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Tuning the cross-gap transition energy of a quantum dot by uniaxial stress

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Abstract

We show that a piezoelectric actuator can be used to apply uniaxial stress to a layer of self-assembled quantum dots. The applied stress leads to a change of the quantum dot's ground state exciton energy by up to a few hundred μeV. This approach allows the possibility of an in situ and continuous tuning of the stress at temperatures down to 4 K and offers an alternative to tuning by temperature and Stark effect. We measure the relative change in the charging energy to the n-doped back contact by capacitance and the change in the exciton energy by photoluminescence. By tuning the uniaxial stress we are able to perform reflection spectroscopy on a single dot.
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Self-assembled semiconductor quantum dots (QDs) are of great interest for quantum optics and quantum information processing [1–3]. QDs have been embedded in cavities to improve their efficiency as a single photon sources because of the directed radiation and the Purcell effect [4]. Recently, strong coupling between a cavity mode and a QD exciton was achieved [5,6]. A crucial requirement for the success of these applications is the ability to tune the QD's energy into resonance with the cavity mode. The different temperature dependencies of QD transitions and cavity modes were exploited to achieve the overlap [5,6]. The tuning of the transition energy is also a key point for absorption spectroscopy on a single QD [7]. The electric Stark effect has been mainly used in this context but tuning was also demonstrated by magnetic fields [8].

In this paper, we present a different way of tuning the QD transition energy by using uniaxial strain. The strain is applied by glueing the sample to a piezoelectric actuator (piezo) as shown in Fig. 1 [9]. This enables a continuous and in situ change of the applied strain at temperatures down to 4 K. The sample is a charge-tuneable QD structure, with an n-doped back contact separated by a 25 nm blocking barrier from a layer of self-assembled QDs grown by MBE. The dot layer, which is shifted in emission wavelength to 950 nm by the partial overgrowth method, is followed by a capping layer, an AlAs/GaAs blocking barrier and a metallic top gate 150 nm above the QDs. This enables control of the QD charge by the applied gate voltage and, further, a tuning of the exciton transition energy by the Stark effect [10]. The [1 1 0] axis of the GaAs crystal is parallel to the direction of motion of the piezo. A second sample is glued on the other side of the piezo and equipped with a strain gauge. An AC resistance bridge circuit in combination with a lock in amplifier is used to measure the change in resistance. The strain gauge is not glued directly onto the QD sample because the QDs are

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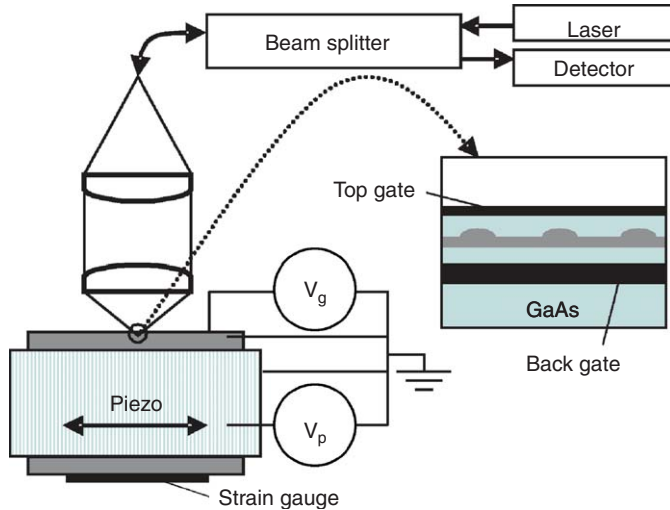*E-mail address:* Stefan.Seidl@Physik.Uni-Muenchen.de (S. Seidl).

