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Nanoquakes at work: A quantum conveyor belt for photons

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Abstract

Storing light in the lateral potential of an intense piezoactive surface acoustic wave propagating on a semiconductor quantum well is demonstrated. We show that the lateral piezoelectric fields of the wave are strong enough to field-ionize and thus dissociate optically generated excitons and to efficiently capture the resulting free electrons and holes. As the wave propagates at the speed of sound across the semiconductor sample, the trapped carriers can be transferred to a location on the sample being different from the one of the optical excitation. Deliberate screening of the lateral electric fields leads to an induced recombination after very long storage times. We explain the physical mechanisms responsible for this remarkable effect and investigate the ionization, trapping, transport, and recombination in detail.

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Keywords: Quantum well; Exciton; Photoluminescence; Surface acoustic waves; Conveyor belt; Photon; Piezoelectricity

The storage of light in some kind of a container and the deliberate release of the radiation at possibly even another location sounds like a very hard task as it is difficult to trap the speedy photons for appreciable long storage times. Especially in semiconductors it seems to be contradicting at first glance. On the one side, there are semiconductors with large absorption coefficients as their direct band structure provides a large probability for a photon to generate an electron–hole (eh) pair. For the same reason, however, the recombination lifetimes are quite short. On the other hand, semiconductors with an indirect bandgap provide longer lifetimes but for the same reason the absorption in form of (eh) pairs is very small. Early attempts to overcome this contradiction relied on the fact that a given band structure in k-space may be efficiently modified if it is modulated in real space. For instance, alternating layers of n-type and p-type material result in the so-called nipi superlattices [1,2], where potential minima of both the conduction and the valence band alternate with the period of the superlattice. In these structures, a spatial separation of optically generated electrons and holes has been achieved which resulted in unusual long recombination times. The reason for the increase in recombination lifetime is the reduced wave function overlap between the photo generated carriers being directly linked to the recombination probability.

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Another recent attempt uses a coupled double quantum well system in which the electrons and holes after their generation reside in different parts of the potential [3]. Illumination with a far-infrared source is then used to transfer the electron in real space towards the hole and to induce a photoluminescence recombination. Hence – it seems quite favorable to rely on a spatial separation of photo generated carriers in a direct gap semiconductor to achieve considerably prolonged recombination lifetimes while retaining the large absorption coefficients.

Here, we would like to report on a different technique to achieve this spatial separation of the photo generated electrons and holes in a semiconductor quantum well [4]. For this purpose, we use surface acoustic waves (SAW) propagating on the piezoelectric semiconductor substrate [5]. Surface acoustic waves are modes of elastic energy that propagate at the surface of a semi-infinite medium. The simplest modes of such waves are Rayleigh waves, in which the particle displacement is elliptic in the sagittal plane perpendicular to the direction of propagation. If the medium is piezoelectric, the waves are accompanied by appreciable lateral and vertical electric elds giving rise to both lateral and vertical modulation of the band edges in the semiconductor. If these fields are large enough, exciton ionization or a spatial separation of the photo generated e–h pairs can result [6]. The SAW are quite efficiently excited on a piezoelectric substrate by means of the so-called interdigital transducers (IDT). Those consist of two comb-like metalized structures being connected to a high-frequency signal generator. Mediated by the inverse piezoelectric effect, the application of a voltage to the IDT leads to a deformation of the substrate right below the transducer. If the frequency of the excitation is chosen such that the condition $f = v/p$ is met, a coherent and monochromatic sound wave is launched along the surface of the crystal. Here, v denotes the SAW velocity for the given crystal cut and p the periodicity of the IDT.

