Interaction of excitons with carriers accelerated by the electric field of a surface acoustic wave in type-II GaAs/AlAs superlattices

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(Received 12 August 2012; published 25 October 2012)

The influence of the lateral electric field of the surface acoustic wave (SAW) on the kinetics of the exciton photoluminescence (PL) in the X_Z and X_{XY} type-II GaAs/AlAs superlattices has been studied in the present work. It has been found that the application of the SAW electric field leads first to the enhancement of the PL intensity of free excitons and then to the acceleration of the PL kinetics of all types of exciton transitions. It has been shown that both effects result from the interaction of the carriers ejected by the SAW from the shallow states formed by the quantum well width fluctuations with each other and excitons. In the first case the ejected carriers form an appreciable amount of excitons that leads to the increase in their PL intensity. In the second case the collision of these carriers with the excitons described by Townsend-Shockley law results in the delocalization of the excitons with their subsequent capture by the nonradiative centers, which leads to the acceleration of the kinetics of the excitonic PL.

DOI: 10.1103/PhysRevB.86.165323 PACS number(s): 78.67.De, 79.20.Kz, 77.65.Dq, 78.47.jd

I. INTRODUCTION

One of the promising opportunities of the practical application of the surface acoustic waves (SAW) is the band gap modulation of semiconductors which does not require the preliminary formation of any artificial heteroepitaxial structures.[1,2] In piezoelectric semiconductors the band structure modulation under the SAW is due to the deformation potential[9] as well as the lateral piezoelectric field accompanying the SAW and demonstrating the same space and time characteristics as the acoustic wave does.[1] In such semiconductors as GaAs the influence of the SAW piezoelectric field dominates at SAW frequencies less than 10^{12} Hz.[3] However, besides the periodic band structure modulation of semiconductors even the application of the SAW meeting this condition results in the appearance of numerous effects not typical of static heteroepitaxial structures.[1–13] For example, the lateral component of the SAW electric field results in the dissociation of excitons with the subsequent capture of electrons and holes into the minimum and maximum of SAW potential.[1,4–6] The separation of electrons and holes in the real space under the influence of the lateral component of the SAW electric field causes an essential increase in the carrier lifetime, which enables one to transport the long-lived nonequilibrium carriers at the macroscopic distance in the potential of the traveling SAW.[5] In heteroepitaxial structures the concentration of free carriers is quite low because most carriers are localized or form excitons at low temperatures.[14,15] Thus, the dynamic potential of the SAW in comparison with that of the heteroepitaxial structures leads to the increase in the concentration of free carries and therefore results in the increase of the interaction between carriers and/or excitons.

The investigation of the SAW influence has been focused on the properties of direct-gap structures so far.[1–7,9–13] In such structures the effects caused by the interaction between carriers and excitons have not been observed, which can be explained by their being masked with some other effects. For example, under the investigation of the SAW influence on the steady-state photoluminescence (PL) this interaction can be masked by the separation of electrons and holes in the minimum and maximum of the wave during the photogeneration of nonequilibrium carriers. The type-II GaAs/AlAs superlattices (SLs) are chosen as the object of the investigation of the interaction between carriers and excitons under the SAW in indirect-gap structures. The studies of the SAW effects in such systems with a long lifetime of nonequilibrium carriers allow considering the influence of the SAW not only on a stationary process but also on the dynamic ones including the kinetics of the interaction between carriers and excitons. Moreover, in type-II GaAs/AlAs SLs the lifetime of excitons and symmetry of a low energy electron state can be chosen by varying the thickness of SL layers.[16–18]

II. SAMPLES AND EXPERIMENTAL METHODS

Type-II GaAs/AlAs SLs were grown on GaAs substrates of the (100) orientation with the buffer layers of 0.2 thicknesses by the molecular-beam epitaxy at the 580 °C temperature. The superlattices consisted of 40 pair layers of GaAs and AlAs. The thickness of the GaAs and AlAs layers for the SLs with the X_Z lower electron state was seven and nine monolayers and that of the SLs with the X_{XY} lower electron state was seven and 30 monolayers, respectively. In the δ-doped structures the doped layers were formed by the method of growth interruption (stopping of the Ga flow at the keeping of the As pressure). The GaAs layers were doped with beryllium atoms being an acceptor whereas the AlAs layers were doped with silicon atoms being mainly a donor impurity. The concentration of the donors and acceptors N_D, N_A were equal and varied from $\sim 2.0\times10^{11}$ to $\sim 7.5\times10^{11}$ cm^{-2} in different samples. The δ layers of impurities were located at the two-monolayer distance from the direct heterointerface (AlAs on GaAs).

