New Journal of Physics
The open-access journal for physics

Manipulating quantum-confined Stark shift in electroluminescence from quantum dots with side gates

Xiulai Xu[1,3], **Aleksey Andreev**[1,2] **and David A Williams**[1]
[1] Hitachi Cambridge Laboratory, Hitachi Europe Ltd, 19 J J Thomson Avenue,
Cambridge CB3 0HE, UK
[2] Advanced Technology Institute, University of Surrey, GU2 7XH, UK
E-mail: xx757@cam.ac.uk

New Journal of Physics **10** (2008) 053036 (7pp)
Received 4 March 2008
Published 29 May 2008
Online at http://www.njp.org/
doi:10.1088/1367-2630/10/5/053036

Abstract. Single quantum dot (QD) light-emitting diodes were fabricated with side gates in a lateral p-i-n structure. The electroluminescence (EL) energy from the QDs can be controlled independently by the side gates and by forward bias. Stark shifts in EL have been observed up to 0.4 meV as a function of forward injection current, and around 0.7 meV by applying an electric field of 36 kV cm^{-1} across the QDs. The independent control of the QD emission energy is an important step towards electrically tuning the coupling between QDs and cavities, and generating entangled-photon sources.

Contents

---

[3] Author to whom any correspondence should be addressed.

1367-2630/08/053036+07$30.00

1. Introduction

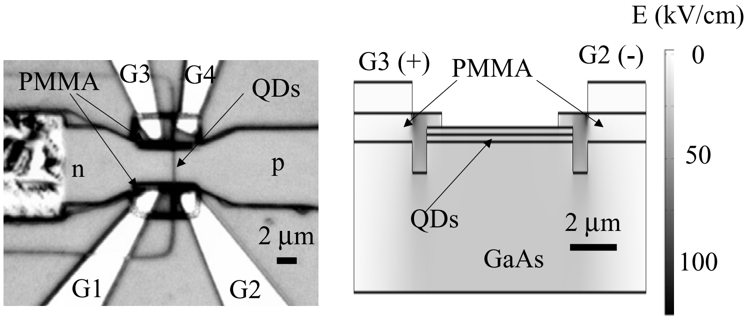
Semiconductor quantum dots (QDs) have attracted much interest in quantum information processing because of their ‘artificial atomic’ nature. Investigations have been performed to realize single-photon and entangled-photon sources [1]–[4], photon–exciton entanglement [5]–[7] and quantum gates [8]. QD based devices can be fabricated easily with standard semiconductor processing techniques for electroluminescence (EL) and quantum confined Stark effect, and it appears feasible to produce electrically-pumped and electrically-controlled entangled-photon sources. Recently, optically-pumped entangled-photon sources have been demonstrated by compressing the fine splitting of single QDs in a magnetic field [3, 4]. Since this fine splitting can be controlled with an electric field [9], electrically pumped entangled photon sources based on QDs are feasible.

To achieve strong coupling between QDs and cavities for exciton–photon entanglement, temperature tuning is normally used to move the peak position of QD emission to match the cavity modes [6, 7]. However, an increased temperature reduces the coherence time of the system, which might limit the application of devices in quantum computation. One way to shift the excitonic transition in QDs is to use the Stark shift, the energy shift due to an electric field applied across the dots. The Stark shift makes it possible to manipulate the QDs by both electric and optical fields. Stark shifts have been observed in single QDs by photoluminescence [10], electrically-gated photoluminescence [11], electroreflectance [12], photocurrent spectroscopy [13, 14] and EL [15] amongst other techniques. Normally the Stark shift observed in EL is due to the forward bias induced electric field, which is also required for injecting electrons and holes [15]. It is desirable to have separate electrodes to inject electrons and holes for EL, and to manipulate the electric field for Stark shift. One way to obtain this is to use a lateral electric field. Recently, a lateral electric field controlled Stark shift has only been demonstrated by photoluminescence spectroscopy [16]. In this work, we report a demonstration to manipulate the Stark shift of a single QD in EL by side gates in a lateral p-i-n junction.