In Fig. 1, we depict the typical sample layout as used in our experiments. The undoped quantum well samples are grown by molecular beam epitaxy on a (1 0 0) – GaAs substrate. The well consists of 10 nm pseudomorphic $In_{0.15}Ga_{0.85}As$ grown on a 1 μm thick GaAs buffer and is covered by a 20 nm thick GaAs cap layer. The active area of the sample is etched into two 2.5 mm long and 0.3 mm wide bars forming a cross-like mesa with an IDT at each end. The SAW velocity for (1 0 0) GaAs and [1 1 0] propagation is $v = 2865$ m/s, and the IDTs are designed to operate at a center frequency $f_{SAW} = 840$ MHz (IDT_1) and $f = 420$ MHz (IDT_3), respectively. They are partially impedance matched to the 50 Ω radio frequency (RF) circuitry using an on-chip matching network thus strongly reducing the insertion loss of each transducer. The sample is mounted in an optical cryostat and the experiments presented here are performed at $T = 4.2$ K. Light from either a pulsed laser diode ($\lambda_{laser} = 780$ nm) or a tuneable titanium–sapphire laser is used for optical interband excitation above band gap and the photoluminescence (PL) of the sample is analyzed in a triple grating spectrometer. Either a photomultiplier or a charged coupled device (CCD) serve as a detector for the PL. Application of a high-frequency signal to one of the IDTs launches a SAW that can be detected at the other IDT after the acoustic delay of the order of 1 μs determined by the spacing of the IDTs. Either pulsed or continuous wave (cw) operation of the SAW transducers is possible.

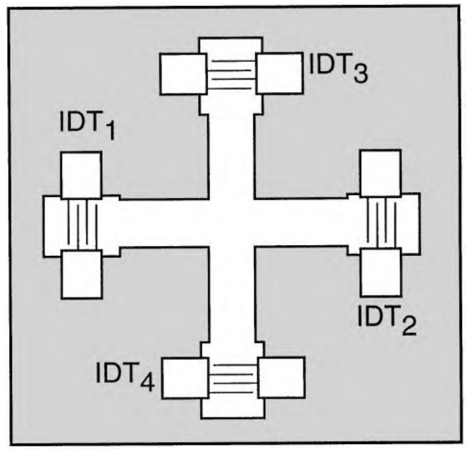

Fig. 1. Sketch of the sample geometry used in our experiments. The active layers of the undoped semiconductor quantum well are etched in the form of a cross-like mesa. On each end of the arms, an IDT is deposited. $IDT_{1,2}$ operate at a frequency of $f = 840$ Mhz, $IDT_{3,4}$ are designed for $f = 420$ Mhz.

In Fig. 2, we show the observed quantum well PL under the influence of a SAW at $f = 840$ MHz for different SAW amplitudes [4]. The PL is analyzed at the same spot where it is excited, close to the mesa center. As can be seen from the figure, an increase

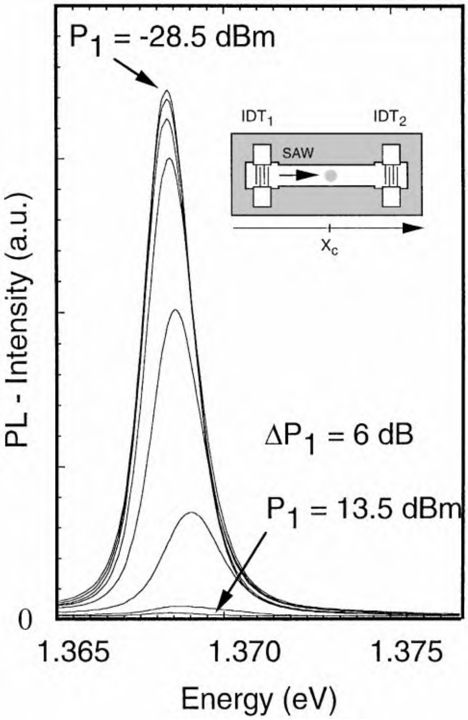

Fig. 2. Photoluminescence (PL) spectra for the quantum well sample under the influence of an intense SAW. With increasing SAW power the PL intensity rapidly decreases whereas its energetic position and line width remain nearly unaffected. At the highest acoustic power show in the figure, the PL is completely quenched [3].

