Dynamic carrier distribution in quantum wells modulated by surface acoustic waves

F. Alsina, P. V. Santos, and R. Hey
Paul-Drude-Institut für Festkörperlelektronik, Hausvogteiplatz 5-7, 10117 Berlin, Germany

A. García-Cristóbal and A. Cantarero
Materials Science Institute, Universitat de València, Burjassot, E-46100 València, Spain

We have investigated the dynamics of photogenerated carriers under surface acoustic wave (SAW) fields in GaAs quantum wells using spatially and time-resolved photoluminescence (PL). The frequency and phase of the PL oscillations under a SAW yield information about the carrier distribution and the band-gap modulation induced by the SAW. We directly prove that the transport properties of the carriers ultimately control their distribution, storage and, subsequent recombination in the modulated potential.

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The periodic modulation of the optical properties induced by a surface acoustic wave (SAW) has been traditionally used to control the intensity and the propagation direction of light beams in piezoelectric insulators. In polar semiconductors, the piezoelectric field of the SAW interacts strongly with carriers, thus opening the possibility of using these waves to induce a dynamic lateral modulation of the electronic properties. In addition to the strong type-II modulation imposed by the piezoelectric field, the strain field of the SAW leads to a weak lateral modulation of the band gap. The SAW fields have been applied to control the lifetime and the transport of photogenerated carriers and of their spins in low-dimensional semiconductor structures.1–3 In these applications, the SAW piezoelectric field ionizes photogenerated electron-hole pairs. The free electrons and holes are then trapped in the region of maxima and minima of the moving piezoelectric potential. The spatial separation considerably increases the carrier lifetime, so that they can be transported over macroscopic distances by the SAW.2

An interesting question regarding the interaction between SAW’s and photogenerated carriers is how the latter distribute in the dynamic strain and piezoelectric fields, when the SAW wavelength $\lambda_{\text{SAW}}$ and oscillation frequency $\omega_{\text{SAW}}$ become comparable to the carrier transport lengths and inverse lifetimes, respectively. In this work, we investigate the carrier dynamics in GaAs quantum wells (QW’s) under high-frequency SAW’s using time-resolved and spatially resolved photoluminescence (PL) spectroscopy. Since the modulation introduced by SAW’s is both spatial and time dependent, this technique gives a deep insight into the mechanisms of the interaction between SAW’s and carriers. We demonstrate that the modulation of the optical properties by high-frequency SAW’s is dominated by nonlocal effects in time and space arising from the dynamic redistribution of photoexcited carriers in the SAW profile. In fact, while for low SAW frequencies the probability of ionization of electron-hole pairs by the piezoelectric field is expected to depend only on the magnitude of the field, and thus to be modulated only at multiples of $\omega_{\text{SAW}}$, the measured PL under a high-frequency SAW displays a strong modulation at the fundamental frequency $\omega_{\text{SAW}}$. This behavior is explained by taking into account the transport properties of the photogenerated carriers and their ability to follow the moving potential. Furthermore, we show that the intensity, energy, and phase of the PL pulses provide a direct mapping of the microscopic carrier distribution and of the band-gap modulation induced by the SAW.

The studies were performed on a 15-nm GaAs QW with Al$_{x}$Ga$_{1-x}$As barriers grown by molecular-beam epitaxy on GaAs (001). The QW is placed 200 nm below the surface. SAW’s propagating along the $x=[110]$ surface direction were generated by aluminum split-finger interdigital transducers (IDT’s) deposited on the sample surface and designed for operation at a wavelength $\lambda_{\text{SAW}}=5.6$ $\mu$m [corresponding to a frequency $\omega_{\text{SAW}}/(2\pi)=520$ MHz at 12 K]. The PL measurements were carried out at 12 K using a confocal microscope with illumination and detection areas with a diameter of about 2 $\mu$m. The continuous radiation from a Ti:sapphire laser ($\lambda=765$ nm) was employed as excitation source. Time resolution was achieved by using a fast photomultiplier (time resolution of approximately 0.4 ns) to detect the PL. Information about the SAW phase was obtained by synchronizing the photomultiplier with the radio-frequency (rf) generator employed to drive the IDT’s. The setup also allows for interferometric measurements of the surface displacement $u_z$ induced by the SAW, which was used to determine the amplitude of the SAW strain field.

