Dynamics of indirect exciton transport by moving acoustic fields

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Abstract
We report on the modulation of indirect excitons (IXs) as well as their transport by moving periodic potentials produced by surface acoustic waves (SAWs). The potential modulation induced by the SAW strain modifies both the band gap and the electrostatic field in the quantum wells confining the IXs, leading to changes in their energy. In addition, this potential captures and transports IXs over several hundreds of μm. While the IX packets keep to a great extent their spatial shape during transport by the moving potential, the effective transport velocity is lower than the SAW group velocity and increases with the SAW amplitude. This behavior is attributed to the capture of IXs by traps along the transport path, thereby increasing the IX transit time. The experimental results are well-reproduced by an analytical model for the interaction between trapping centers and IXs during transport.

Keywords: excitons and related phenomena, quantum wells, acousto-electric phenomena and surface acoustic waves, photoluminescence properties of materials
1. Introduction

The strong interaction with photons makes excitons ideal particles for the processing of optical information in solid-state devices [1]. To reach this goal, functionalities like storage, transport, and manipulation of excitons become mandatory. Spatially indirect (or dipolar) excitons (IXs) are particularly suitable for these applications due to their long lifetime and energy tunability. An IX in a double quantum well (DQW) structure is a bound state of an electron and a hole localized in two different quantum wells (QWs) separated by a thin (i.e., less than the exciton Bohr radius) barrier. As illustrated in figures 1(a) and (b), IXs are formed by applying an electric field $F_z$ across the DQWs to drive the electron and hole constituents into different QWs, while still maintaining the Coulomb correlation between the particles. $F_z$ controls, via the quantum confined Stark effect (QCSE), both the energy and the lifetime of the IXs, the latter of which can reach several hundreds of $\mu$s [2]. These long lifetimes open the way for information storage as well as for the creation of cold bosonic gases for study of coherent exciton phases [3–5]. In addition, the oriented IX electric dipoles give rise to strong repulsive IX–IX interactions [6]. The non linearity associated with these interactions has been explored for the realization of IX gates [6, 7] and exciton transistors [8]. The combination of non linearity with tight lateral confinement using electrostatic gates has recently been explored for the isolation of single IX states [9]. Also, the electric dipole provides a tool for the manipulation of IXs using electric field gradients. Examples of electrically driven device functionalities include exciton storage cells, switches, and transistors [8, 10, 11].

Long IX lifetimes also enables the long-range transport of IX packets, which opens the way for the coupling of remote IX systems. Different approaches have been introduced to transport IXs based on bare diffusion [12], drift induced by repulsive IX–IX interactions [3], or by spatially varying electric fields, including electrostatic ramps [13] and moving electrostatic lattices [14]. Recently, we have shown that IXs can be efficiently transported by the moving (and tunable) type-I band gap modulation ($\delta E_g$) produced by the strain of a surface acoustic wave (SAW, cf figure 1(c)) [15]. During the SAW-induced transport, the long-living IXs are captured in regions of minimum band gap, which move with the well-defined SAW velocity. The transport of IX packets with a constant velocity becomes interesting since it allows synchronization with control gates, optical sources, and detectors [10].

The band structure modulation as well as the long-range acoustic transport of electrons and holes by piezoelectric SAWs is well documented in the literature [16–19]. In this case, the interaction between the SAW and carriers is primarily mediated by the SAW piezoelectric field, which creates a moving type-II modulation of the conduction (CB) and valence band (VB) edges. This type of modulation separates electrons and holes and normally leads to exciton dissociation. Due to that, the acoustic manipulation of excitons rather requires a type-I band gap modulation, which can be produced by the strain of a non-piezoelectric SAW [15]. While the piezoelectric modulation amplitudes can reach several tens of meV, the type-I strain modulation is limited to a few meV. Due to the very different amplitudes, the two types of modulations lead to different transport regimes. Investigations of the IX dynamics under non-piezoelectric SAWs have so far only been carried out in the quasi-static regime, i.e., for time scales much longer than the acoustic period [15].

In this work, we report on the modulation of the energy levels as well as on the transport of IX packets in (Al,Ga)As QW structures by non-piezoelectric SAWs. The studies were carried...
out using spatially and time-resolved photoluminescence (PL) spectroscopy to probe the energetics as well as the evolution of IX packets in space and time with resolutions in the μm and ns ranges, respectively. We show that the application of a SAW induces shifts in the IX energies with very different time scales. The first are the oscillating changes in band gap caused by the strain field, which take place at the SAW frequency. The second type of energetic shifts have a higher amplitude and persist for much longer (up to ms) time scales. They are attributed to charge trapping in the (Al,Ga)As structure, which modifies the external electric fields applied