Fig. 1. Sketch of the experimental set up and the sample. A piezo is used to apply strain, measured by a strain gauge, to a charge-tuneable QD sample. A confocal microscope is used to study the behaviour of a single QD in PL and reflection spectroscopy at 4.2 K.
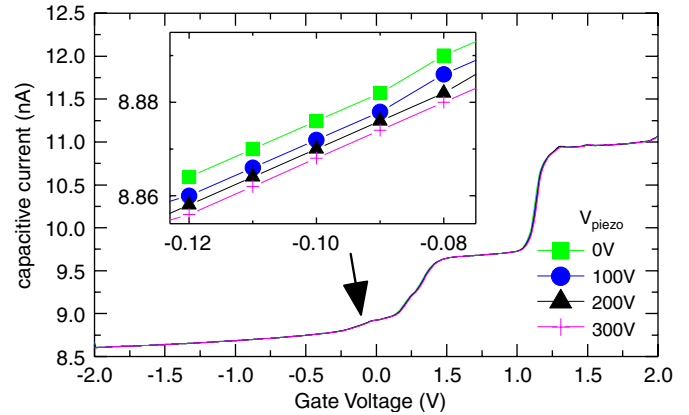

Fig. 2. Capacitance as a function of gate voltage. The curve shifts towards positive voltages when a compressive strain is applied with the piezo. The piezo voltage of 300 V corresponds to a pressure of 20.4 MPa as determined by GaAs bulk PL.
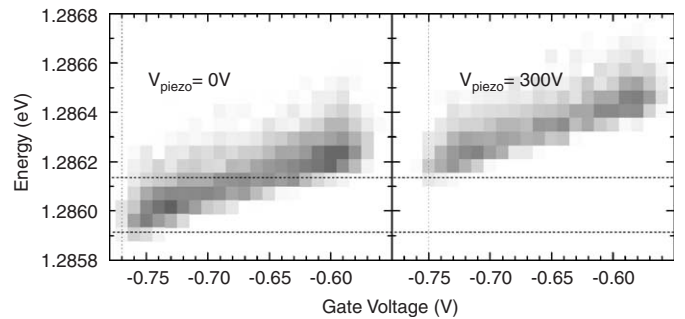

Fig. 3. Grey scale plot of PL as a function of gate voltage for piezo voltages of 0 and 300 V. A clear shift in gate voltage and energy is visible.

studied optically and the strain gauge would block the light path.

In addition, the strain shift of the bulk GaAs photoluminescence (PL) was measured directly with the QD PL in order to calibrate the strain. The GaAs PL consists of four peaks with slightly different dependencies on piezo voltage. We argue that the highest energy PL peak behaves in the most similar way to the GaAs band gap as it has the smallest impurity binding energy. This peak shifts with piezo voltage by $0.82\,\mu\mathrm{eV/V}$. With the known dependence of the GaAs band gap on $[1\,1\,0]$ uniaxial strain, $12\,\mu\mathrm{eV/MPa}$ [11,12], and the Young's modulus of GaAs [13], we find that the relative change of length $\Delta L/L$ is $5.6\times10^{-7}/\mathrm{V}$ applied to the piezo. This value agrees well with other piezo experiments on a GaAs heterostructure at 4.2 K [9]. The polarity convention is chosen that positive voltages lead to a compression of the piezo. The standard method to study the charging of a QD ensemble is capacitance spectroscopy as function of the gate voltage (CV spectroscopy) [14]. Fig. 2 shows CV spectra for four different piezo voltages. While the gate voltage is changed from -2.0 to $+2.0\,\mathrm{V}$, the capacitance between back and top gate is measured. The step in capacitance at voltages between 0.2–0.4 V is caused by the charging of the two-dimensional wetting layer which is formed along with the QDs in the Stranski–Krastanov growth mode and the one between 1.1 and 1.3 V is caused by the formation of a 2 DEG at the GaAs/blocking barrier interface. The QDs themselves charge between -0.2 and $0\,\mathrm{V}$. The inset of Fig. 2 shows a magnification of the charging of the QDs and a shift to more positive voltages with increasing compression. The same shift is measured for the two other charging processes. This shift corresponds to a change in the electrostatic energy of about 2 meV at a piezo voltage of 300 V and, as we show, is much larger than the shift in

the QD and bulk GaAs PL. Its origin is therefore not a shift of the conduction band with uniaxial strain. Rather, it must arise as a change in the energy difference between the Fermi energy of the back contact and the Fermi energy in the metallic gate electrode.