The application of the SAW electric field to the sample under investigation was made in accordance with the scheme illustrated in Fig. 1. The surface acoustic wave was generating and propagating in the niobate litium ($LiNbO_3$) crystal. The sample under study was located near the surface of $LiNbO_3$ crystal and therefore was under the influence of the alternating electric field of the SAW. Measurements were taken in the

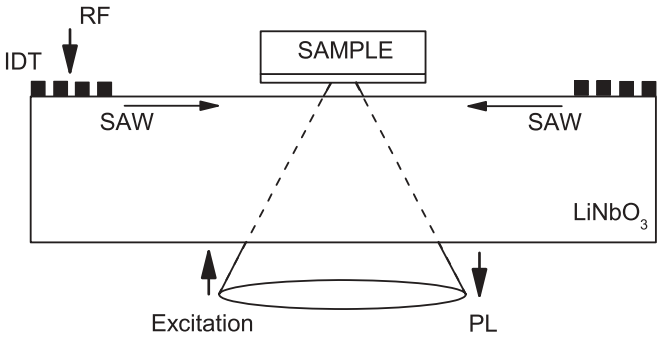

FIG. 1. The scheme illustrated the application of the SAW electric field to the sample under study. IDT, interdigitated transducer; RF, high-frequency ac voltage applied to the IDT, and PL, photoluminescence emission.

standing wave regime due to the generation of the two acoustic waves with the same amplitudes and frequencies traveling towards one another. The maximum of the amplitude-frequency characteristic of interdigital transducers (IDTs) made up of 20 pairs of electrodes was about 72 MHz which corresponded to the 40-μm wavelength. The traveling time of the SAW from the IDTs to the photogeneration area was equal to 3 μs. The electric field strength in the sample was measured on the basis of the efficiency of the laser beam diffraction on the $LiNbO_3$ surface. In the $LiNbO_3$ crystal the maximum values of the lateral and normal components of the SAW electric field were 12.4 and 2.3 kV/cm, respectively. In the samples under study the lateral component of the SAW electric field had the same value while the maximum value of the normal component of the electric field decreased up to 500 V/cm due to the difference between the $LiNbO_3$ and GaAs/AlAs SL dielectric constants.

To excite the PL a semiconductor laser with 638-nm wavelength and maximum of the power density of 2 W/cm^2 operating in both pulse and stationary regimes was used. The spot of the laser beam on the sample was about 500 μm. The excitation and registration of the PL were carried out through the $LiNbO_3$ crystal transparent in the wavelength range used by the spectrometer with the double diffraction monochromator equipped with the cooling photomultiplier operating in the time-resolved photon counting mode. The measurement was taken in helium vapor in the range of 5–30 K. The precision of the temperature keeping was about 0.2 K.

III. PHOTOLUMINESCENCE OF TYPE-II GaAs/AlAs SUPERLATTICES UNDER THE INFLUENCE OF THE SAW ELECTRIC FIELD

A. X_Z superlattices

The no-phonon bands of free and localized excitons dominate in the PL spectra of X_Z SLs due to the existent possibility to scatter the electron quasimomentum oriented across SL layers on the plain heterointerface.[16] The PL intensity of the longitudinal acoustic (LA) and longitudinal optical (LO) phonon-assisted excitonic bands are much smaller (see Fig. 2).

In the absence of the SAW electric field the PL decay kinetics of excitons is described by the power law:

$$I(T) = I(0)e^{-\omega_0 t}(1 + 2\omega_r t)^{-3/2}, \quad (1)$$

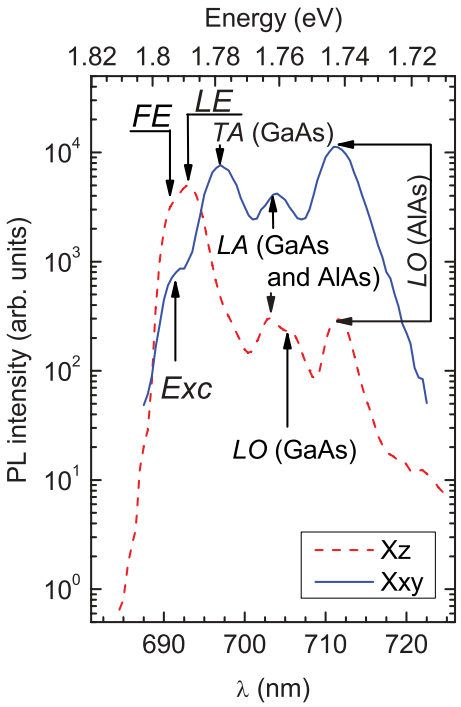

FIG. 2. (Color online) The PL spectra of type-II X_Z and X_{XY} GaAs/AlAs SLs. The FE and LE bands are the free and localized exciton PL bands; TA, LO, LA bands are the phonon replicas of excitonic PL bands. $T = 5$ K. Excitation power of the 1.94 eV laser is 5 mW.

where w_0 and w_r are probabilities of the stochastic and non-stochastic processes of exciton recombination, respectively.[19] For the X_Z SL under study the w_0 and w_r are equal to $(0.6\mp0.3)\times10^5$ and $(1.2\mp0.6)\times10^5$ s^{-1}, respectively (see Fig. 3).