Figure 1. (a) Samples for indirect exciton (IX) transport by surface acoustic waves (SAWs). The IXs are optically excited using a focused laser pulse in a double quantum well (DQW) structure by applying a bias $V_{\text{BIAS}}$ between the doped substrate and a semitransparent top electrode (STE). The SAW is launched along the $x = [100]$ direction by an interdigital transducer (IDT) placed on a piezoelectric ZnO island. IX transport is mapped by photoexciting IXs in the DQW and imaging the PL emitted along the transport path. The superimposed PL image was recorded at 3.8 K using $V_{\text{BIAS}} = -1.6 \, \text{V}$ and a band gap modulation amplitude $\delta E_g = 1.8 \, \text{meV}$. (b) Energy band diagram of the GaAs/(Al,Ga)As DQW along the vertical ($z$) direction showing the direct (DX) and IX transitions under the electric field $F_z$. (c) IX transport by the moving modulation of the conduction (CB) and valence bands (VB) in a DQW. $E_{g, \text{min}}$ and $E_{g, \text{max}}$ denote, respectively, the minimum and maximum band gaps induced by the SAW strain field along the $x = [100]$ direction. (d) Depth dependence of amplitude modulation of the conduction ($\delta E_{\text{CB}}$) and valence band edges ($\delta E_{\text{VB}}$) as well as of the bandgap modulation $\delta E_g = (\delta E_{\text{CB}} - \delta E_{\text{VB}})$ calculated for a SAW with wavelength $\lambda_{\text{SAW}} = 2.8 \, \mu\text{m}$ and linear power density $P_\ell = 200 \, \text{W m}^{-1}$. The band edge modulation is of type-I within the shaded region. The depth of the DQWs (dashed vertical lines) was selected to ensure that $|\delta E_{\text{CB}}| \approx |\delta E_{\text{VB}}|$. 

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to create IXs. In addition, the moving SAW fields can transport IX packets over several hundreds of μm with reduced shape distortion. The transport velocity of the IX packets increases with acoustic amplitude but never reaches the SAW velocity, even when strong acoustic fields are applied. The transport dynamics depends on potential fluctuations in the QW as well as IX trapping, which, as for energetic changes, also take place over a wide range of time scales. Effects on a short time scale (compared to the SAW period) are taken into account by defining an effective exciton mobility under the SAW fields. We show that one also has to take into account exciton trapping along the transport path, which capture IXs over time intervals much larger than the SAW period thus increasing the transit time and decreasing the transport velocity. We present a model for the effects of exciton trapping, which well reproduces their impact on both the transport velocity and the shape of the IX packets.

In the following, we first describe the sample structure and the optical techniques used to probe the acoustic transport of excitons by SAWs (section 2). We then present experimental optical studies of the effects of the acoustic fields on the IX energy levels as well as on the time evolution of IX packets during acoustic transport (section 3). In section 4 the experimental results of IX dynamics are analyzed in terms of a model for the transport, which takes into account IX trapping by centers along the transport path. Finally, section 5 summarizes the main conclusions of this study.

2. Experimental details

The samples used in the experiment consist of three sets of asymmetric GaAs DQWs grown by molecular beam epitaxy on a $n^+$-doped GaAs(001) substrate (cf figure 1(b)). Each DQW is formed by a 14 nm (QW$_1$) and a 17 nm thick QW (QW$_2$) separated by a thin (4 nm thick) Al$_{0.3}$Ga$_{0.7}$As barrier. Multiple DQWs were used in order to enhance the photon yield of the photoluminescence (PL) experiments. The different QW widths allow for the selective generation of excitons in either QW$_1$ or QW$_2$ by the appropriate selection of the excitation wavelength: [20] this feature, however, has not been explored in the present studies. The electric field $F_z$ for the formation of IXs was induced by a bias voltage $V_{BIAS}$ applied between the n-doped substrate and a thin (10 nm thick) semitransparent Ti electrode (STE) deposited on the sample surface, as illustrated in figure 1(a).

The moving acoustic field was provided by a Rayleigh SAW with a wavelength $\lambda_{SAW} = 2.8 \mu m$, corresponding to a frequency $f_{SAW} = 1$ GHz at 4 K. The SAW was generated along a ⟨100⟩ non-piezoelectric surface direction using aluminum interdigital transducers (IDTs) deposited onto a piezoelectric ZnO island. In order to minimize the screening of the radio-frequency (rf) field by carriers in the doped substrates, the DQW stack were embedded within thick, undoped Al$_{0.26}$Ga$_{0.74}$As layers. In this way, the total thickness of the undoped overlayers could be increased to approx. one $\lambda_{SAW}$.

The use of non-piezoelectric SAWs is essential to prevent exciton ionization by the piezoelectric field [15]. As illustrated in figure 1(c), the strain field produces, via the deformation potential interaction, a moving type-I modulation of the band edges, which confines IXs close to the SAW phases of lower band gap (cf figure 1(c)) and transports them with the acoustic velocity $v_{SAW}$. The SAW strain field and, therefore, the modulation of the band edges change with depth. The solid lines in figure 1(d) display the depth dependence of the
conduction \((\delta E_{CB})\) and valence \((\delta E_{VB})\) bands, as well as the band gap modulation \(\delta E_g = (\delta E_{CB} - \delta E_{VB})\) calculated for a SAW with a linear power density \(P = 200\, \text{W m}^{-1}\) \((P\) is defined as the acoustic power per unit length perpendicular of the SAW beam). The profiles were determined using a \(k \cdot p\) approach by taking into account the deformation potentials and the full SAW strain field obtained from an elastic continuum model for SAW propagation in the layered structure of the sample [21]. The amplitude and relative phases of the band edged modulation change with depth. For depths between 0.15 \(\lambda_{SAW}\) and 0.35 \(\lambda_{SAW}\) \(\delta E_{CB}\) and \(\delta E_{VB}\) have opposite phases, thus producing a type-I lateral potential modulation, which confines electrons and holes at the same spatial position \(x\) along the SAW path. The dashed vertical lines represent the positions of the three DQWs, which were selected in order to get band edge modulations of approximately the same amplitude but opposite phases for electrons and holes [15]. Different depths also lead to slightly different modulation amplitudes \(\delta E_g\) in the three DQWs. For the range of used acoustic powers, however, these differences are small compared to the spectral linewidth of the IXs. Finally, it is worth noting that while metallic gates (such as the ones used to apply the electric field in figure 1) can be used to screen the piezoelectric field of piezoelectric SAWs, the screening is restricted to the surface near region, where the strain field does not produce the type-I band gap modulation required for IX confinement.

