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Received 18 April 2006, revised 6 June 2006, accepted 14 June 2006
Published online 18 July 2006

PACS 73.21.–b, 73.63.–b, 78.55.Cr, 78.67.–n

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phys. stat. sol. (b) **243**, No. 14, 3754–3763 (2006) / **DOI** 10.1002/pssb.200642196

WILEY-VCH

physica status solidi b

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Feature Article

Manipulating luminescence in semiconductor nanostructures via field-effect-tuneable potentials

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1 Introduction

Confining and manipulating carriers via field-effect-tuneable potentials enabled not only modern MOSFET (Metal-Oxide-Semiconductor Field-Effect-Transistor)-based microelectronics but also opened the door to create low-dimensional carrier systems of enormous flexibility and study their physical behaviour. Most prominent examples are the integer and fractional quantum Hall effects, the heterojunction bipolar transistor and the heterojunction laser, all honoured with Nobel Prizes. Today semiconductor physics is dominated by the studies of low-dimensional carrier systems that started with the investigation of the electronic transport properties of two-dimensional electron systems about 40 years [1]. These were soon followed by initial spectroscopic studies of such two-dimensional electron systems in which Gerhard Abstreiter, to whom we dedicate this volume, played a leading role [1, 2]. Here the tuneability of the carrier density via field effect was essential to enable spectroscopic experiments with relatively few electrons.

The realization of semiconductor heterostructures confining carriers of highest mobility by epitaxial growth techniques in the mid-seventies of last century was another event with an enormous impact on both semiconductor technology and semiconductor physics. Soon one was able to combine the growth of layered heterostructures containing two-dimensional carrier systems with lateral quantum confinement of

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the carrier motion. This was achieved by variety of techniques such as patterning by lithography and etching, employing finely patterned electrodes to generate nearly arbitrary potential landscapes for carrier confinement via field effect, and epitaxial growth techniques utilizing atomic self-organization within the plane of the epitaxial layers. Thus spectroscopy of semiconductor nanostructures such as quantum wires and quantum dots became a new research topic that remains very active until today [3]. Again the tuneability of spatial carrier confinement and number of charge carriers by field effect was essential to spectroscopically investigate these quantized systems. This enabled both intraband and interband spectroscopy of such artificial atoms with as little as one electron showing a variety of phenomena until then restricted to studies of real atoms [3]. Epitaxially grown self-assembled quantum dots combined with field-effect control of the electron occupation, particular examples of such atom-like quantum system, have been studied extensively with many significant contributions from the Munich groups reflecting their stimulating interactions (e.g. [4–8]). As will be discussed in detail elsewhere in this volume such quantum dots may form a stepping stone towards a future solid-state-based quantum computer.

In the following we want to focus on optical studies of carriers confined in quantum wells under the influence of voltage-tuneable electric fields. The spectrum of experiments that will be discussed reflect the wide control of the recombination lifetime and position of photo-generated electron–hole pairs that can be achieved in semiconductor nanostructures via field effect. Essentially, the investigations rely on manipulating the spatial overlap of the envelope wave function of conduction band electrons with the one of valence band holes via a field-effect-controlled potential landscape. Carriers are optically generated in an epitaxially grown heterostructure by interband absorption and confined to the plane of a quantum well. An electrostatic potential generated and tuned by field-effect electrodes serves to control the spatial overlap of the electron and hole wave functions. The thus achieved voltage control of interband transition probabilities is similar to so-called nipi structures [9], layered structures consisting of alternatively p- and n-doped layers, but will prove to exhibit a significantly larger flexibility.

The experiments summarized and discussed in the following are performed at low temperatures of typically 10 K. We employ single and double quantum wells within Ga(In)As–AlGaAs heterostructures in which the direct band gap in both real and momentum space yields an excitonic recombination lifetime of about 1 ns. We first will discuss how the controlled ionization of quantum well excitons by field effect can be used to spatially separate and store photo-generated electron and holes. We demonstrate that after a widely tuneable temporal delay up to seconds the electron–hole separation can be reversed and results in excitonic luminescence at either the position of excitation or even at another spatial position. With a suitably designed field-effect device this enables the storage of optical images for a controlled temporal delay. We then discuss how such field-effect-generated potential landscapes imposed on quantum wells can also be employed to move and trap excitons in the quantum well plane while prolong-

