Tunable photo-emission from an excitonic antitrap: Supporting Information

Katarzyna Kowalik-Seidl,[1] Xaver P. Vögele,[1] Bernhard N. Rimpfl,[1] Georg J. Schinner,[1] Dieter Schuh,[2] Werner Wegscheider,[3] Alexander W. Holleitner,[4] and Jörg P. Kotthaus[1]*

1 Fakultät für Physik and Center for NanoScience (CeNS), Ludwig-Maximilians-Universität, Geschwister-Scholl-Platz 1, D-80539 München, Germany

2 Institut für Experimentelle und Angewandte Physik, Universität Regensburg, Universitätsstraße 31, D-93053 Regensburg, Germany

3 Laboratorium für Festkörperphysik, HPF E 7, ETH Zürich, Schafmattstr. 16, 8093 Zürich, Switzerland

4 Walter Schottky Institut and Physik-Department, Technische Universität München, Am Coulombwall 4a, D-85748 Garching, Germany

Corresponding author: Katarzyna Kowalik-Seidl e-mail: k.kowalik@physik.uni-muenchen.de

S1. Sample structure and device fabrication:

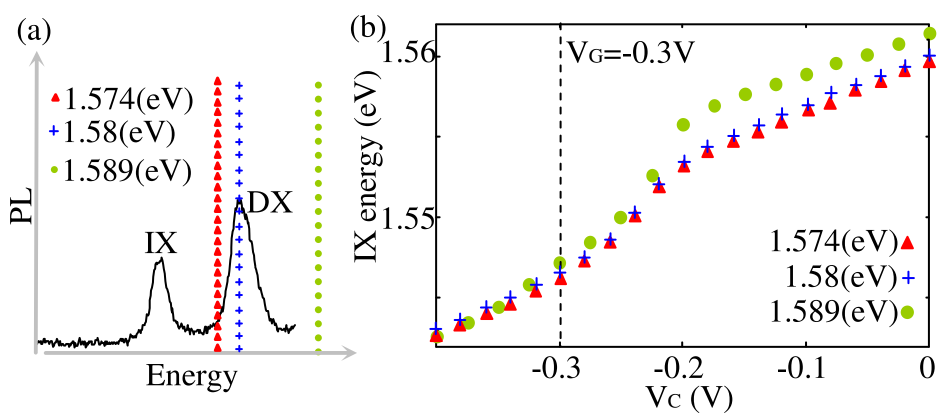
The studied heterostructure was grown by molecular beam epitaxy on a (001)-oriented GaAs substrate. It contains two 8-nm thick GaAs coupled quantum wells, which are separated by a thin 4-nm Al0.3Ga0.7As barrier and are embedded between two Al0.3Ga0.7As barriers. Structure details were previously reported[1,2]. This heterostructure is embedded in a field effective device defined by an n-doped GaAs back gate and top electrodes. In order to laterally vary the electrostatic potential on a sub-micrometer scale we defined the top gates by electron beam lithography. We fabricated two different traps: T1 and T2 with the C-gate diameters of 23.4 μm and 16.5 μm, respectively. In both cases, the gap between the central and the guard gate was kept constant at ~120 nm. The voltage working regime for guard and central gates was +0.7 to -0.7V covering the electric fields range: 0 to 38 kV/cm.

S2. Experiment:

We excited the quantum wells with a 780 nm diode laser. See Supporting Information §S3 for the characterization of the device T1 under quasi-resonant excitation. The measurements were performed with the sample cooled by He-exchange gas to 4.2K in a confocal setup with a spatial resolution of ~1 μm, in which the same lens was used to focus the excitation beam and to collect the photoluminescence from the sample. The relative positioning in all three directions with sub-micrometer precision was ensured by piezo-positioners.