2. Device fabrication and experimental details

In our previous work, lateral p-i-n junction devices have been fabricated using standard micro-fabrication processing with electron-beam lithography, reactive ion etching and lift-off techniques [1, 17]. These devices have demonstrated single photon emission from single layer dots [1] and the coupling between stacked two layer dots [17] in EL, in which no metal mask is needed to confine the emitting site. A AuGeNi alloy annealed at 420 °C was used to form n-type ohmic contacts. Cr/Au was deposited onto the surface to act both as p-type contacts and as bond pads. In this work, four Cr/Au side gates (defined as G1–G4) have been patterned around the active channel in a lateral p-i-n junction with one layer of diluted QDs embedded, as shown in figure 1(a). A layer of polymethylmethacrylate (PMMA) with a thickness of 500 nm was used as an insulating layer between the side gates and the active channel.

The sample was mounted in a He-flow cryostat and cooled to 5 K. The emitted light was collected by a large numerical aperture objective, dispersed through a 0.55 m spectrometer and then detected with a cooled charge-coupled device (CCD) camera. Electric field orientation across the QDs at the etched edge were controlled by biasing different side gates.



(a) (b)

Figure 1. (a) SEM image of a lateral p-i-n junction device with side gates. Active regions are mesas. n and p are n-type and p-type electrodes, respectively. Electroluminescence is obtained from the dots in the active channel under forward bias. (b) Cross-section electric field of the gate 2 and gate 3 in the device with a side-gate voltage of 40 V across the QDs.

3. Simulations

In order to estimate the electric field across the QDs, we simulated the static electric field with COMSOL Multiphysics. There are two electric fields across the QDs, one from the forward bias of lateral p-i-n junction, another one from the biased side gates. The electric field with forward bias is not trivial to model because of the graded electric field across the junction edge in the lateral p-i-n junctions, which has been discussed in [18] in detail. Because the QD position is not well defined in the junction edge, it is difficult to estimate the precise electric field with forward bias. However, the electric field across the QDs between the two side gates is uniform. In this paper, we illustrate what electric field across the QDs can be achieved with these side gates, and that the electric field from the side gates is the main contribution to controlling the stark shift. Future simulation with two electric fields is under investigation. With a 2D geometry model, the electric field is nearly constant across the dots, as shown in figure 1(b). When a bias voltage of 40 V is applied on gate 2 and gate 3 with 6 μm separation, the effective electric field on the QD region is approximately 49 kV cm^{-1}. The electric fields in the rest of this paper are obtained from the simulations with different bias voltages.

4. Results and discussion

Figure 2(a) shows EL spectra as a function of injection current. A single exciton peak at 1.380 eV can be observed when the injection current is approximately 100 μA. With increased injection current, biexciton and exciton complex appear at the low energy side of the exciton peak, while the intensity of the exciton peak decreases. The exciton and biexcition transitions are confirmed with the dependence of emitting intensities on injection currents, which has been discussed in [1] with the same wafers. The exciton peak and the biexciton peak are red-shifted approximately 0.3–0.4 meV with increasing injection current from 100 to 300 μA. One possibility for this red-shift could be a current-induced heating effect. This was investigated by collecting EL spectra from the wetting layer with the same injection currents, as shown in figure 2(b). No apparent shift of EL peak from the wetting layer can be resolved with increasing