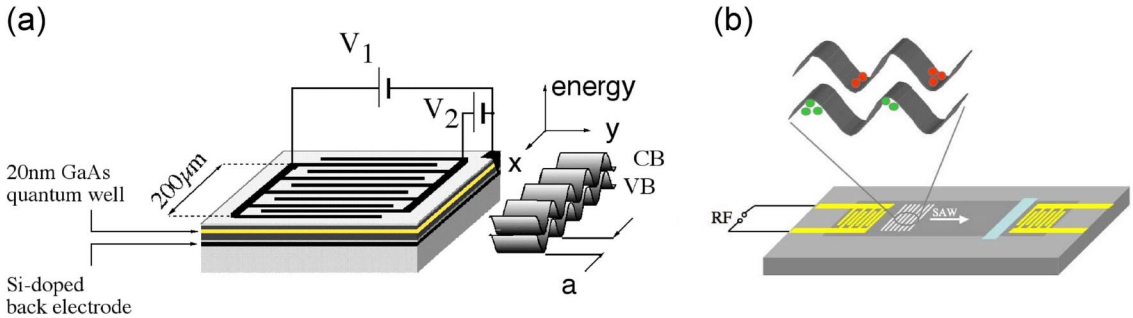

Fig. 1 (online colour at: www.pss-b.com) Conduction (CB) and valence band (VB) in a quantum well under the influence of (a) a periodic field-effect-induced static or (b) piezoelectrically induced dynamic potential caused by a surface acoustic wave (SAW) propagating with sound velocity. (After Refs. [10] and [11].)

ing their recombination lifetime by more than three orders of magnitude. This opens the possibility to tailor confinement and density of long-living excitons at low temperatures and to study their collective behaviour with a chance to create controlled Bose Einstein condensates of excitons.

2 Temporal storage of optically excited electrons and holes

One way to achieve and tune a desired potential landscape within the plane of a quantum well is sketched in Fig. 1a. On the surface of a heterostructure containing a single undoped quantum well we fabricate interdigitated electrodes with periods ranging between a few micrometers down to about 100 nm with standard lithography. Applying different bias voltages to the two electrodes with respect to a back contact located below the quantum well one generates a one-dimensional modulation of the band edges in the quantum well with respect to the back contact. In devices with small periods a lateral Franz–Keldysh effect of the interband absorption becomes observable [10]: Large in-plane electric fields of order 10^5 V/cm cause sub-bandgap absorption as well as oscillations of the interband absorption in dependence of the frequency of the absorbed radiation.

If the in-plane electric fields exceed the ionization threshold of quantum well excitons of typically 10^4 V/cm the formation of excitons is prevented as the photo-generated electrons and holes are spatially separated in the quantum well plane. This reduces dramatically the spatial overlap of the electron and hole wave functions thus increasing recombination lifetimes by many orders of magnitude and suppressing excitonic luminescence. When the amplitude of the lateral potential modulation is again strongly diminished, the Coulomb attraction between electron and holes reverses the spatial separation. Hence excitons are formed again and recombine with short recombination lifetimes of about 1 ns. This process of reversibly storing the energy of photons, strongly absorbed in a quantum well, into spatially separated electron-hole pairs was initially observed in luminescence experiments as sketched in Fig. 1b. There a surface acoustic wave (SAW), generated with radio frequency (RF) excitation of the interdigital transducer at the left, travels across a quantum well with sound velocity v_{SAW}. Since GaAs is piezoelectric the SAW is accompanied by a travelling potential modulation as indicated. Increasing the amplitude of the

