# Effect of surface acoustic waves on low-temperature photoluminescence of GaAs

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The near-band-gap low-temperature photoluminescence (PL) in a pure film of GaAs in the presence of surface acoustic waves (SAW) has been studied experimentally. The complex behavior of the PL peak intensities with SAW power in the excitonic and acceptor spectral regions results from a charge bunching due to the piezoelectric field of SAW.  [S0003-6951(97)01225-4]

The near-band-gap low-temperature photoluminescence (PL) in pure GaAs samples is dominated by the recombination of free and bound excitons.[1,2] The excitonic PL spectra depend on the level of background impurities and therefore the PL is widely used for characterization of the purity of GaAs: a semi-qualitative estimation of the concentration of donors, acceptors, and defects is possible below limits of other analytical methods.[3–8] The excitonic PL is also useful in studying fundamental properties of free and bound excitons in semiconductors, in particular, mechanisms of their generation and dissociation. For this purpose the PL spectra measured in the presence of different external fields are widely used. For example, considerable effects on the excitonic spectra of PL in GaAs were shown due to a dc electric field,[9–12] a high-frequency electric field,[13] and nonequilibrium acoustic phonons.[14]

In this letter we report experimental results on the excitonic PL in GaAs in the presence of surface acoustic waves (SAWs). The interaction between the SAW and charge carriers is due to the deformation potential and piezoelectric field accompanying the SAW. On piezoelectric semiconductors such as GaAs in a SAW frequency range less than $10^{12}$ Hz (we used $10^8$ Hz), the interaction is dominated by the piezoelectric field.[15]

For measurements, a 10-$\mu$m-thick GaAs layer was grown by liquid-phase epitaxy on semi-insulating (100) GaAs substrate from a bismuth melt. At 77 K the layer has an electron concentration of $4.5\cdot 10^{14}$ cm$^{-3}$ and electron mobility of $8.5\cdot 10^4$ cm$^2$/V s.

The 5 K PL spectra with resolution better than 0.2 meV were obtained using the 541.5 nm line of an argon ion laser. The density of excitation was 0.3 W/cm$^2$. To excite SAW an interdigital transducer,[16] which consists of the system of metallic electrodes, was fabricated photolithographically directly onto the GaAs layer. A 30 $\mu$m period of the interdigital transducer was used in order to permit excitation at 5 K of the SAW with frequency of 110 MHz. The crystal cut used here by SAW propagation direction along [110] results in the highest achievable electromechanical coupling for SAW on GaAs. The acoustic power was measured by the optical method, and its maximal value was equal to $P_{\max}=1.1$ mW. Using data on the SAW structure[17] we found the components of the deformation tensor and piezoelectric field for the maximal acoustic power: $T_{11}=3\cdot 10^{-5}$, $T_{33}=9\cdot 10^{-6}$, and $E_1=1.7\cdot 10^4$ V/cm, $E_3=1.7\cdot 10^3$ V/cm (an index of 1 corresponds to the SAW propagation direction [110], an index of 3 corresponds to the normal to the surface).

The heating of the sample due to the active component of the transducer's resistance can also change the PL spectrum. We checked for heating by measuring the PL spectra in two places: by illumination of the sample's surface outside the SAW beam but near the interdigital transducer and by illumination of the sample's surface inside the SAW beam far from the transducer. With cw radio frequency voltage we observed a decrease of the PL lines in both cases, indicating a sample's heating. A decrease in heating of the sample was achieved using short radio frequency pulses (15 $\mu$s) at a small repetition period of 45 $\mu$s. A PL data acquisition was done when the SAW pulse propagated through the region illuminated by the laser. The PL spectra obtained by pulse voltage with and without rf voltage did not change if we illuminated the sample's surface outside the SAW beam but near the interdigital transducer. The changes of the spectra were observed however by illumination of the sample's surface inside the SAW beam far from the transducer. We could therefore rule out the sample's heating as a cause for the PL spectra changes presented in this letter.