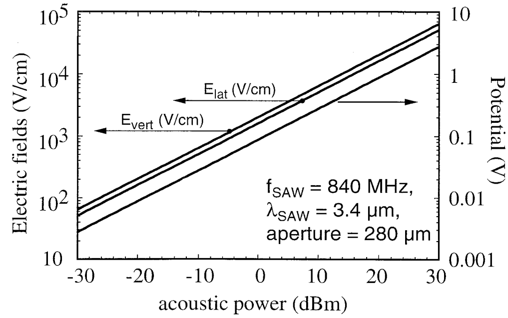

Fig. 3. Lateral and vertical components of the piezoelectric fields in the SAW as a function of the acoustic power and for the given parameters. Also shown (right axis) is the piezoelectric potential associated with the wave.

of the SAW power leads to a decrease of the detected PL intensity, whereas the energetic position and line width remain nearly unaffected. For the highest powers shown ($+13.5\,\mathrm{dBm} = 22.4\,\mathrm{mW}$), the PL becomes completely quenched. This quenching of the PL by the SAW is interpreted by an ionization of the optically generated excitons in the strong lateral piezoelectric fields. To give an impression on the achievable field strengths, we show in Fig. 3 how both the vertical and the lateral fields depend on the acoustic power imposed to our sample. At the same time we plot the magnitude of the corresponding SAW potential. Even for quite moderate SAW powers, very high electric fields of the order of several kV/cm are easily achieved. These piezoelectric fields of the SAW modulate the band edges with respect to the chemical potential similar as in doping superlattices [1,2] or statically imposed laterally periodic electric fields using an interdigitated gate electrode [7]. In our moving potential superlattice with period $\lambda = 3.4\,\mu\mathrm{m}$ the excitons become polarized predominantly by the lateral electric field until they dissociate at high fields into spatially separated e–h pairs. These are then efciently stored in the potential minima and maxima of the conduction and the valence band, respectively. A very simple estimate yields that fields as high as $E_{\mathrm{crit}} \approx E_{\mathrm{b}}/(ea_{\mathrm{B}}^{*}) \sim 10^4\,\mathrm{V/cm}$ will ionize photo generated excitons. $E_{\mathrm{b}} \sim 9\,\mathrm{meV}$ denotes the exciton binding energy, e the elementary charge, and $a_{\mathrm{B}}^{*} \sim 9\,\mathrm{nm}$ the effective (Bohr) exciton radius of our system. Hence, the lateral field of the SAW is definitely high enough to dissociate the photo generated excitons in our sample. The influence of the vertical fields, however, can be neglected in our case as we are working on a comparatively thin ($d = 10\,\mathrm{nm}$) quantum well.

The observed quenching of the PL under the influence of an intense SAW is already an indication of the increased trapping probability in the moving lateral potential of the SAW. As the potential modulation is moving with the speed of sound, consequently, the spatially separated and trapped e–h pairs are swept away by the SAW and propagate across the sample without recombining. The dramatically prolonged recombination time together with their propagation along the surface of the quantum well enables us to directly follow the transport of photo generated carriers over macroscopic distances that may exceed millimetres in our experiment. For this purpose, we need to cancel out the lateral electric fields that are responsible for the trapping of the charges. On a piezoelectric semiconductor, this is easily achieved by a