The effects of the SAW fields on the cw PL are illustrated in Fig. 1(a). The spectra were recorded with coincident illumination and detection areas in the absence (line) and under the influence of a SAW with a nominal excitation power of 16 dBm (dots). In the latter case, the PL intensity becomes strongly suppressed due to the interaction between the SAW piezoelectric field and the photogenerated carriers.1–3 In addition, the PL line exhibits a small blueshift, which arises from the SAW strain field, as will be demonstrated in the following.

The dynamics of the PL quenching becomes apparent in time-resolved measurements. Figure 2(a) shows the PL traces collected at 1.5331 eV, which coincides with the maximum of the spectrum for $P_{\text{rf}}=16$ dBm in Fig. 1(a). The PL signal is time modulated with the periodicity $T_{\text{SAW}}=2\pi/\omega_{\text{SAW}}=1.92$ ns of the applied SAW. The modulation is superimposed on a background, leading to a modulation.
amplitude of approximately 50% of the mean PL value. The latter decreases with the rf power (not shown) in agreement with the time-integrated PL spectra displayed in Fig. 1(a). We can rule out effects other than the interaction with the SAW as the source of the reported changes, since (i) the oscillations in the time-resolved signal were observed on the SAW path in areas far away from the transducer, and (ii) they completely disappear, and the PL signal recovers the value without SAW, when the rf is detuned from the transducer resonance band.

The background superimposed on the oscillations is al-

most suppressed when the PL is recorded with spatially separated illumination and detection spots. The separation was achieved by displacing the detection pinhole in the PL setup away from its confocal position, following the procedure described in Ref. 4. Figure 2(b) displays a time-resolved PL trace recorded when the PL is detected 6 μm away from the generation position along the propagation direction of the SAW. The PL, in this case, arises from carriers that are transported by the SAW and recombine within the detection area. In order to enhance the carrier recombination, the detection spot was placed next to a semitransparent metal stripe used to quench the SAW piezoelectric field.\(^5\) The distinctly detected PL is only observed when the rf is switched on, further evidencing that it is induced by the recombination of carriers transported by the SAW.

The ionization and spatial separation of electron-hole pairs is expected to be a nonlinear function of the SAW piezoelectric field, since it depends only on the magnitude and not on the sign of the field. As a consequence, the PL oscillations should be dominated by components at the second and higher harmonics of the SAW frequency \(\omega_{\text{SAW}}\). The experimental results in Fig. 2, however, show a strong modulation at the fundamental frequency \(\omega_{\text{SAW}}\). The discrepancy is attributed to the fundamental role of the carrier transport properties on the modulation mechanism. In order to clarify this point, we performed simulations of the carrier distribution and of the recombination probability in the dynamic SAW profile. In a first step, the strain field and the strain-induced energy changes of the conduction (CB) and valence bands (VB) were calculated following the method described in Ref. 5. The amplitude of the SAW fields was determined by adjusting the SAW vertical displacement field (\(u_z\)) obtained from an elastic model\(^6\) to the value obtained by interferometry [symbols in Fig. 3(a)]. The calculated strain-induced shifts of the electron (\(\Delta E_c\)) and heavy-hole (\(\Delta E_{hh}\)) energy levels are displayed in Fig. 3(b). In a second step, the carrier distribution in the modulated conduction and valence bands, as well as the recombination rate, were calculated by solving the drift–diffusion equations for electrons and holes in the SAW potential.