S3. Influence of the excitation energy on the trap-antitrap transition:

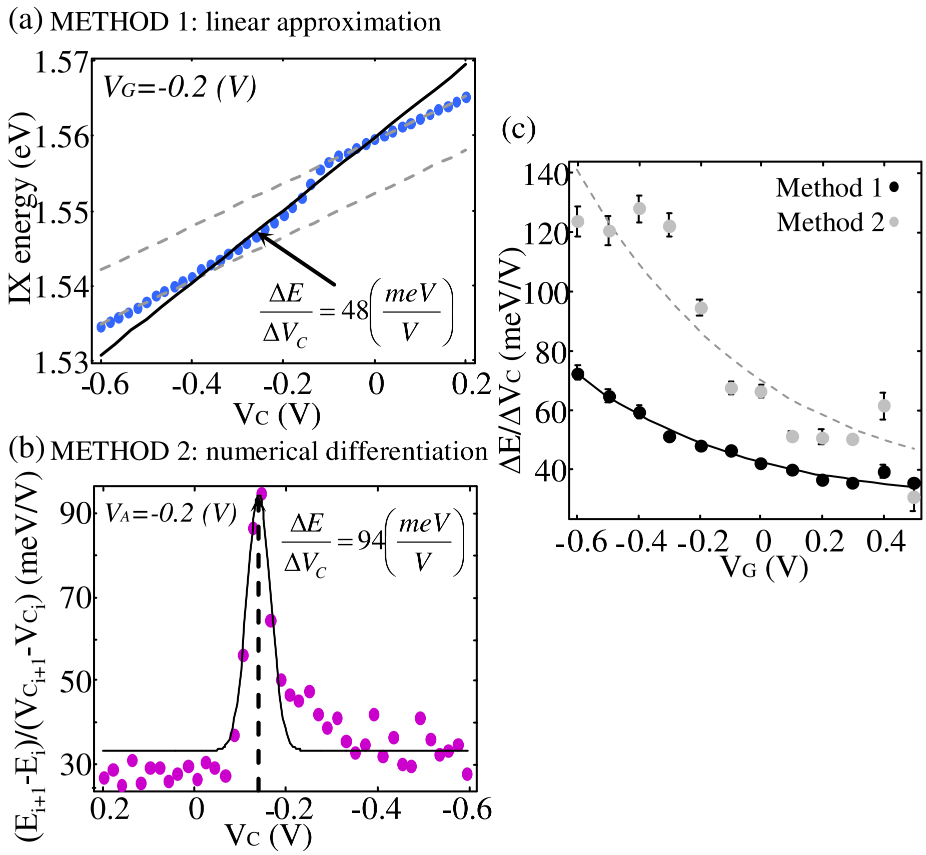
We observe a strong blue shift in the energy of indirect excitons (IX) under the central gate, when the voltage V_C is larger than the voltage on the guard gate V_G (see Figure 3a in the article). We relate this phenomenon to the increase of the exciton density in the antitrap configuration (V_C>V_G) and explain it by a fast escape of photocreated electrons out of the exciton trap[2] (see Figure 2b in the article and the following discussion). If the process of exciton formation is governed by the mobility of the generated electrons and holes, it should be sensitive to the excitation energy. Therefore, in order to support our interpretation we measured the influence of the laser energy on the excitonic emission. We used three different energies of the exciting laser: 1.589eV – non-resonant, 1.58eV – resonant with the spatially direct transitions (DX) within the individual quantum wells, and 1.574eV – quasi-resonant with the indirect transition (see Supporting Figure I a). Photoluminescence of indirect excitons was recorded as a function of different gate configurations under these three chosen excitation energies. The energy shift of indirect excitons (IX) with the voltage V_C is plotted in Supporting Figure I b. We notice a strong reduction of the blue shift at ~-0.2 V with the decreased laser energy.



Supporting Figure I. (a) Scheme of different excitations with respect to the PL signal (black): points (green) – non-resonant excitation, crosses (blue) – resonant excitation into direct exciton states (DX), triangles (red) – quasi-resonant excitation of indirect excitons (below the direct excitonic transition). (b) Fitted energy position of the indirect exciton PL vs. V_C; different symbols (colors) correspond to different excitation energies (see part (a)).