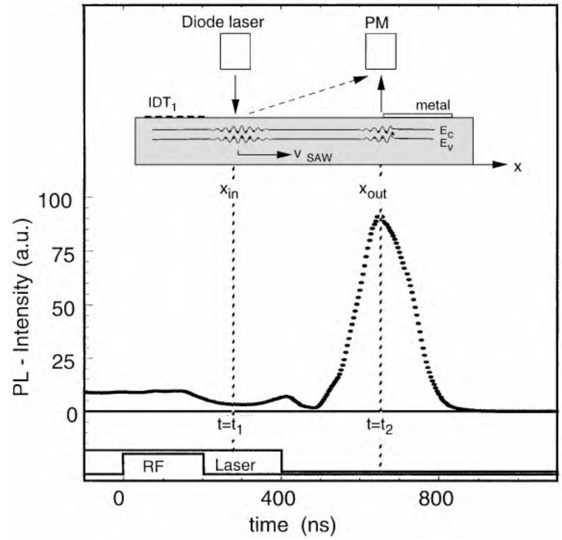

Fig. 4. Experimental evidence for the transport of photo-generated charges in the field of the SAW. A short RF pulse is transformed into a SAW packet at $f = 840$ Mhz. Transversing the excitation region ($x = x_{\mathrm{in}}$), this SAW pulse is “loaded” with e–h-pairs which immediately become spatially separated. The spatial separation dramatically decreases the recombination probability which in turn results in a tremendously increased lifetime. After very long storage or delay times the SAW arrives at a metalized region of the sample where the lateral electric fields are screened and the recombination of the photo-generated charges is no longer impossible. The result is a strong PL signal at this location ($x = x_{\mathrm{out}}$) [3].

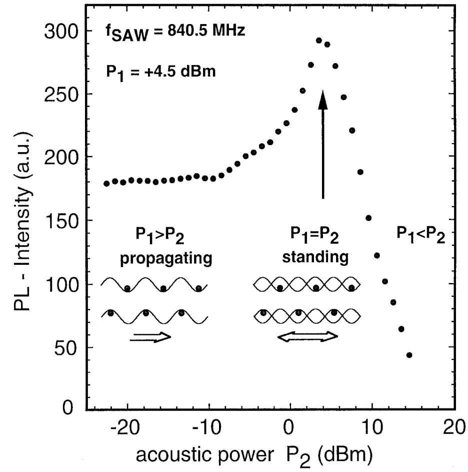

Fig. 5. PL intensity as a function of the acoustic power P_2 at constant power $P_1 = +4.5$ dBm for two counter propagating SAW of the same frequency $f_1 = f_2 = 840$ MHz. Only for $P_1 P_2$ (standing wave condition) the PL recovers, whereas for the other cases the PL is efficiently suppressed [3].

metallization of a part of the samples surface [8]. In this case, the lateral fields are screened and the trapping potentials are flattened out. The carriers are now free again to diffuse, hence considerably increasing their recombination probability. In other words, it should be possible to optically generate excitons at some point of the sample, dissociate them in the field of a SAW and then let them “surf” on the SAW to a different location of the sample. Here, a metallization of the sample surface leads to a re-assembly of the stored bipolar charges into photons which can be detected in the form of a time delayed PL at the remote location.

The corresponding experiment is sketched in Fig. 4. We show the PL being detected at the site x_{out} as a function of time after the optical generation of excitons at site x_{in}. The lower part of the figure indicates the timing sequence of the experiment. A short ($\tau = 200$ ns) SAW pulse at $P_{\mathrm{SAW}} = +13$ dBm is generated at $t = t_0$. To avoid any spurious effects, we switch the laser off after the SAW pulse has transversed the optical excitation area at $x = x_{\mathrm{in}}$ and $t = t_1$. Some 400 ns later ($t = t_2$), a strong PL signal is detected at $x = x_{\mathrm{out}}$, exactly at the time when the “loaded” SAW arrives at the screening electrode. The light has been “stored” in the SAW potential and then transported in the form of a bipolar polarization to this remote location, like on a conveyor belt. The storage time reached in this experiment is mainly given by the transport path on the finite length of our sample ($\Delta x = 1$ mm, in this case). Only a small fraction of the photoexcited carriers is lost along this way [4] and hence much longer storage times can be achieved by a more sophisticated sample design. The fixed time delay between excitation and detection of the PL in the present experiment, however, is given by the fixed distance between excitation area ($x = x_{\mathrm{in}}$) and detection area ($x = x_{\mathrm{out}}$).

