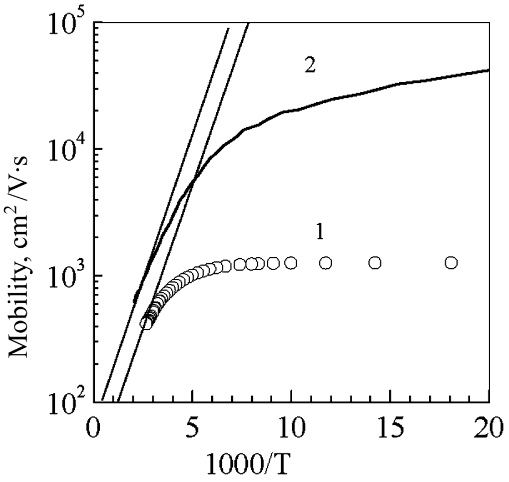

Fig. 4. Dependence of $\log(\mu)$ on the inverse temperature for the structure grown at sapphire. Curve *1* – measurements, curve *2* – calculations [9]. Solid thin lines correspond to the dependence $\mu \propto \exp\left(\frac{\hbar\omega_{\text{opt}}}{kT}\right)$

measurements [10]. Such a dependence testifies to the dominant contribution of the processes of absorption and radiation of optical phonons to the carrier mobility. The calculations performed in [9] directly concern the AlGaN/GaN structure with the electron concentration in a conduction channel equal to 1×10^{13} cm^{-2}, which corresponds to the concentrations of our investigated structures. The discrepancy of the results at low temperatures is related to the essential contribution of defects (dislocations and rough boundaries of heterostructures) to the carrier scattering, which is always typical of real structures. The calculations taken from [9] concern only the scattering processes with participation of acoustical and optical phonons, which allow us to obtain the upper limit of the mobility in the ideal structure.

Using the experimental data presented in Figs. 3 and 4, one can directly obtain the dependence of the carrier temperature on the electric field strength. This dependence can be constructed, by comparing the identical values of the mobilities presented in Fig. 3 and in Fig. 4. In this case, it is assumed that the temperature in Fig. 4 corresponds to the electron temperature in the conduction layer. This procedure of determination of the carrier temperature is known in the literature as the „mobility comparison method" [11]. The use of this method is reasonable in the case where the application of the direct methods of measuring the hot carrier temperature (such as noise spectroscopy, measurements of the conduction oscillations in the magnetic field, the Shubnikov–de Haas effect) is impossible. The dependence of the hot carrier temperature on the electric field strength obtained from the mobility comparison method is depicted in Fig. 5. In the experiment, we managed to measure the temperature dependence of the mobility up to 375 K, Fig. 5. At this temperature, the mobility amounted to 416 cm^2/V·s. At the same time, according to the results presented in Fig. 3, the mobility decreased to 110 cm^2/V·s at an electric field of 155 kV/cm. Thus, as one can see from the data in Fig. 5, the electron temperature can be determined directly from the experiment up to fields of 20–25 kV/cm. The determination of the field dependence of the electron temperature by means of the mobility comparison method in the whole investigated interval below 150 kV/cm required the data on a change of the mobility at higher temperatures, at which it will reduce to 100 cm^2/V·s. This information can be obtained, by extrapolating the experimental data from Fig. 4 to higher temperatures with the help of a function that describes the asymptotic behavior of the mobility at high temperatures.

Another way to obtain the carrier temperature in large fields consisted in the use of the established linear dependence between the temperature and the power of the heating electric field on the logarithmic scale. These results are demonstrated in Figs. 5 and 6. The both approaches gave close dependences of the temperature on the electric field intensity depicted in Fig. 5,*a* by a solid line.

Using the obtained scale of the carrier temperature depending on the heating electric field as well as the data from Fig. 2 for the electric power P introduced to the electron gas in the conduction layer of the structure, we constructed the dependence of the power per electron $P_e = P/n$ on the inverse electron temperature T_e. Here, n denotes the total number of electrons in the conduction channel of the heterostructure. The obtained dependence is depicted in Fig. 6. It displays the pattern of energy losses by hot carriers in the processes of their inelastic scattering with participation of acoustical and optical phonons.