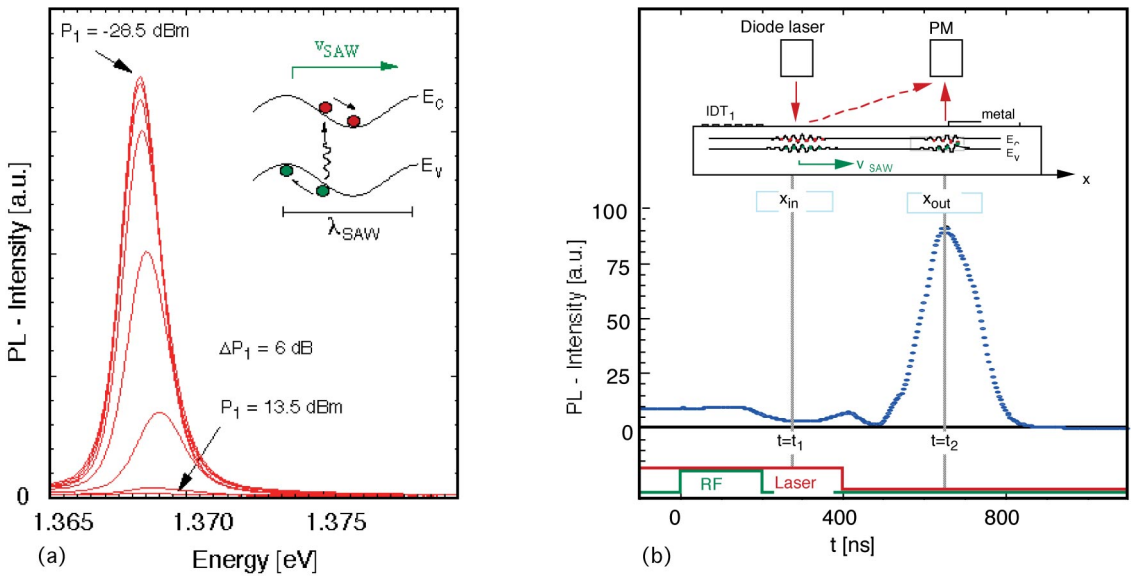

Fig. 2 (online colour at: www.pss-b.com) (a) Quenching of the luminescence with increasing SAW power P. (b) Temporal and spatial delay of the luminescence with the piezoelectric SAW potential acting as conveyor belt for electron–hole pairs that are spatially separated at time t_1 and location x_{in} and can recombine at time t_2 at x_{out}. (After Ref. [11].)

surface acoustic wave one observes a strong suppression of the excitonic luminescence [11] as the SAW passes the region of optical excitation as illustrated in Fig. 2a. Even more surprising, the electron–hole pairs, photo-generated at the illuminating laser spot, get spatially separated by half a SAW wavelength and "surf" with sound velocity as sketched in the upper part of Fig. 2b. After the electrons and holes have travelled macroscopic distances, practically only limited by the sample size, a simple metal stripe, indicated in the inset of Fig. 2b, screens the piezoelectric potential modulation efficiently. As a result excitons can form nearly instantly beneath the metal stripe and recombine within a few ns, emitting a strong luminescent pulse. The surface acoustic wave thus acts as a conveyor belt for the optically excited electron–hole pairs and yields both temporal and spatial control over the delayed luminescence. For typical chip sizes of several millimetres the temporal delay of photonic signals is of order 1 μs.

In a static field-effect-induced potential much longer storage times are possible. Figure 3 illustrates an experiment demonstrating the temporal control of luminescence from a quantum well subjected to an electrostatic potential periodically modulated in the quantum well plane [12]. Once the potential is turned on, the temporally direct luminescence is partially quenched and shifted to lower energy. During this time interval (indicated by "load" in Fig. 3) photoexcited electron–hole pairs are spatially separated and stored in the respective potential extrema. The spatially separated electrons and holes remain stored after the exciting laser is switched off. When the potential modulation is switched off after a desired storage time t_s, one observes a delayed luminescence signal. Storage times as long as seconds have been achieved at liquid helium temperatures [13] while at the same time recombination times of 1 ns are measured after the potential modulation is turned off.

Combining spatially and temporally resolved luminescence experiments allows studying the dynamics of the stored carriers, spreading beneath the stripes of the interdigitated gate [14]. As shown in Fig. 4 the luminescence observed after a chosen storage time yields an image of where the carriers recombine. Here electron–hole pairs are generated by a short laser pulse at time $t = 0$ at the laser spot as indicated at the r.h.s of Fig. 4. Since the metallic gates above the quantum well screen the electron–hole interaction