A simple way to also achieve tuneable time delays is presented in Fig. 5. Here, the recombination of the trapped bipolar charges is triggered by a second sound wave propagating in the opposite direction of the first one. If the amplitudes and frequencies of both waves are the same, a standing wave pattern will form, in which the trapping potential is partially lifted and the e–h pairs are free to recombine again. We show the result of an experiment, where two counterpropagating SAWs at $f = 840$ MHz are used to perform this task.

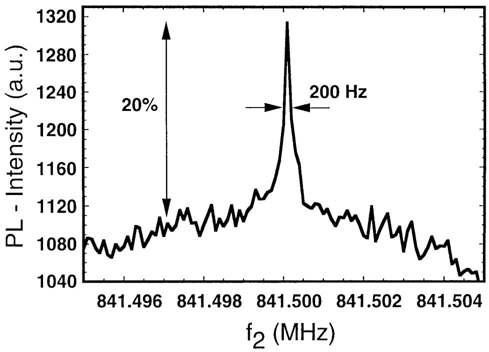

Fig. 6. Corresponding experiment to Fig. 5 in frequency space. Two counter propagating waves of constant and equal power ($P_1 = P_2 = +4.5$ dBm) are launched across the sample. The frequency of the first SAW $f_1 = 841.5$ Mhz, whereas f_2 is tuned. Only for the exact standing wave condition ($f_1 = f_2$) a bright PL is observed. Note that the width of the peak is only some 200 Hz at a center frequency of about 1 Ghz!

We keep the amplitude of the first (pumping) SAW xed such that the PL is already quenched by about 50%. The amplitude of the second SAW is varied during the experiment. As long as it is small as compared to the one of the "conveying" SAW, the PL intensity remains nearly unaffected. However, as soon as both SAW amplitudes are of the same order, and a standing wave pattern forms, the PL intensity increases dramatically and finally at $P_1 = P_2$ reaches its original value. For higher powers P_2 the situation reverses and now SAW_2 starts to efficiently quench the PL.

Even more impressive is the corresponding experiment in frequency space that is shown in Fig. 6. Here, both amplitudes of the SAWs are kept equal and fixed at $P_1 = P_2 = +4.5$ dBm, like in Fig. 5. Now the frequency of SAW_2 is varied. As long as both SAW frequencies are different by more than about 1 part in 10^7 (!), the PL remains efficiently suppressed. Only for the exact standing wave geometry the PL recovers. Then and only then the time-averaged wave function overlap of both electrons and holes becomes non-zero which in turn is equivalent to a non-vanishing recombination probability. The extreme sensitivity of this experiment regarding smallest frequency differences might even have some importance for future device applications.

A crucial point for the above experiments is the electric-field-induced ionization process for the excitons. If the ionization in incomplete, only a fraction of the photo-generated charges will be spatially separated and trapped in the wave. This together with a possible escape of some carriers will cause a reduced transport efficiency of the conveyor belt. Above, we gave a simple estimate for $E_{crit} \approx 10^4$ V/cm, the critical field necessary for a spatial separation of the electrons and holes. From our experiments, however, we extract a somewhat lower value – a disagreement that will be addressed in the following: we are making use of the fact that SAW transmission experiments are very sensitive to small areal conductivities of a close-by charge carrier system [5]. The attenuation as a function of the conductivity indicates a maximum at some critical conductivity $\sigma_m \approx 3 \times 10^{-7} \Omega^{-1}/\mathrm{sq}$ [5], where the impedance of the space-charge layer is matched to the surface SAW admittance of the sample. To directly observe the exciton ionization process in the eld of the "pump" SAW, we monitor the transmitted intensity P_4 of a second SAW propagating perpendicularly to the "pump" SAW as a function of the acoustic power P_1 of the latter [9]. On the length scale of the SAW, the optically generated excitons behave like neutral particles as their effective Bohr radius is much smaller than λ_{SAW}. The areal conductivity related to the field-induced polarization of the excitons is negligible, so we do not expect any screening of the piezoelectric potential of the transmitted SAW and hence no attenuation as described in Ref. [5]. However, once the excitons are field-ionized, their "fragments" – electrons and holes – are spatially separated and subsequently confined in the lateral potential wells of the pump SAW. Now the probe SAW encounters many parallel stripes of free electrons and holes, resembling a *lateral* "nipi"-structure with a period $\lambda_{SAW,1}$. Those electrons and holes are free to move along the direction normal to the propagation of the pumping and confining SAW and are therefore expected to interact with the second SAW according to their areal conductivity.

