Voltage-controlled trapping of excitons and "storage of light" in lateral superlattices

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Abstract

Voltage-controlled lateral superlattices of various periods are employed to demonstrate the trapping of photogenerated excitons in quasi-one-dimensional regions and to store light in form of ionised excitons in the quantum well of a semiconductor heterostructure. The superlattices are induced by applying spatially alternating external voltages via interdigitated metal gates. Exciton localisation arises from a periodical modulation of the strength of the quantum confined Stark effect in the plane of the quantum well. At large superlattice potential amplitudes the excitons are ionised due to the strong lateral electric fields. The thus spatially separated electrons and holes can be stored efficiently in the structure. Resetting the potential amplitude to zero induces their radiative recombination after very long storage times.

PACS: 78.55.Cr; 78.66.Fd; 78.20.Wc; 71.30.−y; 71.55.Eq; 71.35.Ji

Keywords: Excitons; Lateral superlattices; Trapping; Storage of light

Electro-optic interactions involving excitons in semiconductor microstructures and devices are currently attracting much interest [1]. Such devices are usually laterally microstructured in the plane of quantum wells. Consequently, it is interesting to study quantum well excitons in laterally varying potentials and, in particular, the possibility of localising and storing them in distinct quasi-one- or zero-dimensional regions of a sample. This has been realised in semiconductors by strain [2,3], inter-diffusion of a barrier material [4] and the preparation of self-organised lateral structures [5]. In all these approaches, however, the exciton localisation cannot be changed by externally tunable parameters.

Tuneable polarisation of neutral excitons can be effectively induced by electric fields via the quantum confined Stark effect (QCSE) [6]. This effect implies a shift of the exciton energy in the quantum well (QW) by $\Delta E \approx -pF$ governed by a perpendicular electric eld F, where p is the dipole moment induced by the electric field. The energy shift $-pF$ plays the role

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of an effective exciton potential, U_{eff}. If the electric eld is dependent on the in-plane spatial coordinate, tuneable excitonic traps can be realized. This mechanism is effective if the localisation energy $-pF$ is significantly larger than the line width of the excitonic photoluminescence. Due to inhomogeneous broadening effects the latter does not usually fall below 2 meV in GaAs QWs [7]. Therefore, only the use of strong perpendicular electric fields in relatively wide QWs permits to obtain sufficiently large energy shifts [8] since in this case the QW barriers prevent field ionisation of excitons. Lateral transport of indirect QW excitons based on the QCSE was studied by use of two differently biased surface metal gates spatially separated by a macroscopic distance with a spatially resolved technique [9].

In this contribution, we present a detailed study of an extremely versatile system with interdigitated top gates and a back contact [10–13] as shown in Fig. 1. The design (a) allows us to induce a widely tuneable lateral potential superlattice (b, c) and hence both vertical and lateral electric fields in the plane of the QW. The vertical fields are maximal in regions I and II under the gate stripes, the lateral fields in the dashed regions III between the gate stripes. Spatial modulation of the QCSE occurs when we apply different negative voltages V_1 and V_2 to the finger gates with respect to the back contact. In the following, we operate in the non-degenerate regime, where the quasi-Fermi levels remain in the effective band gap. The effective exciton potential, U_{eff}, induced by the interdigitated gates, localises, photogenerated excitons in regions I underneath the more negatively biased gate, where their energy is minimal (b).

The AlAs–GaAs heterostructure used is grown by molecular beam epitaxy and consists of a Si-doped back electrode ($N_{\mathrm{D}} = 4 \times 10^{18}\,\mathrm{cm}^{-3}$) grown on an undoped GaAs buffer, and a 20 nm QW embedded in a short-period AlAs–GaAs superlattice barrier. The QW and the back electrode are separated from the surface by 60 and 390 nm, respectively. On top of the heterostructure we define a $200 \times 200\,\mu\mathrm{m}^2$ semi-transparent titanium gate in an interdigitated geometry with periods a between 250 and 2000 nm and stripe width w from 1300 down to 100 nm. The period of the resulting superlattice in the sample is $2a$. The chosen dimensions of the sample are comparable to the exciton diffusion length of approximately 1 µm which allows to investigate the redistribution of excitons caused by diffusion and drift. The experiments are performed at $T = 3.5$ K to assure PL of excitonic origin. Excitons are photogenerated in all regions I–III of the sample using a diode laser of $E = 1.58$ eV and $P = 0.5$ W/cm.