Figures 4(a–c) display spatial profiles for the electron (n, solid line) and hole (p, dashed line) densities, the recombination probability (\(\propto n p\), dots), as well as the piezoelectric potential (\(\Phi\)), for three successive times. In the calculations, we assumed that the carriers are continuously generated in the dashed region around \(x=0\) starting at time \(t=0\). Electron (\(\mu_c\)) and hole (\(\mu_h\)) mobilities of 5000 and 500 cm\(^2\)/(V s), respectively, were used in the simulations. The same qualitative results were obtained for carrier mobilities in a wide range around these values, as long as \(\mu_c \gg \mu_h\). As time progresses, the carriers are swept along the SAW propagation direction. The concentration profiles away from the generation area can be easily understood by considering that, in order to follow the dynamic modulation induced by the SAW, the mobilities \(\mu_c\) and \(\mu_h\) must exceed \(v_{\text{SAW}}/F_{\text{eff}}\), where \(v_{\text{SAW}}\) denotes the SAW propagation velocity and \(F_{\text{eff}}=|\partial \Phi/\partial x^\prime|_{\text{max}}\) the effective field created by the modulated potential profile \(\Phi\). This condition is normally satisfied for the highly mobile electrons, which display a sharp spatial
distribution around the potential maxima. The holes, however, are less able to follow the dynamic modulation. As a consequence, they show a much wider spatial distribution in the SAW field as compared to electrons (cf. Fig. 4). Therefore, the spatial distribution of the recombination probability, proportional to \( np \), basically reflects that of the electron distribution \( n \). In agreement with Fig. 2 (b), PL pulses appear once within an rf cycle, when the maximum in the electron density crosses the detection point at a fixed position away from the generation area.

The asymmetry in mobilities for electrons and holes also accounts for the time dependence of the PL emission for confocal generation and detection at position \( x = 0 \). The continuous carrier generation makes the profiles more complex in this case. When the potential is maximum in the generation area (cf. Fig. 4(a)), photogenerated electrons are kept around \( x = 0 \). The low mobility of the holes, however, restricts their ability to reach regions of minimum potential, leading to a maximum recombination probability. The situation reverses when the SAW potential reaches a minimum (Fig. 4(c)), since electrons can be quickly extracted from the generation area before substantial recombination occurs. The decrease in the recombination rate leads to significant carrier storage in the modulated potential profile.

The well-defined phase relation between the SAW strain and piezoelectric fields, which are responsible for the modulation of the band gap and of the carrier distribution, respectively, correlates the intensity, energy, and phase of the time-resolved PL pulses. This effect becomes clear in Fig. 3(c), which displays simulated time-resolved PL traces for confocal excitation and detection at the three transition energies indicated by vertical arrows in Fig. 3(b). When the detection energy corresponds to the maximum band gap (\( E_{g,\text{max}} \), dashed line) or to the minimum band gap (\( E_{g,\text{min}} \), solid line), only a single PL pulse per rf cycle is expected. The pulses are displaced in phase by 180°, since emission at these two energies takes place at time intervals differing by \( T_{\text{SAW}}/2 \) (the width of the simulated PL pulses are determined by the spatial extent of the illumination and detection areas indicated in Fig. 4). The PL modulation is the largest for detection at \( E_{g,\text{max}} \) due to the reasons discussed in the previous paragraph. For detection energies between \( E_{g,\text{min}} \) and \( E_{g,\text{max}} \), two pulses per cycle are expected, when the band gap matches the detection energy. According to the calculations in Fig. 3(c), the intensity of the pulses is considerably smaller than in the previous cases due to the strong electric field.

As a consequence of the strain-induced band-gap modu-
FIG. 5. Time-resolved PL detected at energies ranging from (a) 1.5316 eV to (k) 1.5339 eV in steps of 0.25 meV. Measurements were performed with coincident illumination and detection areas. For clarity, the curves are displaced vertically.

In conclusion, we have investigated the dynamic modulation of the band structure and of the carrier density induced by a SAW using spatially and time-resolved PL measurements. This technique allows for a direct mapping of the carrier densities and of the recombination energies. We demonstrate that the modulation of the electronic properties depends not only on the SAW acoustic and piezoelectric fields, but also on the transport properties of the carriers.

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*Electronic address: falsina@pdi-berlin.de