First of all, the SAW electric field with the strength over 3 kV/cm causes sn enhancement of the free excitonic PL intensity (see Fig. 4). The relative amplitude of this enhancement increases with the increasing time delay between the laser pulse and moment of the SAW electric field application (see Fig. 5). The PL intensity of localized excitons and phonon replicas are constant in this moment (see Fig. 4). After that the PL kinetics of localized excitons and phonon replicas

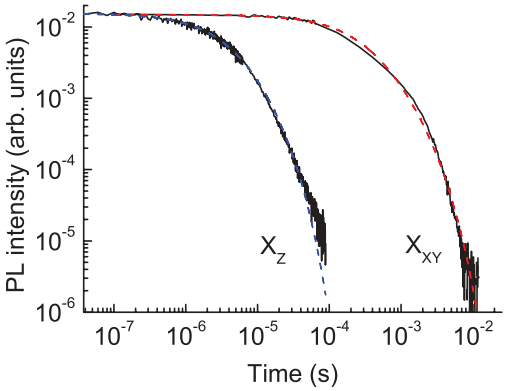

FIG. 3. (Color online) The experimental and fitted (blue and red curves) PL decay curves of type-II X_Z and X_{XY} GaAs/AlAs SLs. $T = 5$ K. Laser excitation power is 5 mW.

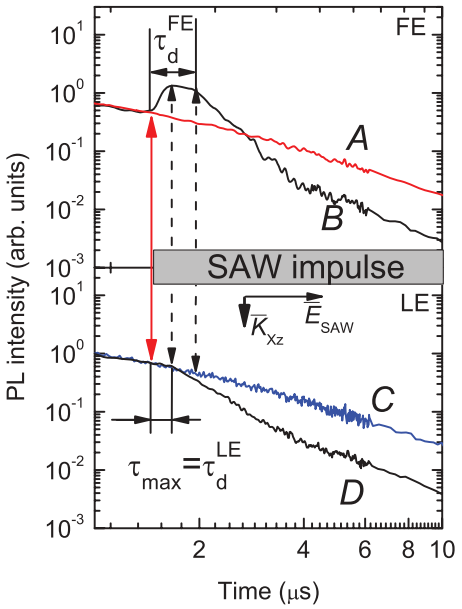

FIG. 4. (Color online) PL decay curves of the no-phonon free (A, B) and localized (C, D) X_Z excitons without (A, C) and under (B, D) the influence of the SAW electric field. The electric field strength is 12 kV/cm. $T = 5$ K. The red solid arrow shows the moment of the SAW impulse arrival to the photoexcited region.

(not shown) accelerates first and then that of free excitons accelerates too. The delay observed between the appearance of the SAW electric field impulse in the photogeneration point and the acceleration of the excitonic PL kinetics can be up to 1 μs. It should be noted that during long impulses of the SAW electric field the PL decay curves of all types of exciton transitions return to the typical power decay law and then do not react to the SAW electric field applied repeatedly. The decay curves of excitonic PL also demonstrate the total insensitivity to the influence of the SAW electric field when the temperature increases up to 20 K, at the doping of the structures ($N_{A,D} \geqslant 2 \times 10^{11}$ cm^{-2}) or application of the repeated impulse of the SAW electric field.

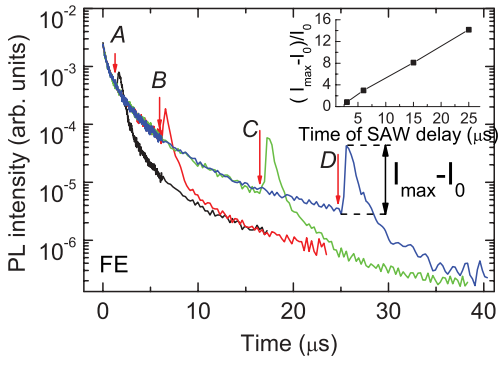

FIG. 5. (Color online) PL kinetics of X_Z free exciton band with various intervals Δ between the excitation laser impulse and SAW electric field impulse. Δ = (A) 3, (B) 7.5, (C) 18, and (D) 26 μs. The SAW electric field strength is 12 kV/cm. The red solid arrow shows the moment of the SAW impulse arrival to the photoexcited region. $T = 5$ K. The inset in Fig. 5 displays the dependence of relative intensity of the maximal enhancement of free exciton PL on this delay.

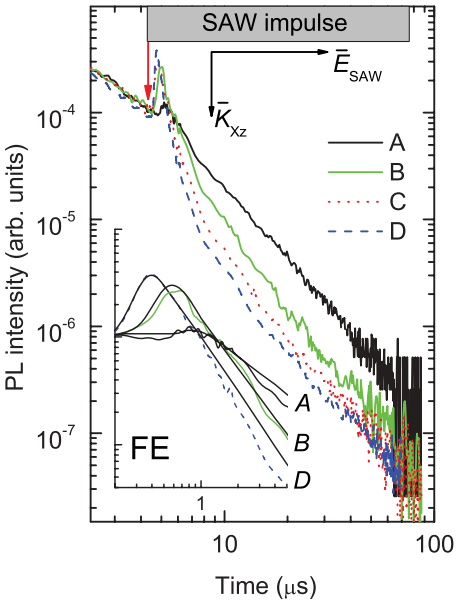

FIG. 6. (Color online) PL kinetics of X_Z free exciton band under the SAW. The SAW electric field strength is equal to (A) 3, (B) 6, (C) 9, and (D) 12 kV/cm. The intervals between the excitation laser impulse and SAW electric field impulse is 6 μs. The red solid arrow shows the moment of the SAW impulse arrival to the photoexcited region. $T = 5$ K. The inset in Fig. 6 displays the experimental and calculated in accordance with a set of rate equations (6)–(9) PL kinetics of X_Z free exciton band. The time reading on the inset of Fig. 6 starts with the appearance of the SAW impulse in the photogeneration point.