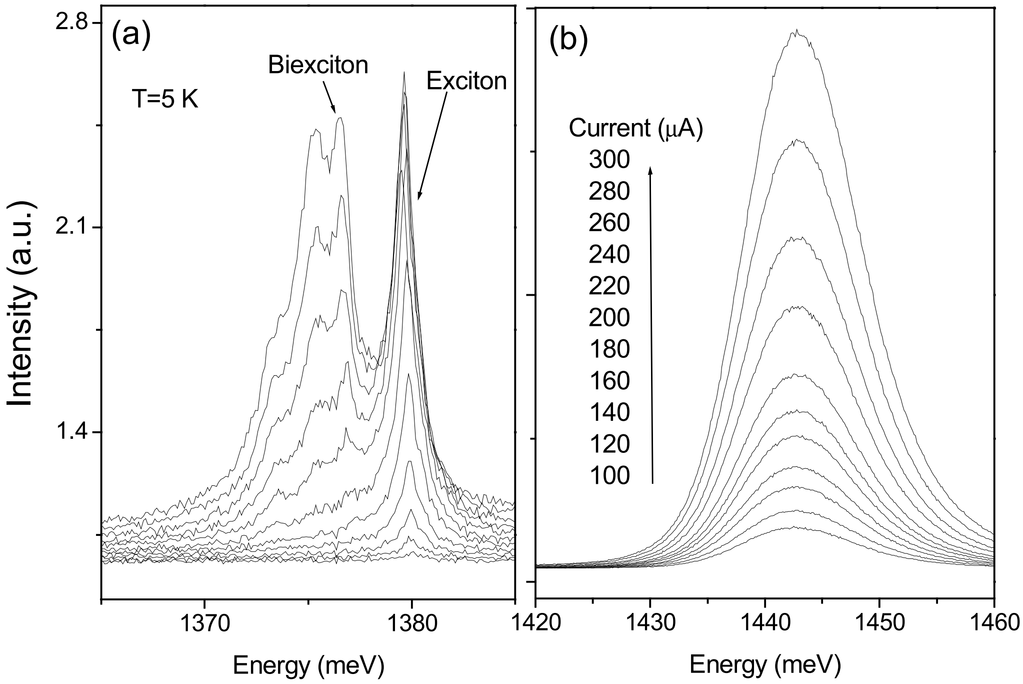


Figure 2. EL spectra from a single QD (a) and the wetting layer (b) with different injection currents in a typical device.

injection current. Therefore, the red-shift cannot be due to a heating effect, but must be due to the forward bias induced Stark shift. The full widths at half maximum of the EL peaks are around 1 meV, which is broader than the usual line width around 300 μeV in our system. The real reason for this broadening is not very clear. We believe it may be due to the dot density for this wafer being extremely low (less than 0.1 dot μm^{-2}), where QDs are not very well formed because of the extremely thin InAs layer. These broadened peaks have also been observed on the low density site with a graded dot density wafer.

With a forward bias current at 120 μA, a bias voltage on side gates between G2 and G3 was applied to observe the Stark shift. The results with bias voltages on side gates G1 and G4 are similar. These Stark shifts with side gates have been observed from many different QDs in different devices with EL. Figure 3 shows the EL spectra as a function of bias voltage in one device. The exciton peak around 1.380 eV is shifted to lower energies with increasing positive and negative bias voltages. The peak position shifts faster with negative bias (0.6 meV for −30 V) than positive bias (0.13 meV for 40 V), resulting in an asymmetric Stark shift because of the built-in dipole in the QD structures. The small energy shift (less than 700 μeV) is of the same order as previous observations on the lateral Stark shift with photoluminescence spectroscopy [16, 19]. The transition energy $E(F)$ depends quadratically on the electric field F, such that $E(F) = E(0) + pF + \beta F^2$, where $E(0)$ is the zero-field transition energy, p is the built-in dipole moment and β measures the polarization of the electron and hole wavefunctions [13, 20, 21]. The built-in dipole (electron–hole separation) in our case is in the sample plane (perpendicular to the growth direction), which is induced by the in-plane component of the built-in electric field in the lateral junction and by a piezoelectric field.