S4. Maximum tuning of indirect exciton energy in a small voltage regime:

In the following, we discuss different methods to estimate the maximum energy tuning of the indirect excitonic emission in the trap-antitrap transition. We focus on the device T1 (trap with the central gate diameter of 23.4 µm). In the article, the energy tuning is estimated by a linear fit in the whole transition regime (see Supporting Figure II a). It gives an "average" energy tuning ratio $\Delta E/\Delta V_C$, which correspond to the situation in which the device is tuned between the two configurations trap-antitrap in wide voltage V_C regime. This method (called later on Method 1) allows us to conclude about the general dependence of $\Delta E/\Delta V_C$ on the guard voltage V_G, as presented in Supporting Figure IIc. Although this Method 1 is useful to characterize the device generally and to predict its behaviour for voltages not directly measured in our experiment, it does not reveal its full capabilities. In order to estimate the maximum energy tuning ratio, which can be achieved with our device we introduce a second method. The modulation ratio deviates from the linear approximation for the voltages V_C between -0.1 V and -0.2 V, (Supporting Figure IIa). Method 2 of obtaining $\Delta E/\Delta V_C$ bases on the discrete differentiation of the IX energy vs. V_C. The result of such numerical operation is presented in the Supporting Figure II b. A constant modulation rate is observed for voltages V_C in the exciton trap and antitrap configuration, respectively. It corresponds to the slope of the Stark shift in the voltage regime $V_C \ll V_G$ ($V_C \gg V_G$)[3]. In the transition region (from 0 to -0.3 V) one can see a clear enhancement of the tuning ratio $\Delta E/\Delta V_C$, which reaches 94 meV/V at maximum. This value gives an upper limit of the tuning ratio $(\Delta E/\Delta V_C)_{max}$, which can be achieved with the device. Method 2 shows the highest tuning ratio under specific optimal conditions (small modulation range of the voltage V_C). It is very sensitive to any changes in the working parameters. Method 2 leads to a slightly larger experimental error than Method 1. Although the changes of $(\Delta E/\Delta V_C)_{max}$ exhibits a clear tendency as a function of the voltage V_G, it cannot be so simply used to predict a maximum energy tuning for other voltage configurations as the parameters $(\Delta E/\Delta V_C)$ obtained from the Method 1.



Supporting Figure II. Comparison of two methods calculating energy tuning of the excitonic emission in the device. (a) METHOD1: Fitted energy position of the indirect exciton PL vs. voltage V_C at fixed voltage V_G=-0.2V for the device T1. Dashed lines mark the Stark shift in the trap/antitrap configurations, solid line – a linear fit for the transition region. The energy tuning ratio $\Delta E/\Delta V_C$ equals the slope of the linear fit. (b) METHOD 2: Numerical differentiation of the energy position of the indirect exciton PL vs. voltage V_C at fixed voltage V_G=-0.2V. The energy tuning ratio $\Delta E/\Delta V_C$ equals the sum of the Gaussian fit amplitude and the constant background. (c) Comparison of the two methods presented in parts (a) and (b): The energy tuning ratio ($\Delta E/\Delta V_C$) measured for different voltages on the guard gate *G* (V_G): Method 1 – black points, Method 2 – gray points.

---

[1] Gärtner, A.; Prechtel, L.;Schuh, D.; Holleitner, A.W.; Kotthaus, J.P. *Phys. Rev. B* **2007**, *76*, 085304; Kowalik-Seidl, K.; Vögele, X.P.; Rimpfl, B.N.; Manus, S.; Kotthaus, J.P.; Schuh, D.; Wegscheider, W.; Holleitner, A.W. *Appl. Phys. Lett.* **2010**, *97*, 011104.

[2] Kowalik-Seidl, K.; Vögele, X.P.; Seilmeier, F.; Schuh, D.; Wegscheider, W.; Holleitner, A.W.; Kotthaus, J.P. *Phys. Rev. B* **2011**, *83*, 081307(R).

[3] The slope of the quantum confined Stark shift is constant in this voltage regime, around 31meV/V. This value is in a good agreement with the slope 33 meV/V obtained from numerical simulations in such a heterostructure using the software Nextnatno3 (http://www.nextnano.de) and measured in other experiments with similar heterostructures [see e.g. Ref.[2]].