The PL decay curves of free excitons at a different strength of the SAW electric field are shown in Fig. 6. As one can see from this figure both the kinetics of the initial enhancement of the PL intensity of free exciton band and the subsequent decay of the PL intensity of all the exciton bands depends on the strength of the electric field. With the increase in the strength of the SAW electric field the amplitude of the enhancement of the free excitonic PL intensity (see Fig. 6) increases whereas the duration of this enhancement decreases (see curve A in Fig. 7). The increase in the strength of the electric field leads also to the decrease in the delay time until the PL intensity starts accelerating (see curves B and C in the Fig. 7) and causes the increase in the decay rate of this acceleration (see Fig. 6).

In the SAW electric field the recombination probability of an X_Z exciton should be defined by the sum of radiative and nonradiative probabilities including the probability of the process leading to the acceleration of the exciton PL kinetics in the electric field, $\omega_{\text{el.field}}(F)$,

$$\omega_{\text{total}} = \omega_{\text{el.field}} + \Sigma\omega_i. \tag{2}$$

Taking into account the fact that at the absence of the electric field the PL kinetics of X_Z SLs is described by expression (1); the PL kinetics during the acceleration in the electric field can be described by the following formula:

$$I(t,F) = I(0)e^{-(\omega_{el.field}+\omega_0)t}(1+2\omega_r t)^{-3/2}. \tag{3}$$

The dependence of the probability $\omega_{\text{el.field}}(F)$ of X_Z excitons upon the strength of the SAW electric field (see Fig. 8) has been obtained as a result of the approximation of the

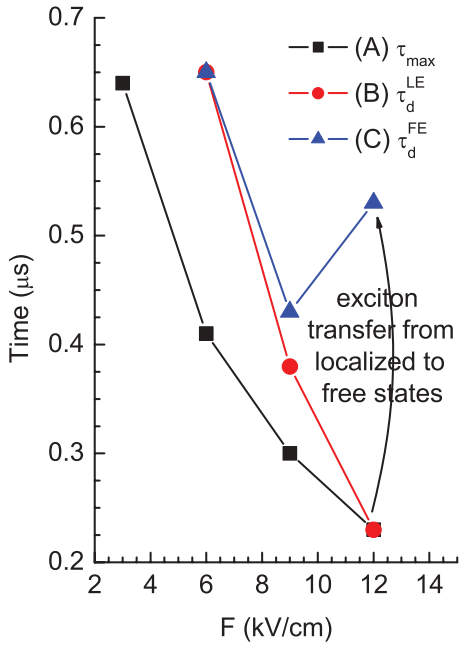

FIG. 7. (Color online) The duration of the enhancement of the X_Z free excitonic PL intensity (A) and delay times until the PL kinetics of X_Z localized (B) and free (C) excitons starts accelerating. $T = 5$ K.

experimental decay PL curves in the SAW electric field (see Fig. 6) by formula (3). This dependence is well approximated by Townsend-Shockley law used frequently for describing the process of impact ionization of excitons by hot carriers in the electric field:[20,21]

$$\omega_{\text{el.field}}(F) = \omega'_{\text{el.field}} \times \exp\left(-\frac{E_A}{e \times \mid F(t) \mid \times l_{\text{eff}}}\right), \quad (4)$$

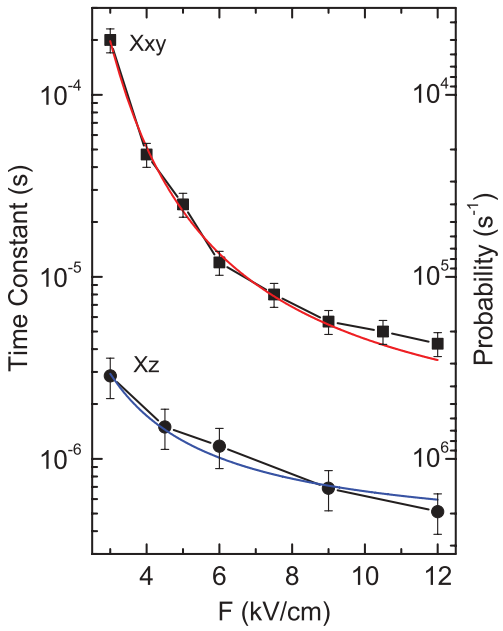

FIG. 8. (Color online) The experimental and fitted (blue and red curves) dependence of the probabilities of the hot carriers induced process leading to the acceleration of the excitonic PL kinetics in SAW electric field. $T = 5$ K.