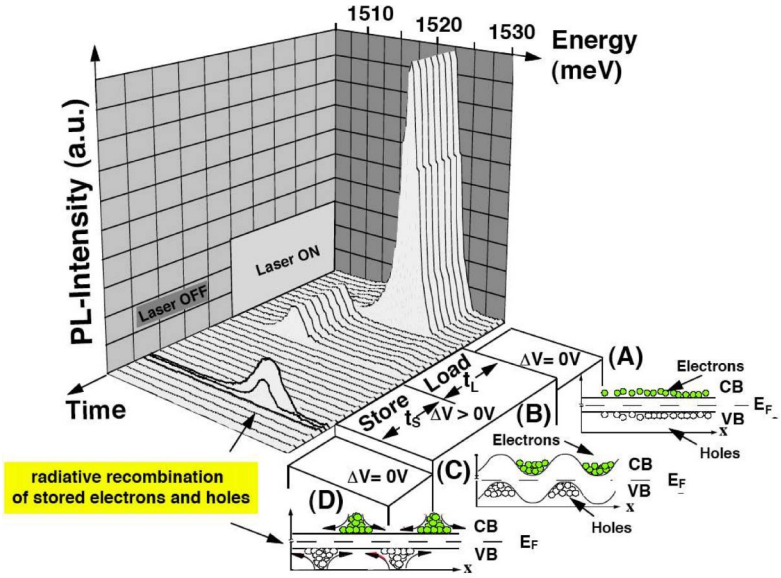

Fig. 3 (online colour at: www.pss-b.com) Temporal storage of photo-excited electron–hole pairs in a quantum well subjected to a periodically modulated electrostatic potential. The direct luminescence in the unmodulated case (A) is shifted to lower energy and reduced when the potential is turned on (B). It vanishes after the exciting laser is switched off (C). Delayed luminescence of stored electron–hole pairs occurs when the electrostatic potential is turned off (D). Here ΔV denotes the voltage difference between gate 1 and 2 and the storage time t_s is 1 μs but can be extended to seconds. (After Ref. [13].)

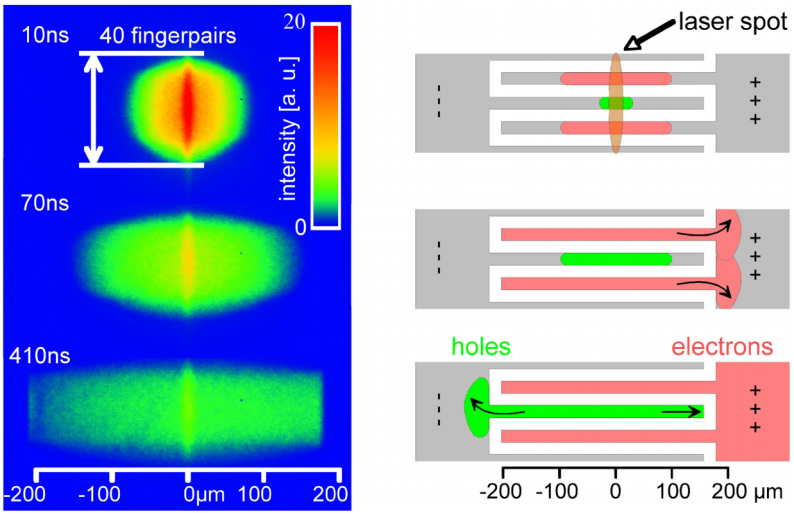

Fig. 4 (online colour at: www.pss-b.com) Spreading dynamics of optically excited carriers as observed with spatially and temporally resolved luminescence. After short excitation with a laser pulse at $t = 0$ s with a voltage difference of $\Delta V = 0.2$ V applied between the two electrodes, luminescence is induced after the storage time indicated by setting $\Delta V = 0$ V. The detected image reflects the spatial distribution of the less mobile carriers. Here these form a 2D hole plasma beneath the respective gate as indicated in the sketch. (After Ref. [14].)

between adjacent gate stripes effectively, the charge spreading is caused by the electrostatic repulsion and diffusion of unipolar carriers. Since the holes are less mobile than the electrons the spreading dynamics observed is that of a two-dimensional hole plasma. Such an experiment made it possible to investigate the Maxwell kinetics in detail with results that are well described by a non-linear model [14].