The spectroscopic experiments were carried out at temperatures between 1.8 and 5.5 K in a He bath cryostat with rf electrical connections for SAW excitation. Excitons were generated on the SAW path using a laser beam focused onto a spot with a diameter of 10 \(\mu\)m using a microscope objective. We used either a tunable cw Ti:Sapphire laser or a pulsed semiconductor laser emitting at 780 nm with pulse duration and repetition rate of 300 ps and 2.5 MHz, respectively. The laser excitation energies were always below the band gap of the (Al,Ga)As barrier in figure 1(b) to selectively excite carriers in the QWs. The PL from IXs emitted along the SAW path was collected by the same objective and detected with energy and spatial resolution using a cooled charge-coupled-device camera connected to a spectrometer. Time-resolved PL measurements were carried out using an avalanche photodiode with time resolution of 400 ps synchronized with the laser pulses.

3. Results

3.1. Bias dependence of the IX lines

The structure of figure 1(b) forms a rectifying Schottky diode with the current \((I)\) versus voltage \((V_{BIAS})\) characteristics illustrated in the inset of figure 2. The diodes have an excellent blocking behavior in the reverse bias region (i.e., for negative \(V_{BIAS}\)). The current levels for voltages in the range \(-2 < V_{BIAS} < 1\, \text{V}\) were less than 1 nA (see inset of figure 2) for devices with an area of 400 \(\times\) 400 \(\mu\)m\(^2\), even under excitation with light energies below the band gap of the (Al,Ga)As barriers. As will become clear later, these blocking characteristics are important to avoid carrier injection from the contacts and, thus, to ensure that the optically generated electrons and holes are both carried along the DQW structures during acoustic transport.

The dependence of the PL emission lines on \(V_{BIAS}\) is displayed in figure 2. Here, \(DX_1\) and \(DX_2\) denote the emission from direct excitons associated with the electron-heavy hole transitions in \(QW_1\) and \(QW_2\), respectively. A closer observation (cf left inset) reveals that the \(DX\)
lines are split into two components. The splitting is attributed to the coexistence of both neutral and charged direct excitons. The $DX_1$ and $DX_2$ energies slightly red-shift with $V_{\text{BIAS}}$ due to the intra-well QCSE induced by the applied bias.

The application of a negative bias creates IXs with the electron and hole constituents confined within the wider (QW$_2$) and narrower (QW$_1$) QWs, respectively. In general, the IX PL splits into different lines (as indicated by IX$_1$ and IX$_2$ in figure 2), whose energy red-shifts linearly with the applied bias. The splitting depends on acoustic power and on the illumination conditions. This last behavior contrasts with the one observed for direct excitons, where, for each QW, the energy splitting between charged and neutral exciton lines does not change with the excitation conditions. As will be discussed in detail later, the splitting of the IX lines is attributed charge trapping in the DQW structure, which creates an inhomogeneous field distribution along the growth direction. The latter can give rise to up to three different IX energies, each corresponding to one of the DQWs. The IX lines red-shifts due to the inter-well QCSE at a rate of approximately $r_v = 6 \text{ meV V}^{-1}$. The latter corresponds approximately to the potential difference between the center plane of the QWs given by $V_{\text{BIAS}} \left( d_{\text{QW}} + d_{\text{QW}} + d_B \right)/d_T = 6.92 \text{ meV V}^{-1}$, where $d_{\text{QW}}$ ($i = 1, 2$) denotes the QW thickness, $d_B$ is the barrier width, and $d_T$ the total thickness of the intrinsic regions between the doped substrate and the STE. Finally, the formation of IXs is also observed for positive bias higher than approximately 2.5 V. This regime, however, will not be further explored here.