where $\omega_{\text{el.field}}(F)$ is the probability of the process associated with the acceleration of the excitonic PL kinetics in the SAW electric field, E_A is an activation energy of this process, l_{eff} is a free path of carriers, $F(t) = F_0 \times \sin(2\pi\varphi t)$ is the strength of the SAW electric field. For X_Z SLs the parameters of the best approximation $\omega_{\text{el.field}}(F)$ by Eq. (4) are $\omega'_{\text{el.field}} = (2.5 \mp 0.4) \times 10^6\ \text{s}^{-1}$, $E_A/l_{\text{eff}} = (0.8 + 0.1) \times 10^4$ eV/cm.

B. X_{XY} superlattices

The radiative recombination of excitons in type-II GaAs/AlAs SLs with the X_{XY} lower electron state is suppressed since the symmetry of these states does not allow them to mix with G states in the absence of potential fluctuations.[16] Consequently, the phonon-assisted excitonic PL bands dominate in the PL spectra of X_{XY} SLs (see Fig. 2). The no-phonon band of free excitons is observed in the PL spectra only as a weak high-energy shoulder of the phonon replicas whereas the no-phonon band of localized excitons is absent. The radiative lifetime of the excitons in the X_{XY} SLs increases by orders of magnitude in comparison with the radiative lifetime of the excitons in the X_Z SLs. So, ω_0 and ω_r—the probabilities of stochastic and nonstochastic processes of the exciton recombination derived from the description of the PL decay kinetics of the X_{XY} SL (see Fig. 3) by law (1)—are equal to $(0.4 \mp 0.1) \times 10^3$ and $(1.2 \mp 0.3) \times 10^3\ \text{s}^{-1}$, respectively.

Like in case of the X_Z SL changes in the PL decay kinetics of the X_{XY} SL start being noticed at the strength of the SAW electric field over 3 kV/cm. Under the influence of the SAW electric field the PL intensity of the no-phonon band of free excitons increases but the PL intensity of phonon replicas remains unchanged. After that with the delay relative to the appearance of the electric field impulse at the photogenerated point the acceleration of the decay kinetics of all the PL exciton bands described by one and the same law is observed (see Fig. 9).

The acceleration of the PL kinetics of the X_{XY} SL in the SAW electric field depends on the laser excitation power and therefore the concentration of nonequilibrium carries. As one can see from Fig. 9 at the high laser excitation power the PL decay kinetics of the X_{XY} SL during the acceleration in the SAW electric field is described by the simple exponential law:

$$I(t,F) = I(0)e^{-\omega_{\text{total}} \times t}. \quad (5)$$

As at a low laser excitation power the kinetics of the exciton PL deviates from the exponential law due to a more quick decay at the initial stage of the SAW application (see inset in Fig. 9).

At the high laser excitation power the dependence of the probability ω_{total} for X_{XY} excitons on the strength of the SAW electric field (see Fig. 8) has been obtained as a result of the approximation of the experimental PL decay curves of the X_{XY} excitons in the SAW electric field (see Fig. 9). The ω_{total} obtained from the approximation is considered to be the probability of the process leading to the acceleration of the PL kinetics of excitons in the SAW electric field, $\omega_{\text{el.field}}(F)$. This probability is several orders of magnitude higher than that of the X_{XY} exciton recombination in the absence of the electric field. Like in the case of X_Z excitons the dependence of $\omega_{\text{el.field}}(F)$ for X_{XY} excitons is well described by

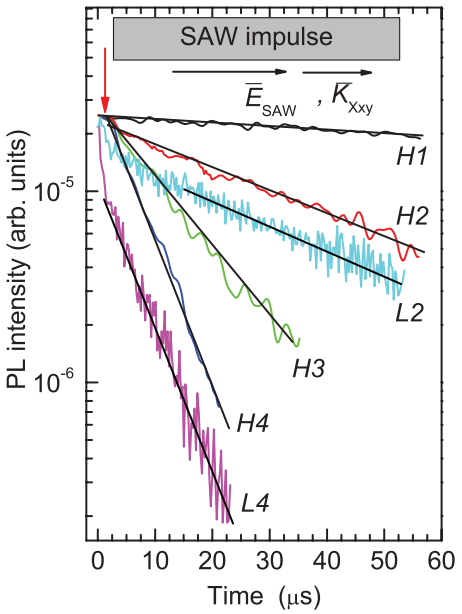

FIG. 9. (Color online) PL kinetics of X_{XY} no-phonon exciton band under the SAW. The SAW electric field strength is equal to (H1) 3, (H2, L2) 6, (H3) 9, and (H4, L4) 12 kV/cm. Indexes H and L indicate the high (6×10^{10} cm^{-2}) and low (3×10^{9} cm^{-2}) laser excitation power, respectively. The arrow shows the moment of the SAW impulse arrival to the photoexcited region. $T = 5$ K.