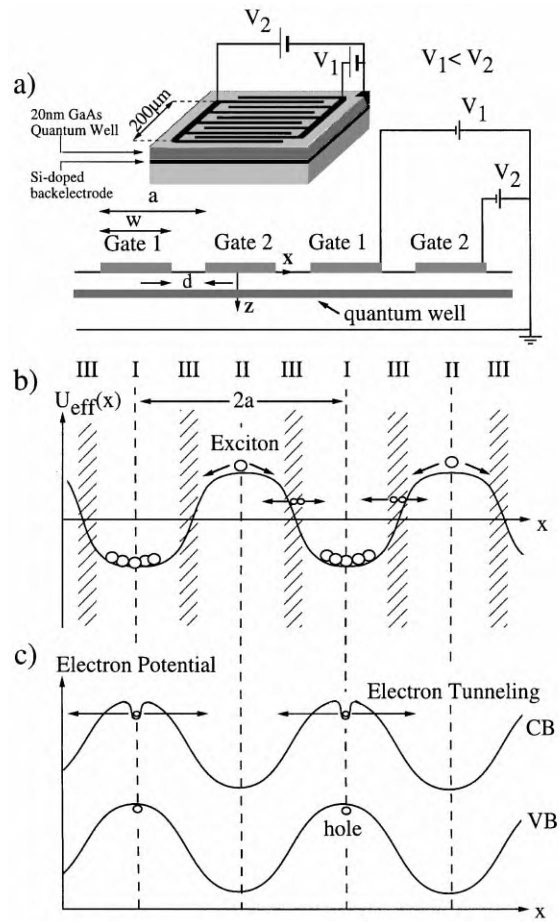

Fig. 1. (a) A sketch of the system with the interdigitated gate and its geometry. (b) The effective exciton potential, U_{eff}, and the resulting exciton transport within the regions I–III of the system as described in the text. (c) The electron potential at finite voltage difference $\Delta V = V_1 - V_2$ applied to the interdigitated gate. The excitons are localised in the regions I, where the electron potential is maximal and in small period superlattices nearly parabolic. The dip in the CB is caused by the Coulomb interaction of the electron with the hole.

Fig. 2 shows photoluminescence (PL) spectra of a sample with 1300 nm stripe width and 200 nm gaps between the stripes. The experiment is performed as described in the figure caption. At $V_1 = V_2$ the PL spec-

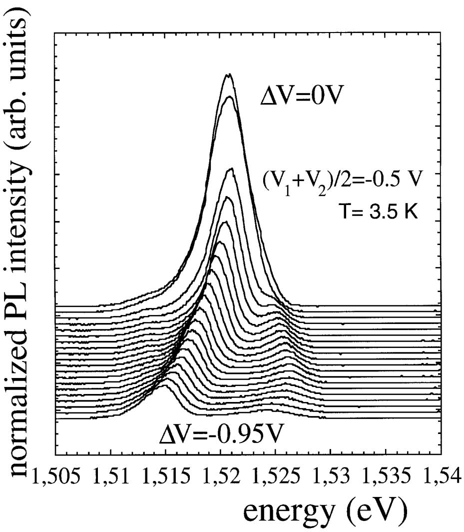

Fig. 2. PL spectra of the sample with the 3000 nm-superlattice period at a temperature of $T = 3.5$ K. The intensities are normalized to the one at zero voltage difference $\Delta V = V_1 - V_2$. The spectra are offset for clarity. The average voltage is $(V_1 + V_2)/2 = -0.5$ V, and ΔV is changed from 0 V (upper curve) to -0.95 V (upper curve) in steps of 0.05 V.

trum exhibits a single narrow heavy-hole exciton peak, its energetic positon being determined by the QCSE. Here, the interdigitated structure behaves essentially like a homogeneous gate. With increasing gate voltage difference $\Delta V = V_2 - V_1$ we observe a splitting of the exciton peak into two main features which shift in energy into opposite directions, each according to the QCSE. We thus conclude that the low-energy peak (LEP) and the high-energy peak (HEP) can be attributed to the PL signal arising from the regions I and II under the correspondingly biased gates. At moderate ΔV the intensity of the LEP is much larger then of the HEP. We interpret this with our model of the effective exciton potential as localising excitons under the more negatively biased gate where their energy is minimal and their PL is most red shifted. The HEP occurs because some excitons recombine before reaching the edges of region II by diffusion from where they drift into the potential minima. The intensity of the HEP is therefore dependent on the ratio of the exciton diffusion length to the stripe width. When localising excitons in short period superlattices, $2a = 500$ nm, with stripe width down to 100 nm, we find that the HEP is hardly visible [14].