![Figure 2.Dependence of the photoluminescence (PL) intensity emission (color scale) on energy and applied bias $V_{\text{BIAS}}$ (cf figure 1(a)). The measurement were carried out at 2 K using an excitation energy of 1.54 eV. $DX_1$ and $DX_2$ denote the emission lines associated with the electron-heavy hole direct excitons of QW$_1$ and QW$_2$, respectively. The indirect exciton line (IX) red-shifts with reverse bias at a rate of 6 meV V$^{-1}$. The inset shows the I-V characteristic of the Schottky diodes, which have an area of approx. 400 $\times$ 400 $\mu$m$^2$. The right plot displays the spectrum measured at the voltage indicated by the dashed line.](image)
3.2. Acoustic modulation of excitons

The color maps of figures 3(a) and (b) illustrate the effects of the acoustic field on the emission of DXs. The plots display the spectral distribution of the PL from the DQWs as a function of the distance (x) from the generation spot in the absence and presence of a SAW beam, respectively. The measurements were carried out at 3.8 K under $V_{\text{BIAS}} = 0$ V, where only the electron-heavy hole direct excitons in QW$_1$ and QW$_2$ are observed ($DX_1$ and $DX_2$, respectively). The DX emission is spatially constrained to a circle of radius of approx. 16 μm around the generation spot. The size of the emission region is determined by the expansion of the DX cloud around the illumination spot. In contrast to the behavior of excitons under piezoelectric SAWs [16], neither a substantial quenching of the integrated PL intensity nor long-range acoustic transport are observed under non-piezoelectric SAWs. This behavior is consistent with the fact that the type-I band gap modulation of figure 1(b) does not ionize excitons by spatially separating electrons and holes. The DX radiative lifetimes remain short, thus preventing the acoustic transport over distances $\gg \lambda_{\text{SAW}}$.

As in the piezoelectric case, [17] figure 3(b) also shows that the periodic modulation of the band gap by the SAW strain splits the DX [15, 17] lines, the splitting being equal to twice the amplitude $\delta E_{\text{g}} = \left( E_{\text{g,max}} - E_{\text{g,min}} \right)/2$ of the band gap modulation. $\delta E_{\text{g}}$ is plotted as a function of $P_{t}^{1/2}$, where $P_t$ is the acoustic power per unit length perpendicular of the SAW beam. The solid line was calculated following the $k \cdot p$ procedure described in the text.

**Figure 3.** Spectral PL maps (on a log color scale) as a function of the distance x from the laser excitation spot recorded for nominal rf-powers applied the IDT of (a) $P_t = 0$ and (b) $P_t = 12$ dBm. The measurements were carried out at 1.8 K under $V_{\text{BIAS}} = 0$ V, where only the electron-heavy hole direct excitons in QW$_1$ and QW$_2$ are observed ($DX_1$ and $DX_2$, respectively). (c) Band gap modulation $\delta E_{\text{g}} = \left( E_{\text{g,max}} - E_{\text{g,min}} \right)/2$ as a function of $P_{t}^{1/2}$, where $P_t$ is the acoustic power per unit length perpendicular of the SAW beam.
The solid line displays the dependence of $\delta E_g$ on $P_{cal}$ calculated using the previously mentioned $k \cdot p$ approach. Both the measured and calculated values reproduce the linear dependence of the modulation amplitude on $P_{cal}^{1/2}$.

The impact of the acoustic fields on the PL spectrum is illustrated in figure 4(a). The bottom spectrum shows the PL spectrum of the samples recorded under a reverse bias ($V_{bias} = -1.6$ V) in the absence of a SAW. Under these conditions, one finds in addition to the direct exciton lines the red-shifted signatures from IXs. The additional solid curves in this figure were recorded for increasing acoustic powers $P_{rf}$ (from bottom to top). The IX lines broaden and shift in energy with $P_{rf}$. The broadening is attributed to the strain-induced modulation of the (spatially indirect) band gap. In contrast to the behavior of DXs under a small applied bias (cf figure 3(b)), the larger spectral width and longer lifetime of the IXs prevent the observation of the strain-induced splitting of the lines.

The IX energy shifts with increasing $P_{rf}$ in figure 4(a) are different for lines IX$_1$ and IX$_2$ and are much larger than the band gap modulation amplitude $\delta E_g$. Note that while the center position of the DX emission lines remain constant, the IX$_1$ and IX$_2$ lines blue-shift and approach DX$_2$ for high acoustic powers. The observation of multiple IX lines (for nominally identical DQWs) as well as the energetic shifts with acoustic power are attributed to previously mentioned changes in the electric field across the DQWs due to charge redistribution induced by the acoustic field. The latter can be induced by charge transfer between the DQWs or by...
charge trapping in the barrier layers. The DQWs are embedded within (Al,Ga)As barrier layers with high electrical resistance. As a result, charges can be stored for long times either in the DQWs or in the barrier layers, leading to variations in the electrostatic field configuration.

The SAW induced IX energy shifts in figure 4(a) have a transient character and persists after the acoustic field has been switched off. In order to justify this assignment the PL was recorded while modulating both the amplitude of the rf-power $P_r$ applied to the IDT and the laser excitation beam with a square wave with a repetition period of 3.6 ms (cf figure 4(b)). The solid lines in figure 4(a) were recorded with the optical and rf square waves in phase (denoted as the phase ON condition in figure 4(b)). In this case, both excitations are applied simultaneously to the sample. For comparison, measurements were also carried out by shifting the phase of the two square waves by 180° (phase OFF condition, indicated by the dashed lines in figure 4(a)). Here, the sample is illuminated while the SAW is switched off. Since the lifetime of the IXs is much shorter than the square wave period, the PL is emitted during the light pulses, when the SAW is turned off. Note, however, that with increasing $P_r$ the IXs blue-shift with respect to the energies measured without acoustic excitation (lowest spectrum), the blue-shift increasing with the amplitude of the previously applied SAW pulses. The observed shifts in IX energy indicate that the charge configuration created by the SAW pulses persists for times scales exceeding 1 ms. In contrast, the DX lines remains essentially the same in the phases ON and OFF. Finally, since the modulation periods are also shorter than the thermal relaxation times, these results also show that the modifications in the IX emission cannot be assigned to thermal effects.