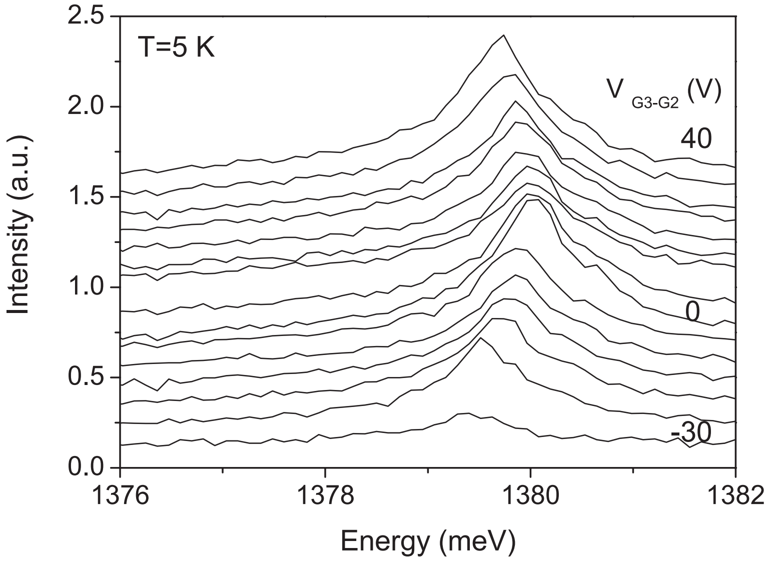
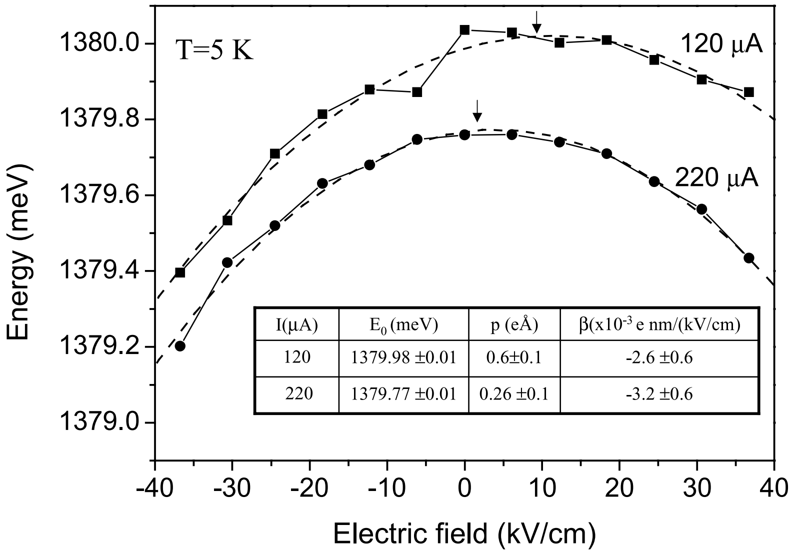


Figure 3. EL spectra as a function of bias voltage on side gates in a step of 5 V. Each spectrum is shifted for clarity.



I(μA)	E_0 (meV)	p (eÅ)	β(x10^{-3} e nm/(kV/cm)
120	1379.98 ±0.01	0.6±0.1	-2.6 ±0.6
220	1379.77 ±0.01	0.26 ±0.1	-3.2 ±0.6

Figure 4. Spectral positions of EL with injection currents at 120 and 220 μA as a function of bias voltage. The arrows indicate the maxima of exciton transition energy. The inset shows the fitting results.

Figure 4 shows the field dependence of the transition energy with two injection currents, 120 and 220 μA. The exciton transition energy changes with changing bias voltage on the side gates in each case. At a certain injection current, the field dependence of the transition energy on side-gate bias voltage can be well fitted with the expression $E(F) = E(0) + pF + \beta F^2$, as shown in figure 4 (dashed line). The fitting parameters are shown in the inset in figure 4. The maximum transition energy positions are located at 11.2 kV cm^{-1} and 4.12 kV cm^{-1} for 120 and 220 μA, respectively. The exciton peak position at 220 μA without a bias voltage on side gates is red-shifted, compared to that of 120 μA. This is due to the forward bias induced Stark shift in EL, as discussed previously.

The polarizability β is determined by the shape of the QDs. The β values (~ 0.003 e nm (kV cm^{-1})$^{-1}$) for the two injection currents are similar, as expected, which also corresponds well with the results in [16]. In self-organized QDs grown on 001 planes, the electrical dipole $\vec{p}_{\text{total}}$ is mainly directed in the growth direction and its sign is controlled by the dot composition distribution and the degree of truncation [13, 22] of the QDs. However, if the external electric field $\vec{F}$ is applied in arbitrary direction, the corresponding term in the energy shift that is linear in the electric field (dipole-related term) is given by $-\vec{p}_{\text{total}} \cdot \vec{F} = -pF$, where $p = |\vec{p}_{\text{total}}| \cos\theta$ is the effective dipole moment determined from the fit above and θ is the angle between the applied electric field and 001-direction. This means that the energy shift is determined by the component of the electric field in the growth 001-direction. Why is the dipole p different for the two injection currents in our case? In this lateral p-i-n junction, the forward biased electric field across the QD does not fully lie in the direction of wafer growth anymore, which has an in-plane component. The built-in electric field in the lateral p-i-n junction is opposite to this in-plane component. The larger forward bias reduces the built-in electric field component in the growth direction, resulting in a smaller effective dipole p. The p values are 0.60 ± 0.1 and 0.26 ± 0.1 eÅ for the injection current of 120 and 220 μA. The smaller dipole with large current injection results in a less asymmetric Stark shift.