Townsend-Shockley law (4). The only difference for X_{XY} excitons is the approximation parameters equal to $\omega'_{\text{el.field}} = (0.8 \mp 0.2) \times 10^6$ s^{-1}, $E_A/l_{\text{eff}} = (1.3 \mp 0.1) \times 10^4$ eV/cm.

IV. DISCUSSION

A. Influence of the saw electric field on the photoluminescence intensity of free excitons

The intensity enhancement in the free excitonic PL decay curves under the application of a SAW electric field impulse may be caused whether by the increase in the probability of the radiative recombination of free excitons or the increase of their concentration. With the increase of the delay time between the laser impulse and the moment of the application of the electric field and therefore along with the decrease in the exciton concentration (see Fig. 5) a relative enhancement of the PL intensity of free excitons in the electric field rises. However, even if the probability of the radiative recombination of excitons depends on the exciton concentration, for example, because of the scattering of exciton quasimomentum while interacting with each other it cannot increase at the decrease in the exciton concentration. Therefore, the enhancement of the PL intensity of free excitons results from the increase in the exciton concentration. As at the enhancement of the PL intensity of the free excitons the PL intensity of the localized ones and phonon replicas does not change (see Fig. 4) the initial increase in the concentration of free excitons is not caused by the delocalization of the excitons in the SAW electric field and can be explained only by the formation of additional free excitons. The appearance of nonequilibrium free carriers under the electric field is necessary for this process. Such carriers can be ejected from the localized states in the SLs. It is well known that interface roughnesses in quantum wells (QWs) lead to spatial fluctuations of the QW width, and consequently to fluctuations of energy levels.[14,15] The localization of nonequilibrium carriers at the levels formed by QW width fluctuations (hereinafter referred to as levels of wide QWs) can lead to the separation of electrons and holes from each other at the distance more than the exciton Bohr radius and thus, they are not able to form excitons.

As one can see from the position of the free and localized exciton bands in the PL spectra of the X_Z SL under study (see Fig. 2) the average energy of the carrier localization at the levels of wide QWs is approximately 5 meV. Due to the absence of the band of localized excitons in the PL spectra of the X_{XY} SL the average energy of the exciton localization can be measured only indirectly on the basis of the width of the exciton band on the half height equal to 6 ∓ 2 meV (see Fig. 2). The maximum energy gained by the carriers on the free path in the electric field can be estimated by the formula $E = e \times F \times l$, where l_{eff} is the free path of carriers and F is the strength of the SAW electric field. The energy gained by the electrons is equal approximately to 3 meV in the SAW electric field of 3 kV/cm when changes in the PL kinetics begin and at $l_{\text{eff}} = 10$ nm that is compared with the free path estimation from the next part of the discussion. Thus, the energy gained by the electrons on the free path in the SAW electric field is compared with the localization energy at the levels of wide QWs. The further increase in the strength of the SAW electric field makes possible the carrier delocalization from these levels which leads to the subsequent increase in the free carrier concentration and therefore, the increase in the amplitude of the enhancement of the exciton PL intensity (see Fig. 6).

The assumption of carriers being delocalized in the SAW electric field exactly from the levels of wide QWs is also confirmed with the experimental data available indicating the disappearance of any changes in the PL decay curves under the influence of the electric field at the depletion of these wells. First of all, the depletion of wide QWs at the temperature increase up to 20 K (kT = 2 meV) results in the disappearance of the initial enhancement of the PL intensity of the free exciton band at the application of a SAW electric field impulse. Secondly, in the doped SLs the capture of carriers from the levels of the wide QWs to the impurity levels with the ionization energy equal to 50–100 meV (Refs. 22,23) also leads to the total insusceptibility of the PL decay curves to the influence of the SAW electric field. In the doped structures the levels of wide QWs are depleted in the following cases: (1) the average distance between the impurity centers is less or comparable with the average lateral size of the heterointerface roughnesses of the SL and (2) the impurity centers are not filled. The simple estimation shows that the conditions required are fulfilled in the samples investigated in our experiment. Indeed, at the minimum concentration of the doping impurities $N_{A,D} = 2 \times 10^{11}$ cm^{-2} the average distance between the impurities is equal approximately to $S_{A,D} \approx 20$ nm that is comparable with the lateral size of the heterointerface roughnesses equal to 18–26 nm.[24,25] At the maximum laser excitation power the concentration of nonequilibrium carriers in one layer of the SL is approximately 6×10^{10} cm^{-2} that is less than the concentration of the doped impurities $N_{A,D} \approx 2 \times 10^{11}$ cm^{-2}. Moreover, the total

insusceptibility of the PL decay curves of the doped SLs to the influence of the SAW electric field directly indicates that there is no delocalization of the carriers from the deep impurity centers in the applied SAW electric field up to 12 kV/cm.

Thus, we can conclude that the initial enhancement of the PL intensity of free excitons in the PL decay curves under the application of the SAW electric field impulse is caused by the increase in free carrier concentration due to the delocalization of the carriers from shallow levels formed by quantum well width fluctuations.