4. Discussion of Results and Conclusions

At carrier temperatures higher than 200 K, the radiation of optical phonons becomes the dominant mechanism of energy losses in GaN. Under stationary conditions, where the pulse duration of an applied electric field τ_I is much larger than the characteristic time of the spontaneous emission of an optical phonon τ_{sp}, the

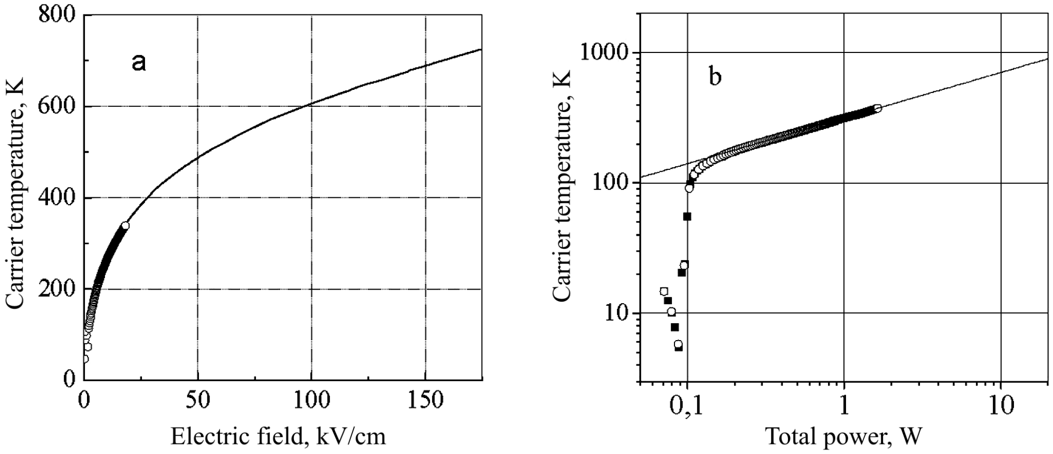

Fig. 5. Dependences of the carrier temperatures in the conduction cannel of the heterostructure on the electric field intensity (*a*) and the electric power of carrier heating (*b*). Dots – experiment, solid thin lines – approximation

introduced electric power is balanced by the emission power of optical phonons [12]

$$P_e = [(1 + N(\varepsilon_0)]\,\frac{\hbar\omega_{\rm opt}G(\varepsilon_0)}{\tau_{\rm sp}}, \qquad (3)$$

where $N(\varepsilon_0)$ denotes the population function for optical phonons with the energy $\varepsilon_0 = \hbar\omega_{\rm opt}$, $\frac{G(\varepsilon_0)}{\tau_{\rm sp}}$ is the rate of optical phonon emission, $\tau_{\rm sp}$ is the time of spontaneous optical phonon emission, and $G(\varepsilon_0) = \exp\left(-\frac{\hbar\omega_{\rm opt}}{k_{\rm B}T_e}\right)$. The first parenthesized term in expression (3) is related to the spontaneous emission of phonons, whereas the second one is responsible for their induced emission. As for this expression, it is worth noting that we neglected the component associated with the phonon absorption on its right-hand side.

At liquid-helium temperatures, the phonon occupation number $N(\varepsilon_0)$ in low and medium heating electric fields remains much less than unity. In this case, dependence (3) acquires a simple form

$$\log P_e = \log\left(\frac{\hbar\omega_{\rm opt}}{\tau_{\rm sp}}\right) - \frac{\hbar\omega_{\rm opt}}{k_{\rm B}T_e}. \qquad (4)$$

It follows from this expression that, in semilogarithmic coordinates, there must be a linear dependence with the slope angle equal to the optical phonon energy. Indeed, according to the data of Fig. 6, such a linear dependence exists in the temperature interval 250–500 K. The characteristic energy obtained from this slope amounts to 90 meV. The intersection point of this linear dependence with the coordinate axis allows one to obtain the time $\tau_{\rm sp}$, by taking into account (4). From the data of Fig. 6, it follows that $\tau_{\rm sp} = 27 \times 10^{-15}$ s.

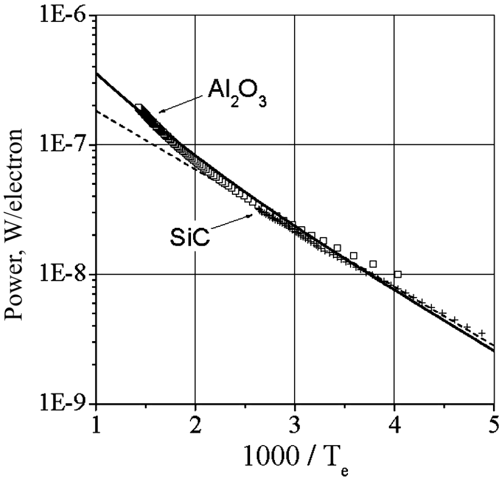

Fig. 6. Scattered electric power per electron in the conduction channels of the heterostructures grown on SiC and Al_2O_3 substrates as functions of the inverse carrier temperature. Dashed line – approximation by (4), solid line – approximation by (7)