The charge spreading along the stripes of the interdigitated gates, however, prevents the storage of optical images in the field-effect-generated potential landscape. A two-dimensional storage device as illustrated in Fig. 5a can suppress charge spreading. Here the electrostatic potential is also modulated periodically along the stripes of the interdigitated gate by fabricating a SiO_2-grating between the hetero-structure and the gate, which is oriented perpendicular to the gate pattern. In such a device field-effect can provide a two-dimensional potential landscape in which optically generated electrons and holes are stored in a checkerboard-like pattern and prevented from spreading. Thus it becomes possible to store whole images and release them at will as luminescence light as shown in Fig. 5b [15]. Such a photonic camera is similar in principle to a CCD (Charge Coupled Device) camera, which also records images with pixels of photo-excited charge packets confined in a field-effect-controlled electrostatic potential landscape. Whereas a CCD camera only stores unipolar charges and reads them out electronically, the photonic camera presented here stores both, electrons and holes, in the extrema of the two-dimensional potential landscape for a desired storage time. Turning off the potential modulation it can release the full image optically as luminescent light within about 1 ns. Via the quantum confined Stark effect one has the potential to colour-code rows or even individual pixels, an option that would allow wavelength division multiplexing.

Unfortunately, the comparatively shallow barriers between the gate electrodes and the quantum well with energies of order 100 meV cause appreciable leakage of the stored carriers to the gates at temperatures above about 100 K, thus preventing room temperature operation with the AlGaAs–GaAs quantum wells used. Quantum wells with significantly larger barriers would be needed to allow room temperature operation of such a photonic camera. When such quantum wells structures become available one can envision a practical photonic camera that would be able to record optical images and convert them into an optical data string that can be directly fed into a photonic fiber.

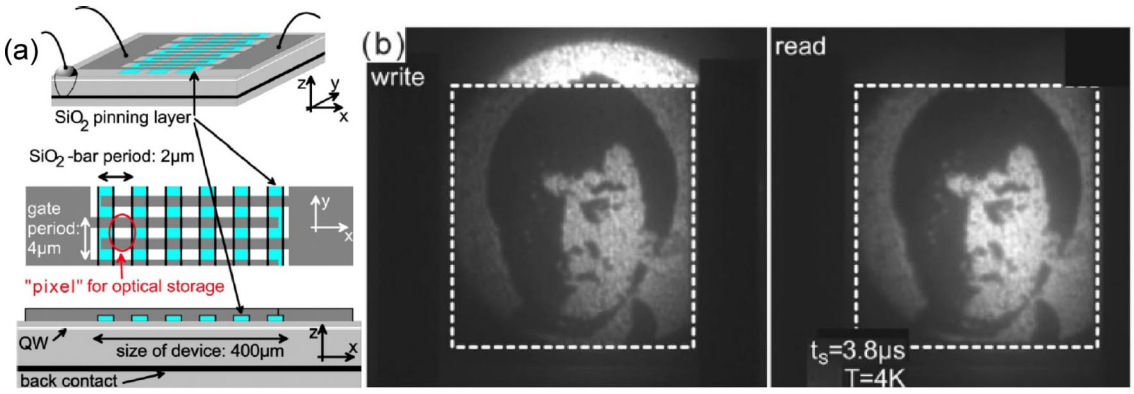

Fig. 5 (online colour at: www.pss-b.com) A photonic storage device: A voltage-controlled two-dimensional potential modulation mediated by the gate structure sketched in (a) enables the storage of full images in terms of spatially separated electrons and holes. The stored image is released as luminescence after a variable storage time t_s as exemplified in (b). Here the recorded image consists of 125 × 200 pixels. (After Ref. [15].)