The acoustically induced energy shifts for IXs in figure 4(a) appear even for very weak acoustic powers, which correspond to SAW amplitudes far below those required for efficient acoustic transport along the SAW propagation direction (see section 3.3). Furthermore, we have observed that illumination with photon energies above the band gap of the barrier layers can lead to large shifts in the IX energies even in the absence of acoustic excitation. Here, the electric field becomes perturbed by the photo-excited electrons and holes, which are spatially separated by the applied vertical field. For the selective excitation of the QWs using laser energies below the band gap of the barriers, in contrast, these shifts are very small in the absence of a SAW. They increase, however, under the application of a SAW (cf figure 4(a)). Carrier redistribution along the growth direction may be related to the acoustic transport along the QW plane (see the following section). The microscopic mechanisms for the acoustically assisted charge redistribution are presently not understood and require additional investigations.

**3.3. IX transport**

The optical technique used to probe acoustic transport is illustrated by the time-integrated PL image superimposed on the sample layout of figure 1(a), which maps the average distribution of IXs transported along the channel defined by the SAW beam underneath the STE. In this image, the contributions from exciton diffusion to the transport, which are only significant close to the generation spot, were eliminated by subtracting a similar image recorded in the absence of the SAW beam. The PL along the transport path is attributed to the recombination of IXs captured by trapping centers in the DQW plane. While it allows to visualize the IX distribution, trapping also reduces the transport efficiency and, as will be discussed in detail below, the effective IX transport velocity. The mechanism for the strong PL at the edge of the STE opposite to the IDT has a different origin. Here, the potential barrier created by the abrupt reduction of the vertical field $F_z$ blocks further transport and forces IX recombination.
In order to provide further evidence for the acoustic transport of IXs, we have also carried out transport experiments with \( V_{\text{BIAS}} \) close to the flat band condition, where no IXs are formed. In this case, no PL was observed for distances exceeding a few tens of \( \mu \text{m} \) from the generation spot, thus ruling out the acoustic transport of neutral or charged [22] direct exciton species. In addition, we show in [23] that in our samples both electrons and holes are transported along the DQW channels. As a consequence, the remote PL at the IX energy (as in figure 1(a)) cannot be attributed to the recombination of carriers of one polarity transported along the DQW channel with carriers of the opposite polarity injected from the contacts. Finally, the acoustic transport of charged exciton species [22] along the DQW channels cannot account for the remote PL. In fact, the motion of charged species would quickly induce a space charge field, which would then block the steady-state acoustic transport observed in figure 1(a).

Additional information about the IX transport mechanism was obtained from the spectral distribution of the PL along the transport path measured for different acoustic powers in the lower panels of figure 5. These PL maps were recorded under the phase ON condition described above, where the optical and acoustic excitations are applied in phase (cf figure 4(b)). The IX are captured by the acoustic field and transported up to the end of the STE, which is located at a distance \( d = 250 \mu \text{m} \) away from the generation spot (indicated by the horizontal solid arrow in (a)). The upper plots display, for comparison, the corresponding maps measured in the phase OFF conditions (cf figure 4(b)). The IX cloud extends, in this case, up to distances from the generation point of at most 80 \( \mu \text{m} \).

The solid and dashed vertical arrows in figure 5 mark the energy of the main indirect and direct exciton lines determined in the absence of acoustic excitation. For low acoustic power (lower panel in figure 5(a)) transport takes place preferentially through the lowest lying IX\(_1\) state, which has the longest recombination lifetime. For intermediate SAW amplitudes (figure 5(b)), the strongest emission along the transport path is observed for IX\(_2\), which blue-shifts with acoustic power. In contrast, most of the PL at the end of the transport channel has an energy close to the one of DX\(_2\). Since the lifetime of direct excitons is expected to be much smaller than the transit time of the carriers (on the order of \( d/v_{\text{SAW}} = 100 \text{ ns} \), where \( v_{\text{SAW}} \) is the acoustic velocity), they cannot be transported over such large distances. The emission at the DX\(_2\) energy along the transport path is attributed to the conversion of IXs to DX\(_2\), followed by a fast radiative decay of the DX\(_{2s}\). The interconversion becomes enhanced at the edges of the STE, where the suppression of \( F_z \) reduces the energy separation between the direct and indirect excitonic species.