This is exactly what we observe experimentally. The result is shown in Fig. 7, where we plot the transmitted SAW intensity $P_4 = P_3 \exp(-\Gamma d)$ as a function of the power P_1 of the "pumping" SAW and for two different optical excitation energies E_{las}, as will be discussed below. P_3 is the incident power of the "probe" SAW, d the length of the interaction region, which in our case corresponds to the width of the pumping SAW path, namely $d = 300$ μm.

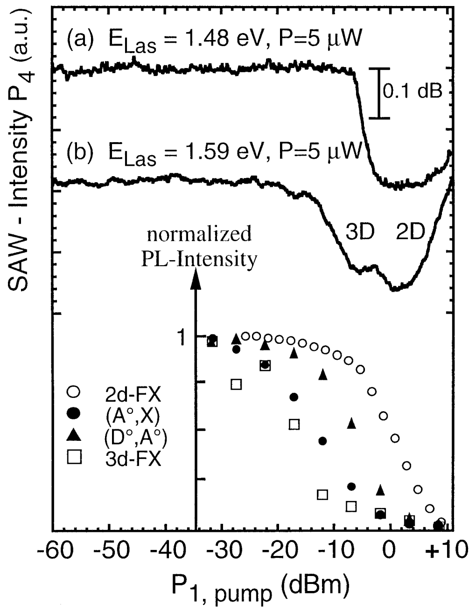

Fig. 7. SAW transmission experiment to study the process of the exciton ionization in the field of a pumping SAW P_1. A second SAW is propagated at low power P_3 perpendicular to the first one and is analyzed in intensity P_4 at IDT_4. The attenuation of this "probe" SAW strongly depends on the areal conductivity of the photo-generated charges. As long as the excitons are not yet dissociated by the SAW_1, they behave like neutral particles with zero areal conductivity. The sudden inset of SAW absorption indicates the occurrence of a finite areal conductivity caused by the ionization of the excitons. In (a), only the InGaAs quantum well is optically excited, resulting in purely 2d excitons, whereas in (b) also the barriers are excited and 3d excitons are generated simultaneously [8].

The inset of the figure shows the measured intensity of some prominent PL lines as a function of the SAW pumping power P_1. 2d-FX denotes the quantum well (2d) free exciton as already shown in Fig. 2, the other symbols are attributed to the bulk (3d) free exciton and some acceptor (A) or donator (D) bound excitonic states [10]. It is interesting to note that – in agreement to the observations in Ref. [10] – all different PL lines become suppressed under the influence of the SAW. The threshold fields, however, differ slightly which can be attributed to their different binding energies. At very low pumping power levels P_1, the probing SAW is nearly unaffected as indicated by a constant transmitted SAW intensity P_4 over several decades of P_1. However, for pumping power levels greater than approximately $P_1 = -10$ dBm, a strong decrease of the transmitted SAW intensity P_4 or equivalently an increase of the attenuation coefficient Γ is observed. This decrease of the probe SAW intensity is strongly dependent on the energy E_{las} of the exciting laser, as can be seen in the upper two traces in Fig. 7.

In Fig. 7a, the energy of the incident laser $E_{las} = 1.48$ eV is chosen such that only the InGaAs quantum well is optically excited, resulting in a selective population of the QW by photo generated excitons. For low acoustic pump powers P_1, their quasi-static conductivity in the QW is negligible, indicated by a constant probe intensity P_4.