Fig. 3 shows the PL of a neutral exciton as a function of the gate voltage for a single QD with 0 and 300 V applied to the piezo. The on and off switching of the PL is related to charging of the QD [10] and is again shifted to positive voltages. The shift for this QD is about 15 mV which is in very good agreement with the 13 mV measured from the CV spectroscopy for the whole ensemble. The figure also shows the change in the PL energy which is caused by the enlargement of the band gap due to the strain; approximately 0.22 meV for this QD. This translates into a pressure dependence of the QD energy of $8.5\,\mu\mathrm{eV/MPa}$, slightly smaller than the bulk GaAs value.

The strain-induced change of the transition energy can be used to tune the QD into resonance with a constant wavelength laser line, a form of modulation spectroscopy [15]. Fig. 4 shows the laser spectroscopy of a single QD in reflection. The laser wavelength is kept constant while the voltage on the piezo is continuously changed. The reflected
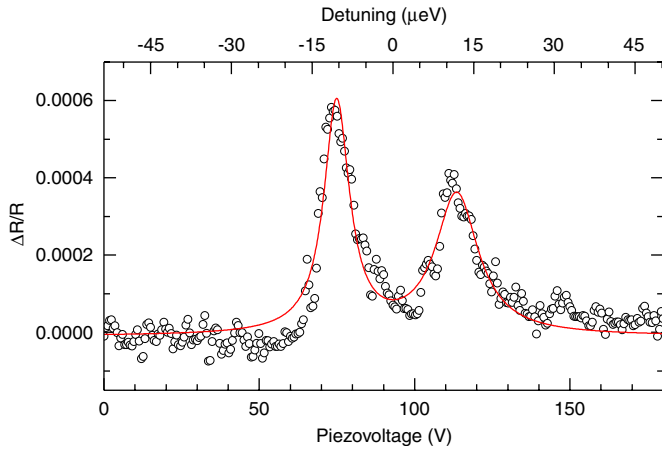
Fig. 4. Reflection spectroscopy on a single QD. The energy shift caused by the piezo strain is used to tune the exciton transition energy through a laser line of fixed wavelength. The splitting of 23 µeV is the fine structure splitting between the horizontally and vertically polarised transitions. The solid line is the fit of two Lorentz functions to the data.

light is collected by the same confocal microscope which is used to illuminate the QD and a fiber-coupled beam splitter sends about 95% of the light to a p–i–n diode detector. To improve the signal-to-noise ratio the gate voltage is modulated with a square voltage of 100 mV to use the lock in technique. The splitting of the peak is the exciton fine structure splitting of 25 µeV which is not visible in the PL because of the spectrometer resolution of about 100 µeV.

In conclusion, we have shown that the energy levels in a self-assembled QD can be changed in situ by a piezo. This leads to a change in the charging voltages of the QD and in the exciton transition energies. The uniaxial stress can be used to tune a QD transition energy into resonance with a constant energy mode, such as a laser and potentially a micro-cavity mode.

References

[1] A. Imamoglu, et al., Phys. Rev. Lett. 83 (1999) 4204.
[2] E. Biolatti, R.C. Iotti, P. Zanardi, F. Rossi, Phys. Rev. Lett. 85 (2000) 5647.
[3] P. Chem, C. Piermarocchi, L.J. Sham, Phys. Rev. Lett. 87 (2001) 067401.
[4] M. Pelton, et al., Phys. Rev. Lett. 89 (2002) 233602.
[5] J.P. Reithmaier, et al., Nature 432 (2004) 7014.
[6] T. Yoshie, et al., Nature 432 (2004) 7014.
[7] B. Alen, F. Bickel, K. Karrai, R.J. Warburton, P.M. Petroff, Appl. Phys. Lett. 83 (2003) 2235.
[8] A. Högele, et al., Phys. Rev. Lett. 93 (2004) 217401.
[9] M. Shayegan, et al., Appl. Phys. Lett. 83 (2003) 5235.
[10] R.J. Warburton, et al., Nature 405 (2000) 926.
[11] R.N. Bharagava, M.I. Nathan, Phys. Rev. 161 (1967) 695.
[12] F.H. Pollak, M. Cardona, Phys. Rev. 172 (1968) 816.
[13] O. Mandelung, Semiconductors - Basic Data, Springer, Berlin, Heidelberg, New York, 1996.
[14] B.T. Miller, et al., Phys. Rev. B 56 (1997) 6764.
[15] M. Cardona, Modulation spectroscopy, Academic Press, New York, London, 1969.