3 Trapping excitons in electrostatic potentials

The separation of photo-excited electron–hole pairs as discussed above relies on electric fields in the plane of the quantum well comparable or larger than the excitonic ionization threshold of about 10^4 V/cm. The same devices can also be used to trap excitons, i.e. photo-excited electron–hole pairs that remain bound by their Coulomb interaction without being ionized as discussed in the following. The field-effect-induced potential between patterned gate electrodes has both a component in the quantum well plane as well as one perpendicular to it. They can be tuned nearly independently in a device with an imbedded back contact as shown in Fig. 1a. Here the voltage difference between the fingers of the interdigitated gates controls the in-plane electric field whereas the voltages between the gates and the back contact yield control over the out-of-plane electric field. The latter influences the energy of a quantum well exciton via the quantum confined Stark effect, causing the luminescence to be red-shifted as, e.g., visible in Fig. 3 at bias situation (B). Hence spatial variation of the out-of plane electric field creates an effective potential for excitons with minima at locations of strongest electric field. In such a potential landscape excitons accumulate in these minima and thus are "high-field seekers" as schematically illustrated in Fig. 6a. At zero gate bias our field-effect devices have a built-in electric field perpendicular to the quantum well resulting from the Schottky contact between the metallic gates and the heterojunction. Therefore the flat-band condition, at which the quantum well is not tilted by the quantum confined Stark effect, is typically reached at a gate bias of $V_1 = V_2 = 0.7$ V, corresponding in energy to half the band gap of GaAs [16]. Hence strongest confinement can be achieved if one of the gates is biased negative with respect to the back contact as this configuration further increases the perpendicular electric field.

Trapping of excitons in heterostructures with single quantum wells, provided with interdigitated gate electrodes as in Fig. 1a, has been demonstrated in a series of experiments by Zimmermann et al. [16, 17]. It is nicely reflected in spatially resolved luminescence experiments carried out jointly with the group of Gerhard Abstreiter [17] as shown in Fig. 6b. Here the luminescence is recorded in the presence of a potential modulation caused by the gate bias as indicated and decays within about 1 ns. Both demonstrates that this is direct excitonic luminescence and not luminescence resulting from electrons and holes that are spatially separated in the quantum well plane. Since the quantum well employed has a width of typically 20 nm the out-of-plane electric field that causes the quantum confined Stark effect does not decrease the spatial overlap between the electron and hole wave functions strongly. Therefore we do not observe a strong dependence of the luminescence intensity and the recombination lifetime on the gate potential. The good confinement of the excitons in the minima of the effective potential is further mani-

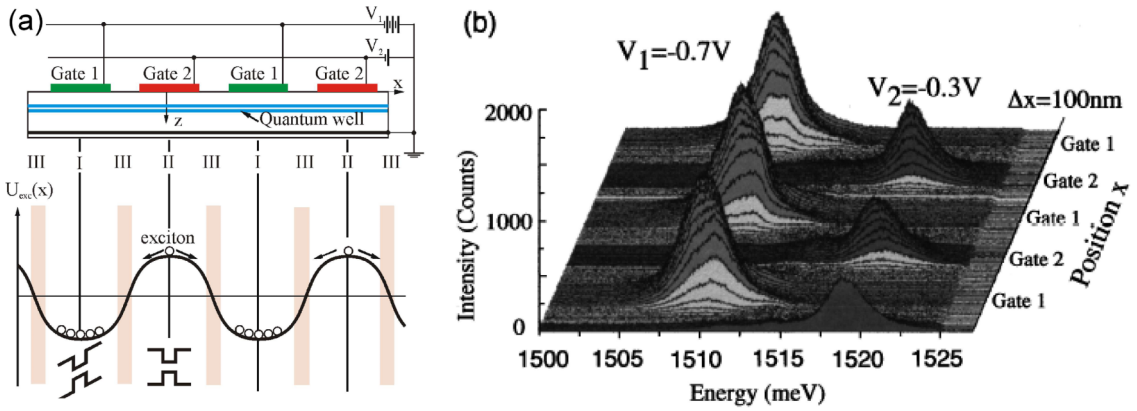

Fig. 6 (online colour at: www.pss-b.com) Quantum confined Stark effect resulting from the electric field component perpendicular to the plane of a quantum well causes a red-shift of the excitonic energy. Modulating it in the quantum well plane causes a laterally modulated excitonic potential U_{exc}. An accumulation of excitons occurs in the regions I of large fields as indicated in (a). Here the shaded regions III are the ones where the lateral electric field can cause exciton ionization. (b) Spatially resolved luminescence from excitons in a 20 nm wide quantum well confined under an interdigitated gate with a period of 2 μm showing an accumulation of excitons beneath the more negatively biased gate electrode. (After Ref. [17].)

fested when the exciting laser is focused onto the more negatively biased gate finger while the detection area is scanned across the periodic gate. Under this condition hardly any luminescence is seen when the detection spot collects light from the potential minimum adjacent to the one where the excitation takes place. The barrier in the excitonic potential, induced by the more positively biased gate, prevents efficiently the spreading of excitons generated in one minimum into the adjacent minimum, at least at liquid helium temperatures.