B. Acceleration of the photoluminescence kinetics of excitons in the SAW electric field

The next part of the discussion is devoted to the acceleration of the excitonic PL kinetics in the SAW electric field. This effect may be caused whether by the ionization of excitons or increase in their recombination probability.

Consider the first possibility, namely the ionization of excitons in the SAW electric field. The main mechanisms of the exciton ionization in the electric field are direct ionization, tunneling ionization, and impact ionization by free carriers. However, the experimental results explicitly indicate that the acceleration of the PL kinetics in the SAW electric field is caused by the interaction of excitons with free carriers heated in the lateral SAW electric field. In the absence of free carriers ejected from the localized states by the SAW electric field the acceleration of the PL kinetics is not observed. Moreover, the experimentally defined dependence of the recombination probability of X_Z and X_{XY} excitons upon the strength of the SAW electric field (see Fig. 8) is described by Townsend-Shockley formula (4). According to the published data (Refs. 20,21) formula (4) is used to describe the impact ionization of excitons by free carriers in the area of relatively small electric fields ($e \cdot F \cdot l_{\text{eff}} \leqslant \text{hw}_{\text{phonon}}$). Then it should be expected that the acceleration of the PL kinetics is caused by the impact ionization of the excitons by the free carriers which is the main mechanism of the exciton ionization in the electric field.[13,26] However, the return of the PL decay curves to their typical decay law still under the influence of the impulse of the standing SAW indicates that the concentration of free carriers decreases significantly during the acceleration of the PL kinetics. Whereas the impact ionization must be on the contrary accompanied by the increase in the free carrier concentration when the return of the PL decay curves to their typical behavior would not take place. Thus, we can conclude that the acceleration of the excitonic PL kinetics in the SAW electric field is not caused by the impact ionization of excitons.

In type-II GaAs/AlAs SLs indirect-gap excitons have to scatter the large quasimomentum $\sim \pi h/a$ (where h is Plank's constant, and a the lattice constant) to recombine. Therefore, the no-phonon scattering of the quasimomentum occurs only in the regions with abrupt changes of the potential. Due to the law of momentum conservation the impact of excitons with free carries heated in the lateral electric field oriented along heterointerfaces cannot directly lead to the relaxation of the exciton quasimomentum oriented across the heterointerfaces and therefore, to the increase in the probability of exciton recombination in the X_Z SLs. As the kinetics of both X_{XY} and X_Z excitons demonstrate similar peculiarities and are described by the same laws in the SAW electric field we can assume that the acceleration of the excitonic PL kinetics are not caused by the increase in the probability of their radiative recombination. At the same time it is well known that in the low-dimensional structures at low temperatures the nonradiative recombination of excitons occurs mainly during the diffusion between the localized states when excitons are captured and recombine on the chaotically located nonradiative recombination centers.[27]

Excitons interacting with hot free carriers gain the kinetic energy enough to delocalize from the levels of wide QWs. Then after being delocalized the excitons can be captured on the recombination centers and recombine nonradiatively which leads to the acceleration of the exciton PL kinetics. In a weak electric field ($E < 3$ kV/cm) the ejection and subsequence diffusion of excitons towards the nonradiative recombination centers are governed by the temperature only. As a result the PL kinetics of the exciton bands follows its typical decay law. As the strength of the SAW electric field increases free carrier concentration increases also. Therefore there is an increase in the probability of the exciton ejection from the levels of wide QWs due to the impact with hot electrons described by Townsend-Shockley law (4). This in turn leads to the increase in the exciton capture on the chaotically located nonradiative recombination centers and therefore, the acceleration of the PL kinetics of SLs. Thus, the activation energy (E_A) in formula (4) which describes the dependence of the probability of the exciton recombination on the strength of the SAW electric field is the localization energy of excitons at the levels of wide QWs. This energy is equal to 4–6 meV (see one part of the discussion) in the samples under study. Then from the ratio of the approximation parameters of formula (4) E_A/l_{eff} we can estimate the free path of electrons in the samples under study which is $6.0 \mp 1.5/3.9 \mp 0.33$ nm in the X_{XY} and X_Z SLs, respectively. The free path of electrons with the energy of several meV (E) estimated by the formula $l_{\text{eff}} = \sqrt{2E/m} \cdot t$, reaches 300 nm if the scattering at the acoustic phonons with the process duration up to tens of picoseconds (t) dominates.[28] Therefore, the small value of the free electron path obtained testifies the fact that the relaxation of hot electrons in the SLs under study results from some other mechanisms of scattering. We suppose that in the studied SLs the scattering of the electrons by the heterointerface roughness dominates.