5. Conclusion

In summary, we have fabricated single quantum dot light-emitting diodes using lateral p-i-n junction with side gates, and demonstrated that the exciton transition energy can be tuned by forward bias voltage and side-gate bias, respectively. The asymmetric Stark shift induced by the biasing side gates is also influenced by forward bias voltages, which balances the in-plane built-in electric field. We believe this method of independently controlling the transition of excitons using side gates is useful in the application of observing quantum coupling between QDs and cavities in EL. Fine splitting control has not been resolved with side gates in this work because of the relatively broad peak width. Further investigation is under way to realize electrically-pumped entangled photons [9].

Acknowledgments

We acknowledge Professor M Hopkinson and Dr H Y Liu from the University of Sheffield for growth of the QD wafer.

References

[1] Xu X L, Williams D A and Cleaver J R A 2004 *Appl. Phys. Lett.* **85** 3238
[2] Xu X L, Toft I, Phillips R T, Mar J, Hammura K and Williams D A 2007 *Appl. Phys. Lett.* **90** 061103
[3] Stevenson R M, Young R J, Atkinson P, Cooper K, Ritchie D A and Shields A J 2006 *Nature* **439** 179
[4] Akopian N, Lindner N H, Poem E, Berlatzky Y, Avron J, Gershoni D, Gerardot B D and Petroff P M 2006 *Phys. Rev. Lett.* **96** 130501
[5] Hennessy K, Badolato A, Winger M, Gerace D, Atature M, Gulde S, Falt S, Hu E L and Imamoglu A 2007 *Nature* **445** 896

[6] Yoshie T, Scherer A, Hendrickson J, Khitrova G, Gibbs H M, Rupper G, Ell C, Shchekin O B and Deppe D G 2004 *Nature* **432** 200

[7] Reithmaier J P, Sek G, Loffler A, Hofmann C, Kuhn S, Reitzenstein S, Keldysh L V, Kulakovskii V D, Reinecke T L and Forchel A 2004 *Nature* **432** 197

[8] Li X, Wu Y, Steel D, Gammon D, Stievater T H, Katzer D S, Park D, Piermarocchi C and Sham L J 2003 *Science* **301** 809

[9] Gerardot B D *et al* 2007 *Appl. Phys. Lett.* **90** 041101

[10] Sanguinetti S, Gurioli M, Grilli E, Guzzi M and Henini M 2000 *Appl. Phys. Lett.* **77** 1982

[11] Heller W, Bockelmann U and Abstreiter G 1998 *Phys. Rev.* B **57** 6270

[12] Jin P, Li C M, Zhang Z Y, Liu F Q, Chen Y H, Ye X L, Xu B and Wang Z G 2004 *Appl. Phys. Lett.* **85** 2791

[13] Fry P W *et al* 2000 *Phys. Rev. Lett.* **84** 733

[14] Zrenner A, Beham E, Stufler S, Findeis F, Bichler M and Abstreiter G 2002 *Nature* **418** 612

[15] Itskevich I E, Rybchenko S I, Tartakovskii I I, Stoddart S T, Levin A, Main P C, Eaves L, Henini M and Parnell S 2000 *Appl. Phys. Lett.* **76** 3932

[16] Stavarache V, Reuter D, Wieck A D, Schwab M, Yakovlev D R, Oulton R and Bayer M 2006 *Appl. Phys. Lett.* **89** 123105

[17] Xu X L, Andreev A, Williams D A and Cleaver J R A 2006 *Appl. Phys. Lett.* **89** 091120

[18] Kaestner B, Hasko D H and Williams D A 2002 *Japan. J. Appl. Phys.* **41** 2513

[19] Kowalik K, Krebs O, Lemaitre A, Laurent S, Senellart P, Voisin P and Gaj J A 2005 *Appl. Phys. Lett.* **86** 041907

[20] Sheng W and Leburton J-P 2002 *Phys. Rev. Lett.* **88** 167401

[21] Barker J A and O'Reilly E P 2000 *Phy. Rev.* B **61** 13840

[22] Pryor C 1998 *Phys. Rev.* B **57** 7190