Under the action of a reverse bias \( V_{\text{BIAS}} \), the IXs in the structure of figure 1(b) consist of electrons stored in the wider (QW\(_2\)) and holes in the narrower (QW\(_1\)) QWs. As a result, the IX-DX\(_2\) conversion followed by the DX\(_2\) recombination requires the excitation of the IX-holes from QW\(_1\) to the wider QW\(_2\). For a given SAW phase, the strain-induced shifts of the band edge energies are expected to be approximately the same for both QWs. As a result, the hole tunneling probability between them is not expected to be substantially affected by the SAW strain field. During transport, however, an exciton (or one of its constituents) initially stored at the minimum of the modulation may be trapped and then subsequently released at a SAW phase corresponding to the maximum modulation (i.e., highest band gap). The kinetic energy gained during relaxation to the positions on minimum band gap, which can be as high as the peak-to-peak band gap modulation amplitude, may then assist the transition of a hole from QW\(_1\) to QW\(_2\).
required for the interconversion to a $DX_2$. The efficiency of this process is expected to increase when the difference in energy between the hole levels in the two QWs becomes comparable to the peak-to-peak amplitude of the acoustic modulation of the VB edge, on the order of $1–2$ meV in the present case. The latter is supported by enhanced emission at the $DX_2$ energy for high acoustic power in figure 5(c), when the electric field changes induced by charge trapping blueshifts $IX_2$ towards $DX_2$. In this case, most of the emission along the transport path takes place at the direct exciton energy.

3.4. Transport dynamics

The dynamics of the acoustic transport was investigated by recording time-dependent PL profiles at different distances $d$ from the pulsed laser excitation spot using an avalanche photodiode synchronized with the laser pulses. The integrated PL over the energy range of excitonic emission was collected over a 10 μm wide stripe across the propagation path of a SAW. The time resolution of the experiments is then given by the ratio between this length and the average velocity of the $IX$ packets (see below). The SAWs were generated by a continuous rf-source. Figure 6(a) displays time-resolved profiles recorded for different transport distances $d$ under a strong acoustic modulation amplitude ($\delta E_x = 1.8$ meV). In all cases, well-defined PL
pulses are observed with time delays $t_m$ increasing with propagation distance according to $t_m = d/v_{IX}$, where $v_{IX}$ is the average IX transport velocity (cf figure 6). In addition, the rising edge of the time-resolved PL pulses becomes less abrupt for increasing $d$ while the trailing edge develops a tail indicating a distribution of arrival times at the detection position.

The initial radius of the IX cloud created by the laser was estimated from the size of the PL emission region around the laser spot (cf figure 3(a)) to be $w_{IX} = 16 \, \mu m$. The cloud extends, therefore, over several SAW wavelengths $\lambda_{SAW} = 2.8 \, \mu m$. For the shortest transport distance ($d = 49 \, \mu m$), the width $w_t$ of the PL pulses corresponds closely to the ratio $w_{IX}/v_{IX}$ between the initial Gaussian width ($w_{IX}$) of the IX cloud and the average IX transport velocity ($v_{IX}$).

The effects of the SAW amplitude on the IX dynamics are illustrated in figure 6(b). Here, the PL profiles were recorded at a fixed distance $d = 49 \, \mu m$ while varying $P_{rf}$ to change the band gap modulation amplitude $\delta E_g$. The shape of the pulses is almost the same for large modulation amplitudes ($\delta E_g > 1.2 \, \text{meV}$), under which the IXs are efficiently trapped and transported by the SAW fields. For lower amplitudes, in contrast, $t_m$ increases substantially whereas the PL pulses broaden and develop a pronounced tail. Similar features have been observed during the transport of electrons by weak piezoelectric fields reported in [24].

Figure 7 summarizes the dependence of the average transport velocity $v_{IX}$ on the band gap modulation amplitude $\delta E_g$ recorded at different transport distances $d$. $v_{IX}$ increases with $\delta E_g$ until it saturates for $\delta E_g > 1.2 \, \text{meV}$. Interestingly, the saturation velocity increases with $d$ but never reaches the SAW group velocity along the transport path of $v_G = (2.5 \pm 0.1) \, \mu m \, \text{ns}^{-1}$ (dashed line). Due to the presence of the ZnO layer, $v_G$ in the region in-between the ZnO islands differs from the product of the IDT resonance frequency and its wavelength. $v_G$ was determined by measuring the propagation time of an acoustic pulse in a delay line with two transducers.

Figure 6. (a) Time-resolved PL profiles from IXs recorded at 3.8 K different distances $d$ from the laser spot under a SAW-induced band gap modulation $\delta E_g = 1.8 \, \text{meV}$. (b) Profiles recorded at $d = 49 \, \mu m$ for different $\delta E_g$. The dashed lines are fits to equation (2).
built on the same sample. These measurements were carried out using a network analyzer with time-domain capabilities.

According to figures 6(b) and 7, long-range acoustic transport takes place for modulation amplitudes $\delta E_g > 0.5$ meV, for which the relationship $\mu_{ix}(V_g, \delta E_g) > v_{ix}$. The velocity of the fastest propagating IXs (which can be calculated from the onset delays of the profiles of the time-resolved profiles) is close to the SAW velocity. Using in the previous expression the modulation amplitude at onset of acoustic transport, we estimate a lower limit for the IX mobility in our sample of $\mu_{ix} = v_g \left( k_{\text{SAW}} \delta E_g \right) = 2.2 \times 10^4 \text{ cm}^2 \cdot \text{(eV s)}^{-1}$ and an IX diffusion coefficient $D_{ix} = 7.3 \text{ cm}^2 \text{s}^{-1}$ at 3.8 K [15]. These values agree well with those reported for IXs in DQWs with comparable QW thicknesses [12]. Note, however, that the efficient transport of
IXs requires modulation amplitudes much larger (by a factor of approx. 3) than those for the onset of transport.