The interplay between electrostatic exciton confinement and tunnel ionization of excitons was subsequently studied theoretically [18]. It was predicted that a strong magnetic field applied perpendicular to the quantum well will stabilize excitons against ionization. This remains to be experimentally verified.

4 Drift and confinement of long-living excitons in double quantum wells

As discussed above the recombination lifetime of excitons in a typical GaAs–AlGaAs quantum well with width of 20 nm or below is about 1 ns and not widely tuneable by the quantum confined Stark effect. To create and control excitons in GaAs-based quantum wells with recombination lifetimes that are of order 1 μs one has to carefully tailor the quantum wells. By employing excitons that are indirect either in momentum space or in real space or in both one can strongly decrease the interband transition matrix element. Experiments with so-called long-living quantum well excitons are motivated by the wish to study excitonic drift and diffusion in quantum wells but also by the desire to generate an excitonic Bose–Einstein condensate (BEC) in a suitably designed confining potential. Such excitonic condensates, predicted decades ago by Keldysh and Kozlov [19], still lack a convincing experimental realization. Quantum well structures are likely to be the best approach to observe excitonic BEC at liquid helium temperatures. In these systems one can realize confinement to a two-dimensional plane as well as in-plane trapping potentials, tuneable and long excitonic lifetimes, and efficient exciton generation. Consequently, advantageous conditions, namely high exciton densities with long lifetimes at low temperatures, increase the chances for BEC. Even if such condensation occurs one has to identify experiments that provide a unique signature of the BEC state.

Narrow coupled GaAs–AlAs quantum wells can be tuned via the quantum confined Stark effect such that electrons are located at the X-point of the conduction band of the AlAs barrier whereas heavy holes are confined at the Γ-point of the valence band of the adjacent GaAs quantum well. This enables the

formation of excitons which are indirect in both real and momentum space and exhibit recombination lifetimes in excess of 100 ns. Hagn et al. in the Abstreiter group studied successfully the drift and diffusion of such long-living excitons under the influence of an in-plane gradient of the excitonic potential over distances of about 10 μm [20]. However, excitonic mobilities in such heterostructures with values of about 500 $cm^2/eV\,s$ are relatively modest. In suitably designed GaAs double quantum wells with a separating AlGaAs barrier excitonic lifetimes in excess of 1 μs can be achieved. In such double quantum wells excitonic motion is observed across macroscopic distances and reveals unexpected spatial luminescence patterns [21–24]. Though initially suspected as an indication of quantum degeneracy and formation of a BEC, a series of experiments established that the luminescence patterns are essentially a consequence of a classical non-equilibrium distribution: Electron–hole pairs and excitons, strongly generated at the location of laser focus, spread in a highly non-linear fashion as a consequence of drift and diffusion [25, 26]. Some of the observed spatial luminescence features, however, are continued to be discussed in terms of quantum degeneracy of the excitonic systems and quantum statistical corrections [27, 28].

These investigations triggered renewed interest in trapping long-living excitons, both theoretically [29, 30] and experimentally [31, 32]. Recently, studies of the excitonic transport through diffusion, in part driven by dipolar repulsion between excitons, have been reported [33]. A classical model describing the non-linear dynamics of such a high-density dipolar exciton gas compares well with the observed features [34]. To learn more about the dynamics of such dipolar excitons and to explore efficient ways of generating high densities of cold excitons, a prerequisite for BEC, we have started to study their motion in well-defined in-plane potential gradients caused by a spatial variation of the out-of-plane electric field [35, 36]. In a drift experiment we use a resistive and transparent gate electrode to create a gradient in the electrostatic potential applied between the gate and the back electrode. The quantum confined Stark effect causes a corresponding voltage-tuneable gradient in the effective excitonic potential, which can be quantitatively determined by spatially resolving the energetic shift of the indirect luminescence. In a time-of-flight experiment we use spatially and temporally resolved luminescence to study the dynamics of dipolar excitons and separate drift, induced by the potential gradient, from diffusive motion as illustrated in Fig. 7. A quantitative analysis of such experiments yields excitonic mobilities in excess of 10^5 $cm^2/eV\,s$ at temperatures below 10 K. This corresponds to scattering times of about 15 ps, a value