The PL spectra of GaAs in the excitonic spectral region for various SAW powers are shown in Fig. 1. The well-studied emission lines of free exciton $FX$, donor-bound exciton $(D°,X)$, ionized donor-bound exciton $(D^+,X)$, and/or

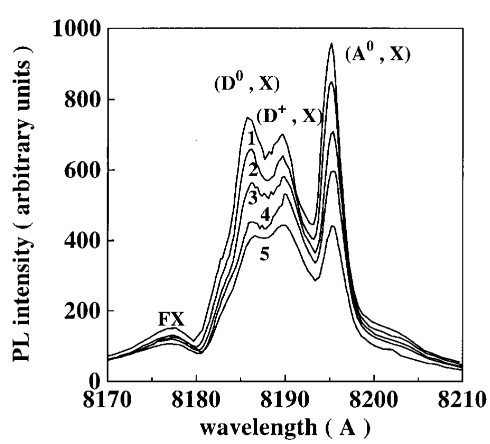


FIG. 1. PL spectra in the excitonic region by different SAW power $P$. (1) $P=0$, (2) $P=0.25P_{\max}$, (3) $P=0.33P_{\max}$, (4) $P=0.5P_{\max}$, and (5) $P=P_{\max}$.

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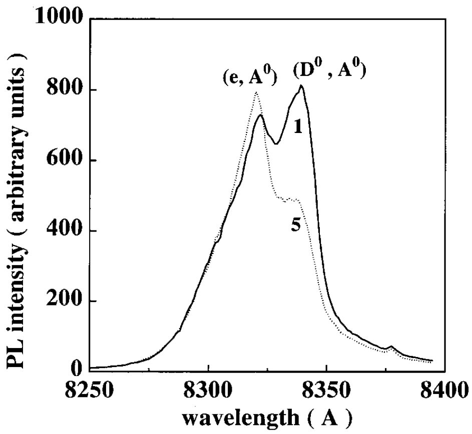


FIG. 2. PL spectra in the acceptor region for (1) $P=0$ and (5) $P=P_{\max}$.

neutral donor-free hole $(D°,h)$, and acceptor-bound exciton $(A°,X)$ are clearly resolved. The transitions are identified in Fig. 1.[2] As seen, an increase in the SAW power causes a decrease of the total PL intensity. The intensity of each particular line depends on the SAW power in varying degree and therefore the total excitonic spectra changes considerably. The SAW has the strongest impact on the intensity of $(A°,X)$ and $(D°,X)$ lines, and it has only a slight effect on the line of free exciton $FX$. We did not observe any changes in the peak's positions.

Figure 2 shows the PL spectra in the acceptor spectral region. Two main peaks involving transitions terminated on beryllium/magnesium acceptor states are dominated:[18] the transition from the conduction band $(e,A°)$ and the transition from the neutral donor $(D°,A°)$. In the presence of SAW we observed a suppression of the $(D°,A°)$ transition but the intensity of the $(e,A°)$ line increases with SAW power. An increase in the intensity of the $(e,A°)$ line does not compensate the total decrease in the intensity of the excitonic lines and $(D°,A°)$ line.

The dependence of the integral intensity of the excitonic lines on SAW power is shown in Fig. 3. By calculation the PL spectra was approximated by the sum of Lorentz curves. As seen in Fig. 3 the dependence of the intensity of $(A°,X)$ and $(D°,X)$ lines on SAW power differs from the behavior of the intensities of the ionized donor-bound exciton $(D^+,X)$ and free exciton $(FX)$ transitions.

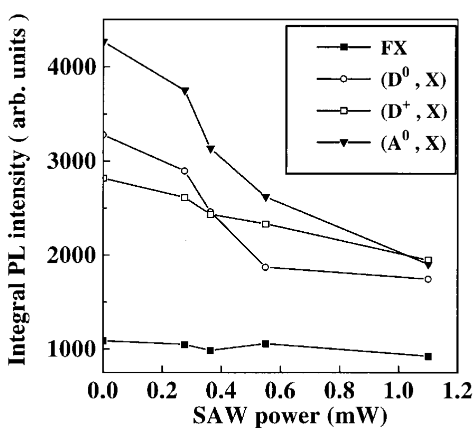


FIG. 3. Integral PL intensity vs SAW power for different lines in the excitonic region.

To understand this strong impact of the SAW on the low-temperature PL spectra of the GaAs layer we notice that in our experimental conditions the piezoelectric field accompanying the SAW exceeds the value of the electric field sufficient for the field ionization of free excitons $(\sim 2.6 \cdot 10^3$ V/cm).[19] The characteristic time[20] of the excitons generation, its bounding on the donors and acceptors, and the exciton recombination is less than a quarter of the SAW's period, and one can neglect a time dependence of the piezoelectric field. The piezoelectric field causes currents to flow. During the Maxwell relaxation time a part of the photoexcited carriers bunches by the space-periodic piezoelectric field into domains with different signs of carriers. The distance between the domains of opposite sign of charges [a half of the SAW wavelength (15 $\mu$m)] is large and the photoexcited carriers in these domains are inhibited from the formation of excitons. This may be a possible explanation for the observed quenching of the total PL intensity.