Another prominent feature in the spectra is the decrease of the total PL intensity with increasing gate voltage difference. This is associated with the ionisation of excitons due to lateral electric fields in regions III between the gate stripes. A voltage difference of $V = 0.15$ V corresponds to a calculated lateral electric field of 4×10^4 V/cm which is consistent with the typical ionisation field of excitons in bulk GaAs [7]. Thus at voltage differences $\Delta V > 0.15$ V the regions I and II are decoupled by the exciton current and the intensities of LEP and HEP become comparable. There is no PL originating from regions between the stripes. Excitons created here are either field-ionised or reach the potential trap before they recombine. Our model is also confirmed with spatially resolved PL measurements [14].

We now demonstrate in time-resolved PL measurements that lateral superlattices of larger periods can be employed to efficiently store light in the quantum well even at elevated temperatures of up to 100 K. Applying a large ΔV quenches the PL due to field-ionisation of the photogenerated excitons by strong lateral electric fields in regions III [10,14,15]. The electrons and holes created in this process are spatially separated under the differently biased gate stripes. To ensure effective storage we used 1100 nm stripe width and 900 nm stripe distance resulting in a small overlap of the wave functions. One gate is held at slightly positive potential. When the gate voltage difference is reset to zero, the electrons and holes being Coulomb attracted recombine radiatively within the same superlattice period they were stored. The energy of the PL emitted in this way can be controlled by the common bias of the gates with respect to the backelectrode.

Fig. 3 shows the PL intensity of the reemitted light with increasing storage time. We obtain decay times of the order of $t_{1/2} \approx 14\,\mu$s, hence orders of magnitude longer than the usual lifetime of radiative excitons of some 1 ns in quantum wells. For not too high laser power the signal behaves linear with incident power. Fig. 4 shows a time-resolved measurement of the reemitted light. Here, the electrons and holes that had been stored for 14 μs, recombine within only 40 ns and with excellent signal-to-noise ratio. We found that up to 10% of the incident light can be recovered after storage. Losses are assumed to be caused by carrier tunneling to the gate electrodes.

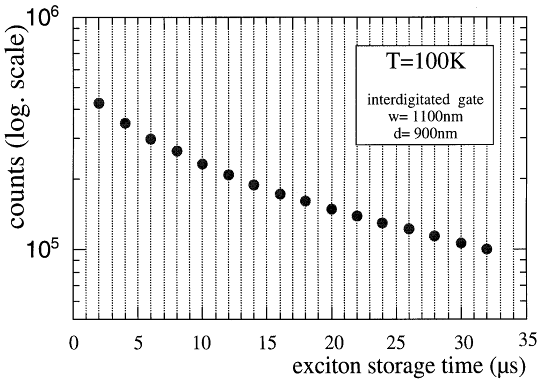

Fig. 3. PL intensity of the reemitted light for increasing storage time at a temperature of $T = 100\,\mathrm{K}$.

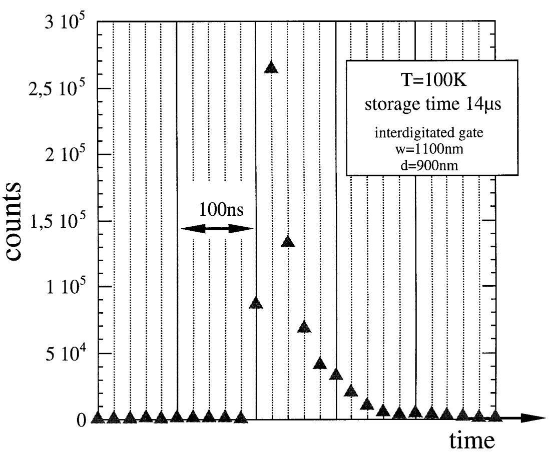

Fig. 4. Timeresolved PL signal after setting $\Delta V = 0\,\mathrm{V}$ at a temperature of $T = 100\,\mathrm{K}$. The light had been stored for 14 μs in the structure.

We wish to note that localisation of 2D excitons and storage of light can also be obtained by means of surface acoustic waves which induce a moving lateral superlattice in the quantum well plane [15]. This allows to transport stored light at the speed of sound over macroscopic distances and release it time delayed at any arbitrary lateral position in the semiconductor sample.

Acknowledgements

This work was supported by the Sonderforschungsbereich 348 of the Deutsche Forschungs-gemeinschaft. One of us (A.O.G.) gratefully acknowledges support by the A. v. Humboldt Stiftung.

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