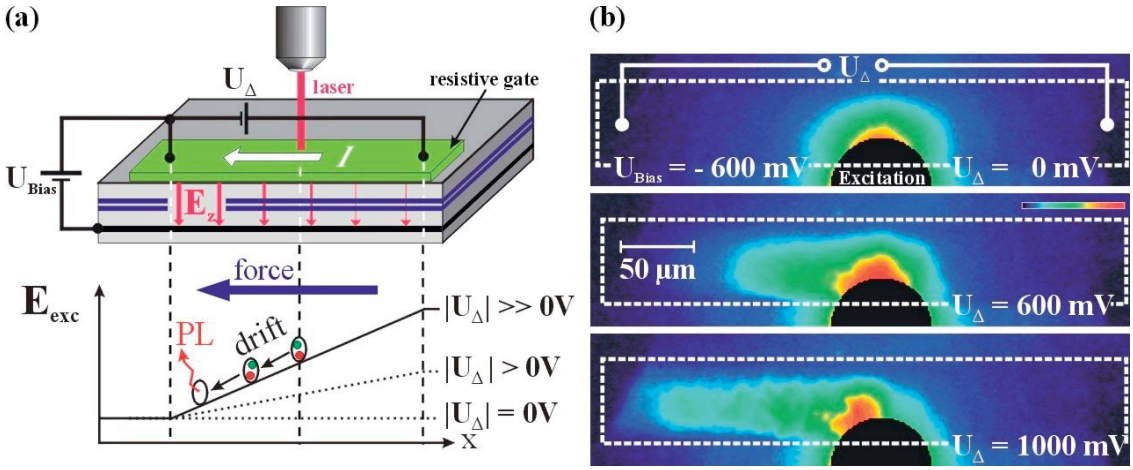

Fig. 7 (online colour at: www.pss-b.com) Drift of long-living excitons in a GaAs–$Al_{0.3}Ga_{0.7}As$ double quantum well caused by a voltage-induced gradient of the effective exciton potential. (a) Schematic set-up with bias voltage $U_{bias} = -0.6$ V applied between the l.h.s. of the gate and the back contact and a lateral voltage U_Δ across the resistive Ti gate. (b) Top-view of the excitonic luminescence observed 50 ns after the excitation with a 50 ns long laser pulse is switched off at different values of U_Δ, thus enabling to separate drift induced by U_Δ from diffusion. (After Ref. [35].)

comparable to the scattering times of electrons in similarly narrow high-mobility quantum wells, a factor of 200 larger than previously observed in coupled quantum wells [20]. A next step will be to combine drift of such long-living excitons with suitable trap designs to create long-living and spatially confined exciton ensembles of high density and low temperatures. This might finally open the door to studying the transition to an excitonic BEC in quantum well structures under well-defined experimental conditions.

5 Conclusion

With the experiments discussed above we have tried to demonstrate that field-effect-tuneable potentials employed to study the optical properties of carriers confined in semiconductor nanostructures still enable novel and often surprising experimental results and physical insights, even more than 30 years after this field was introduced with very essential contributions in the doctoral thesis of Gerhard Abstreiter. This is meant to show beyond doubt that maturity does not necessarily imply boredom, a fact also reflected in the present activities of the person we honour with this volume.

Acknowledgements First of all I want to thank Gerhard Abstreiter for over thirty years of scientifically fruitful and constructive collaboration and close friendship. This review is based on contributions of many students and collaborators as identified in the references. In particular I want to thank Andreas Gärtner, Sasha Govorov, Wolfgang Hansen, Alexander Holleitner, Jan Krauß, Carsten Rocke, Andreas Schmeller, Achim Wixforth, and Stefan Zimmermann for their important scientific contributions. The experiments discussed above would not have been possible without the many excellently grown heterostructures provided by Max Bichler, Gerd Böhm, Art Gossard, Micah Hanson, Christoph Kadow, Dieter Schuh, Günther Tränkle, Werner Wegscheider, and Günther Weimann.

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