However, for $P_1 > -6$ dBm, corresponding to a lateral piezoelectric field strength of $E_1 > 600$ V/cm, the probability for the dissociation of the excitons by field-induced tunnelling processes rapidly increases which is marked by a sharp onset of the absorption of the probe SAW. This change in the SAW transmission can be understood by the absorption process as described in Ref. [5]. The point of minimum transmission (or equivalently maximum attenuation) corresponds to the situation, where the averaged conductivity of the spatially separated electrons and holes reaches the critical conductivity σ_m as defined above. Further increase of the pumping power P_1 results in an increase of the carrier densities and thus, caused by an increased screening, in a smaller interaction between the probe SAW and the mobile carriers. The result is a significantly reduced attenuation coefficient Γ.

Optical excitation at a laser energy of $E_{las} = 1.59$ eV (see Fig. 7b) being larger than the band gap of the quantum well barriers leads to the generation of both 3D excitons in this GaAs barrier (bulk) material and in the InGaAs quantum well. This simultaneous generation of 2D and 3D excitons is clearly observed in our experiment, as the transmitted SAW intensity exhibits two well-defined minima at about $P_1 = -8$ dBm and $P_1 = 0$ dBm. Those minima correspond to maxima in the SAW attenuation Γ as described above. The onset of the SAW attenuation, however, is now shifted towards lower pumping powers of $P_1 = -13$ dBm, corresponding to a piezoelectric field strength of only $E_1 = 300$ V/cm. This attenuation at smaller pumping powers can be attributed to the dissociation of the 3d excitons in the GaAs barrier material. As the exciton binding energy of 3d excitons is considerably smaller than the one for the 2d excitons in the InGaAs quantum well, the piezoelectric fields necessary for ionization will also be smaller. Caused by the variation of the SAW – induced fields with depth into the crystal, the dissociation rate of the 3d excitons also varies with depth. Both this field strength variation as well as the presence of different excitonic states with different binding energies in 3d will result in a somewhat smoother onset of SAW attenuation in the 3d case as compared to the 2d case. Note, that the onset of exciton ionization, indicated by the onset in the SAW absorption, agrees very well with the decrease of the PL intensity of the most intense neutral acceptor bound exciton (A^0, X) as shown in the inset of Fig. 7. A theoretical estimate of the critical electric elds necessary for the ionization of either 2d or 3d excitons is given in Ref. [9]. This estimate is based on a calculation of the tunnelling ionization time for excitons in the presence of an electric field [6] and turns out to be of the order of 0.5 ns for an electric eld of 1 kV/cm. Time-resolved measurements of the PL on the same samples [1] showed a very good agreement between our calculation, the measured ionization threshold fields and the tunnelling ionization lifetime. It would be very interesting to study the dependence of the lifetime on different external parameters like a magnetic field or the temperature. According to our model the ionization threshold electric field should then be also strongly affected.

In summary, we have demonstrated that it is in fact possible to capture light in a container and then release it at some other time and at some remote location. We showed that the combination of vertical confinement of bipolar charges in a quantum well together with a strong lateral confinement mediated by the lateral piezoelectric fields of a surface acoustic wave can result in what we call a “photon conveyor belt”. Combining the large absorption coefficient of direct band gap semiconductors and the long lifetimes for optical excitations in indirect band gap semiconductors yields a new and promising approach also for future optoelectronic device applications.

Finally, I would like to acknowledge the valuable input and efforts of many of my colleagues and dear friends to the work presented in this manuscript. Without Carsten Rocke, Stefan Manus, Peter Müller, Martin Streibl, Markus Rotter, Sascha Haubrich, Alexander Govorov, and Jörg P. Kotthaus it would have been impossible to realize. This work has been generously sponsored by the Deutsche Forschungsgemeinschaft (DFG), and the Bayerische Forschungsstiftung (FOROPTO).

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