The suggested model explaining the acceleration of the excitonic PL kinetics in the SAW electric field by the capture of the excitons by the nonradiative recombination centers is confirmed by the fact that the acceleration of the PL kinetics of free excitons starts with a delay after the acceleration of the PL kinetics of the localized excitons (see Fig. 7), that is, the conversion of the localized excitons to the free excitons experimentally testifies. To reveal a reason for the time delay between the acceleration of the PL kinetics of free and localized excitons as well as the time delay between the acceleration of the PL kinetics and the appearance of the SAW impulse in the photogeneration point we write the set of the rate equations for the concentration of free and localized excitons and carriers taking into account the capture and ejection of carriers from localized states. The resulted system of equations

is the following:

$$\frac{dN_{\mathrm{FE}}}{dt} = -\left(\omega_{\mathrm{rec}} + \omega_{\mathrm{capture}} + \omega_{\mathrm{loc}}^{\mathrm{Exc}}\right)N_{\mathrm{FE}}(t) + \omega_{\mathrm{deloc}}^{\mathrm{Exc}}N_{\mathrm{LE}}(t) + \omega_{\mathrm{form}}n_{\mathrm{FC}}^2(t), \quad (6)$$

$$\frac{dN_{\mathrm{LE}}}{dt} = -\left(\omega_{\mathrm{rec}} + \omega_{\mathrm{deloc}}^{\mathrm{Exc}}\right)N_{\mathrm{LE}}(t) + \omega_{\mathrm{loc}}^{\mathrm{Exc}}N_{\mathrm{FE}}(t), \quad (7)$$

$$\frac{dn_{\mathrm{FC}}}{dt} = -\omega_{\mathrm{form}}n_{\mathrm{FC}}^2(t) - \omega_{\mathrm{loc}}^{C}n_{\mathrm{FC}}(t) + \omega_{\mathrm{deloc}}^{C}n_{\mathrm{LC}}(t), \quad (8)$$

$$\frac{dn_{\mathrm{LC}}}{dt} = -\omega_{\mathrm{deloc}}^{C}n_{\mathrm{LC}}(t) + \omega_{\mathrm{loc}}^{C}n_{\mathrm{FC}}(t). \quad (9)$$

Equations (6) and (7) describe the changes in the concentration of free (N_{FE}) and localized (N_{LE}) excitons, Eqs. (8) and (9) connect the concentrations of free (n_{FC}) and localized (n_{LC}) carriers, respectively. At the calculation the probability of the exciton formation ($\omega_{\mathrm{form}} \sim 10^{12}$ s^{-1}) and the probability of the localization of the carriers ($\omega_{\mathrm{loc}}^{C} \sim 10^{11}$ s^{-1} equal to the probability of the LA phonon emission in the GaAs) are taken from the literature (Refs. 28,29) and do not vary as these probabilities are several orders of magnitude higher than the delay times observed. The probability of the exciton recombination in the absence of an electric field (ω_{rec}) and that of the exciton delocalization under the influence of the electric field ($\omega_{\mathrm{deloc}}^{\mathrm{Exc}}$) are determined from the experimental data (see Figs. 3 and 8). The probability of the exciton capture by nonradiative centers ($\omega_{\mathrm{capture}}$) and that of the exciton localization ($\omega_{\mathrm{loc}}^{\mathrm{Exc}}$) are varied. To simplify calculations the concentrations of the nonequilibrium electrons and holes were taken equal. The concentrations of nonequilibrium carriers and excitons in the initial moment of the SAW application are set explicitly. To solve the system of linear differential equations numerical methods were used.

As one can see from the inset in Fig. 6 the introduced set of rate equations describes the behavior of the PL kinetics of excitons in the SAW electric field in a microsecond range quite well. The following correlations between the varying parameters are necessary to do this: (1) The probability of the exciton capture by nonradiative centers is much higher than that of the exciton localization, that is, the exciton capture by nonradiative centers is limited by the rate of the exciton delocalization. (2) The probability of the free exciton localization in the SAW electric field is less than 10^6 s^{-1}. The fulfillment of the first condition is experimentally confirmed in the SLs under study. The increase in the temperature and therefore the increase in the exciton mobility due to the exciton delocalization lead to a significant increase in the exciton capture on nonradiative centers.[27] The second condition, that is, the small probability of the exciton localization in the SAW electric field in comparison with the expected probability of the LA phonon emission ($\sim 10^{11}$ s^{-1}) is quite unusual. We assume that this can be explained by the lateral SAW electric field heating the excitons and preventing their reverse localization.

V. CONCLUSION

Thus, it has been shown that the interaction between carriers and/or excitons in the SAW electric field can significantly modify the kinetics of the PL in the X_Z and X_{XY} type-II GaAs/AlAs superlattices. Moreover, in the SLs with an X_{XY} lower electron state the changes in the exciton PL kinetics caused by this interaction dominate. All the changes in the kinetics of the exciton PL observed under the influence of the SAW electric field are associated with the two simultaneous processes: (1) formation of excitons from the carriers ejected by the SAW from the levels formed by quantum well width fluctuations which leads to the initial enhancement in the intensity of the excitonic PL; (2) the delocalization of excitons with their subsequent capture by nonradiative centers caused by the impact with the hot carriers described by Townsend-Shockley law, which leads to the acceleration of the excitonic PL kinetics.

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