The dependence of the IX dynamics on IX density was investigated by recording time-resolved profiles as a function of the laser pulse intensity (cf figure 8). The experiments were carried out in the regime of strong acoustic excitation (i.e., for $\delta E_g > 1$ eV in figure 7), where $v_{IX}$ is approximately independent of the SAW power. The profiles exhibit a weak dependence on the excitation density, thus indicating that non linear effects are negligible in the range of studied densities. The dependence of the profiles on temperature is illustrated in figure 9. Due to the strong reduction of the remote emission along the transport channel with temperature, the measurement could only be carried out over a relatively small temperature range (up to a maximum temperature of 5.5 K). As for the excitation density, the temperature induced changes are also relatively small with the profiles becoming narrower and the effective IX velocity $v_{IX}$ slightly increasing with decreasing temperature (by 5% between 5.5 and 2 K).

4. Discussions

Previous studies of acoustic transport efficiency using piezoelectric SAWs have identified two main regimes [19]. For small acoustic powers, the carriers are dragged by the SAW with an effective velocity much smaller than the acoustic velocity. This behavior corresponds to dynamics of IXs observed for $\delta E_g \leq 0.5$ meV in figure 6(b). In contrast, high acoustic modulations efficiently trap IXs, as depicted in figure 1(c). In this regime, a Gaussian IX packet with initial width $t_w = w_{IX}/v_{IX}$ should move with the SAW group velocity $v_G$ while maintaining its shape. The time-dependent PL profiles at a distance $d$ would then be given by

$$g(t, d) = A_g \exp \left[ -\left( \frac{t - t_m}{\sqrt{2} t_w} \right)^2 \right],$$  

(1)
where $A_g$ is the maximum PL intensity and $t_m = d / v_G$. The IX kinetics displayed in figures 6(a) and 7, however, does not follow this prediction: the exciton velocity $v_{IX}$ increases with the propagation distance and never reaches the SAW group velocity $v_G$. In addition, the IX packets broaden (indicating an increase in $t_w$) for increasing transport distances and develop a tail towards longer delays.

We have mentioned in section 3.2 that carrier trapping may change the potential distribution in the DQWs, thus leading to changes in the energy of the IX species. We show in this section that trapping can also account for the reduced transport velocity as well as for the deviations of the profile shapes from equation (1). In order to model the effects of the trapping centers, we will assume that they can capture and retain the IXs over an interval $t_d$ described by the exponential distribution $f(t_d) = \frac{1}{t_d} e^{-\frac{t}{t_d}}$. Here, $t_d$ is the average time the IXs remain immobilized in a trap during transport over a distance $d$. Since the trapping probability increases with the transport length $d$ (due to multiple trapping events), $t_d$ is expected to increase linearly with $d$, as will be shown later in the text. Within this approximation, an initially Gaussian profile (of the form in equation (1)) will evolve in time according to

$$h(t, d) \approx (g * f)(t, d)$$

where $t$ is the complementary error function, $t_m = t_m + \frac{t_m^2}{v_t}$, and $\approx$ denotes the convolution operator. The approximation given by equation (2) is valid for $t_d > t_w$, which is always satisfied under the used experimental conditions.

While the maximum of equation (1) occurs for $t = t_m = d / v_G$, the maximum of equation (2) (as well as for the spectra of figure 6) takes place for a delay $t' > t'_{m}> t_m$. It is possible to expand equation (2) around $t = t'_m$ to estimate the delay $t_{max} \propto t_m + \frac{t_m^2}{v_t} + \frac{\delta E_g}{v_G}$ (valid for $t_d > t_w$) corresponding to the maximum PL intensity during a PL pulse. Using the previous definition of the effective IX propagation velocity, namely as the rate between the distance and $t_{max}$, we then obtain $\nu_{IX} = d / t_{max} < d / t_m = v_G$. One of the main effects of trapping is, therefore, to increase the transit time due to an extra delay proportional to $t_d$, leading to an IX propagation velocity lower than the SAW velocity (see discussion below).

The predictions of the model are shown by the dashed lines superimposed on the data solid lines in figures 6 and 8. For high acoustic powers (i.e., for $\delta E_g > 1.2$ meV), these lines were obtained by using $t_d$ and $A_g$ of equation (2) as fit parameters and assuming $t_w \approx 5$ ns. For weaker modulation amplitudes ($\delta E_g \leq 1$ meV), the quality of the fits improves considerably by also allowing $t_w$ and $t_m$ to vary (as in figure 6(b)). The excellent agreement with the experimental results over a wide range of transport distances and modulation amplitudes is a strong indication that the model correctly describes the IX dynamics during acoustic transport.