With increase in the power of carrier heating, at which the carrier temperature exceeds 500 K, relation (4) becomes inappropriate for the determination of the power balance. In this case, one should consider again expression (3) and derive the contribution of the processes of induced emission of optical phonons proportional to $N(\varepsilon_0)$. This function can be obtained from the following considerations. The rate of change of the number of phonons with the energy ε_0 is determined by the rate of their generation $\frac{G(\varepsilon_0)}{\tau_{\rm sp}}$ and the rate of their spontaneous decay with the characteristic time $\tau_{\rm dec}$.

Thus, the balance equation for the number of phonons can be presented in the form:

$$\frac{\partial N}{\partial t}=\frac{G(\varepsilon_0)}{\tau_{\rm sp}}-\frac{N(\varepsilon_0)}{\tau_{\rm dec}}. \qquad (5)$$

Under stationary conditions, where $\tau_I > \tau_{\rm sp}, \tau_{\rm dec}$, Eq.(5) equals zero. From here, the following expression for the phonon function can be obtained:

$$N(\varepsilon_0)=\frac{\tau_{\rm dec}}{\tau_{\rm sp}}G(\varepsilon_0). \qquad (6)$$

With regard for (6) and (3), the final expression for P_e has a form

$$P_e=\left[\left(1+\frac{\tau_{\rm dec}}{\tau_{\rm sp}}\right)\exp\left(-\frac{\hbar\omega_0}{k_{\rm B}}T_e\right)\right]\frac{\hbar\omega_0\exp\left(-\frac{\hbar\omega_0}{k_{\rm B}}T_e\right)}{\tau_{\rm sp}}. \qquad (7)$$

This expression has one free parameter, namely the lifetime or the time of spontaneous decay of an optical phonon $\tau_{\rm dec}$, since the other parameters in this expression, $\tau_{\rm sp}=27\times10^{-15}$ s and $\varepsilon_0=\hbar\omega_0=90$ meV, were derived from the analysis of the results for low and medium electric fields heating the carriers. The best agreement between expression (7) and the experimental results in Fig. 6 is observed in the case where $\tau_{\rm dec}=85\times10^{-15}$ s.

The obtained optical phonon lifetime is less by more than one order of magnitude as compared to the values calculated in [13], recently measured in the investigations of luminescence in heating electric fields [14], and obtained from the comparison of the field dependence of the noise temperature with the results of Monte-Carlo calculations [15]. In these works, it was shown that the optical phonon lifetime lies in the range 1–5 ps. At the same time, the results of Monte-Carlo simulations of the field dependence of the electron drift velocity in GaN-based structures prove that the best agreement of the results of calculations and measurements [5] is obtained in the case where the effect of accumulation of optical phonons is neglected. Formally, this means that the lifetime tends to zero. Even the optical phonon lifetime equal to 0.3 ps resulted in the substantial discrepancy of the results of calculations and experimental data. On this basis, the authors made an assumption that the optical phonon lifetime must be essentially lower. According to the presented work, the value of 0.085 ps was obtained. It agrees with the assumption on the low optical phonon lifetime made in [5].

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ВИЗНАЧЕННЯ ЧАСУ ЖИТТЯ LO-ФОНОНА В GaN

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Резюме

В роботі наведено результати експериментальних досліджень розігріву та енергетичних втрат гарячих електронів, локалізованих у провідних каналах $Al_{0,33}Ga_{0,67}N/GaN$ гетероструктур, в електричних полях розігріву носіїв до 150 кВ/см. Результати отримано шляхом прикладання імпульсів електричного поля 10–30 нс до структур при температурі 4,2 К. З аналізу результатів транспортних вимірювань отримано для нітриду галію значення енергії оптичного фонона $\hbar\omega_{\rm LO}=90$ меВ, час його спонтанної емісії $\tau_0=27$ фс та час життя оптичного фонона $\tau_{\rm LO}$. Отримане в роботі значення часу розпаду оптичного фонона $\tau_{\rm LO}=85$ фс є на порядок меншим порівняно з існуючими на сьогодні результатами визначення $\tau_{\rm LO}$ шляхом оптичних методів досліджень та теоретичних розрахунків.