The screening of the piezoelectric field due to the bunch of the photoexcited carriers causes an increase of the probability of the exciton generation and hence the probability of these excitons to be bound on impurities also grows. In the domains the charge state of donors or acceptors is determined by concentration of the bunch carriers. These carriers become trapped on the impurities, and in the electron domains they ionize acceptors; in the hole domains they ionize donors. It results in a decrease of the intensity of $(A°,X)$ and $(D°,X)$ lines and an increase of the relative intensity of the $(D^+,X)$ line. As the SAW power grows, the size of the domains increase, and this causes a decrease of the intensity of $(A°,X)$ and $(D°,X)$ lines. In the region between domains, the photoexcited electrons is accelerated by the piezoelectric field and ionize the excitons and donors. This process reduces the PL of the excitons and donor-acceptor pairs. The band-acceptor recombination may, most probably, be a channel for the electrons and holes induced because of this ionization. Therefore the intensity of the corresponding line grows.

In conclusion, we have shown experimentally that the surface acoustic waves reduce the total intensity of the 5 K excitonic and impurity PL spectra in GaAs. The strongest effect was observed on the lines of excitons bound on the neutral donors and acceptors. Also, the SAW suppressed the donor-acceptor recombination that can be used in the selection of PL lines by identification of the shallow acceptors in a low-doped GaAs.

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[1] E. W. Williams and H. B. Bebb, in *Semiconductor and Semimetals*, edited by R. K. Willardson and A. C. Beer (Academic, London, 1972), p. 321.
[2] U. Heim and P. Heisinger, Phys. Status Solidi B **66**, 461 (1974).
[3] Z. H. Lu, M. C. Hanna, D. M. Szmud, E. G. Oh, and A. Majerfild, Appl. Phys. Lett. **56**, 177 (1990).
[4] E. C. Larkins, E. S. Hellman, D. G. Schlom, J. S. Harris, Jr., M. H. Kim, and G. E. Stillman, J. Cryst. Growth **81**, 344 (1987).
[5] D. C. Reynolds, D. C. Look, D. N. Talwar, G. L. McCoy, and K. R. Evans, Phys. Rev. B **51**, 2572 (1995).

[6] C. R. Stanley, M. C. Holland, A. H. Kean, J. M. Chamberien, R. T. Grimes, and M. B. Stanway, J. Cryst. Growth **111**, 14 (1991).
[7] T. D. Harris, J. Cryst. Growth **89**, 21 (1988).
[8] B. S. Elman, E. S. Koteles, S. A. Zemon, and Y. J. Chi, J. Vac. Sci. Technol. B **5**, 757 (1987).
[9] W. Bludau and E. Wagner, Phys. Rev. B **13**, 5410 (1976).
[10] Y. Horikoshi, A. Fisher, and K. Ploog, Appl. Phys. A **39**, 21 (1986).
[11] B. J. Skromme, and G. E. Stillman, Phys. Rev. B **28**, 4602 (1983).
[12] H. Weman, Q. X. Zhao, and B. Monemer, Solid-State Electron. **31**, 791 (1988).
[13] B. M. Ashkinadze, V. V. Bel'kov, and A. G. Krasinskaja. Sov. Fiz. Tekn. Polupr. **24**, 883 (1990).
[14] B. L. Gelmont, N. N. Zinov'ev, D. I. Kovalev, V. A. Kharchenko, I. D. Yarosheckii, and I. N. Yassievech, Sov. Zh. Exp. Teor. Phys. **94**, 322 (1988).
[15] For a review see, e.g., H. McFee, in *Physical Acoustics*, edited by W. Mason (Academic, New York, 1966), Vol. 4A, pp. 1–47.
[16] R. M. White and T. M. Voltmer, Appl. Phys. Lett. **7**, 314 (1965).
[17] K. W. Loh, W. S. C. Chang, W. S. Smith, and T. Grudkowski, Appl. Opt. **15**, 156 (1976).
[18] N. A. Yakusheva, K. S. Zhuravlev, O. A. Shegai, and S. I. Chikichev, Cryst. Res. Technol. **24**, 235 (1989).
[19] R. S. Knox. *Theory of Excitons* (Academic, New York, 1963).
[20] R. Hoger, E. O. Gobel, J. Kuhl, K. Ploog, and H. J. Queisser, J. Phys. C **17**, L905 (1984).