Further information about the trapping centers can be obtained from the characteristic trapping times $t_d$ determined by the fittings, which are summarized in figure 10(a). The dependence of $t_d$ on $\delta E_g$ mimics the one displayed for $\nu_{2X}$ in figure 7 (measured at 3.8 K). In fact, $t_d$ decreases exponentially with $\delta E_g$ with a characteristic decay energy $E_u = (0.8 \pm 0.1)$ meV in
the region of low acoustic amplitudes and saturates for $\delta E_g > 1.2$ meV. $E_a$ is assigned to the energy required for acoustic excitation of trapped IXs to the transport path. It exceeds the thermal energy at the measurement temperature ($k_B T = 0.33$ meV for $T = 3.8$ K) by more than a factor of two. Note, however, that $E_a$ cannot be directly related to a thermal activation energy for IX release from traps. In this case, one should expect a narrowing of the profiles with increasing temperature. In contrast, figure 9 shows a weak dependence of the profiles on temperature with even a slight broadening with increasing temperature.

The trapping time $t_d$ saturates for high SAW amplitudes, thus indicating that the transport in this regime becomes controlled by trapping centers with capture and emission kinetics independent on the acoustic intensity. Very little is known about the effects of the SAW strain field (which involves both hydrostatic, uniaxial, and shear contributions) on potential fluctuations as well as on the binding energy of trapping centers. Theoretical studies have shown that the binding energy of shallow impurities in GaAs normally reduces under a tensile hydrostatic strain (see, e.g. [25]). The reduction of $t_d$ observed in figure 10(a) increasing the acoustic modulation up to 1.2 meV is consistent with these studies. The saturation of $t_d$ observed for higher amplitudes, as well as the weak temperature dependence, could be due to a non-homogeneous energetic distribution of release energies. The determination of the microscopic mechanism responsible for this behavior requires further investigations, which are beyond the scope of the present paper.

While $t_w$ remains essentially constant for high acoustic powers, $t_d$ increases linearly with the transport time $d/v_G$, as illustrated in figure 10(b). This behavior is attributed to the expected increase in the number of trapping events with transport distance. Interestingly, $t_d$ does not vanish for zero transport times but rather approaches a characteristic dwell time $t_{d,\text{min}} = 10$ ns. This behavior is probably due to the fact that the laser pulse excites IXs over a wide spot (approx. 20 $\mu$m wide). A fraction of these IXs is almost instantaneously trapped and retained for $t_{d,\text{min}}$ before being released and transported by the SAW.

**Figure 10.** Dependence of the characteristic trapping time ($t_d$) on (a) the band gap modulation amplitude $\delta E_g$ and on (b) the transport time $d/v_G$ recorded at 3.8 K for high modulation amplitudes ($\delta E_g = 1.8$ meV). The inset of (b) compares the measured (blue solid circles) and calculated $v_{IX}$ (red solid line) as a function of distance. The calculations assumed the $t_d$ dependence on distance given by the dashed line in the main plot. The dotted curve shows, for comparison, $v_{IX}$ calculations assuming $t_{d,\text{min}} = 0$.
Finally, the dependence of $t_d$ on transport distance leads to an increase of the effective velocity $v_{IX}$ with propagation distance. This behavior is illustrated in the inset of figure 10(b), which compares the predictions of the model for $v_{IX}$ (solid line) assuming the $t_d$ values of the main plot with the experimentally determined velocities (blue solid circles). The increase of $v_{IX}$ with distance is thus not caused by changes in the IX mobility along the path but rather by the changes in the profile shape induced by IX trapping. Note that this behavior persist even if $t_{d,\text{min}} = 0$. This is illustrated by the dotted line in the inset of figure 10(b), which was determined assuming the same linear dependence as for the solid line, but by setting $t_{d,\text{min}}$ to zero. While $v_{IX}$ also increases with $d$, the agreement with experimental results is not a good is in the previous case.

5. Conclusions

We have carried out a detailed investigation of the effects of high-frequency acoustic fields on dipolar IXs in (Al,Ga)As DQW structures. We have shown that the SAW strain shifts the excitonic energies via two mechanisms. The first is the modulation of the band gap by the SAW strain, which produces mobile potentials for the trapping and transport of IXs. The second arises from electrostatic changes in the electric field applied across the DQWs induced by acoustically induced charge trapping. While the former takes place in the nanosecond time scale defined by the SAW frequency, the latter is transient and persist over times exceeding one millisecond. We have also carried out a detailed investigation of the IX transport dynamics using time-resolved techniques. These studies have shown that the IXs are carried as well-defined packets moving with velocities close to the SAW velocity. The dynamics of the packets is determined by trapping centers along the transport path, which capture IXs and reduce their effective transport velocity. We present a detailed model the transport process including the effect of traps, which reproduces very well both the time and the spatial evolution of IX packets during acoustic transport.

The strong impact of traps on the IX dynamics is partially associated with the small band gap modulation induced by the SAW strain, which is comparable to the IX spectral linewidths. Different approaches can be followed to increase the transport efficiency. One of them consists in improving sample growth conditions to increase the mobility and reducing, e.g., the density of trapping sites. A second explores the enhancement of the acoustic fields. In fact, since the acoustic power densities produced by piezoelectric transducers scale with the $1/\lambda_{SAW}^2$, much strong modulation amplitudes are expected for high frequency SAWs. Finally, the present experiments were carried out using relatively small exciton densities. For higher densities, one can also take advantage of the repulsive interactions between IX, which can smooth potential fluctuations [26] and, therefore, increase the mobility.

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