Modulation of single quantum dot energy levels by a surface-acoustic-wave

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This letter presents an experimental investigation into the effect of a surface-acoustic-wave (SAW) on the emission of a single InAs quantum dot. The SAW causes the energy of the transitions within the dot to oscillate at the frequency of the SAW, producing a characteristic broadening of the emission lines in their time-averaged spectra. This periodic tuning of the transition energy is used as a method to regulate the output of a device containing a single quantum dot and we study the system as a high-frequency periodic source of single photons. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2976135]

Surface-acoustic-waves (SAWs) are elastic waves that can be generated on piezoelectric materials such as GaAs using interdigitated transducers. They are widely used in radio-frequency (rf) filters for electronic devices and a diverse range of other applications including sensors, and microfluidics is developing.[1,2] An associated potential modulation can give rise to charge transport where carriers are trapped within traveling potential wells. Such confinement can be strong enough to reduce the dimensionality of the carriers, as proposed for applications including current standards[3] and quantum computing.[4]

Much of the previous work on SAWs in GaAs has focused on the type II modulation of the band structure caused by the potential wave.[5–9] In addition to this, however, the strain wave causes a type I modulation of the band structure. As the strain wave compresses (stretches) the crystal structure, it causes a small increase (reduction) in the GaAs bandgap (E_g) and so periodically changes the energy of emission from the device.[10,11]

We investigate the effect of the strain wave on the emission spectrum of a single InAs quantum dot. We show that the modulation caused by the SAW can be used to create a high-frequency periodic source of single photons. The SAW modulation causes an alternating shift in the dot transition energy. By collecting photons in a narrow energy range we ensure that only photons emitted over a specific part of each cycle are collected (see Fig. 1). Once the dot line has moved out of the energy range there should be no probability of detecting another photon until the next SAW cycle when the dot line returns into the energy window [as shown in Fig. 1(a)]. If the time taken to refill the dot (which depends on the excitation power) is much longer than the time the dot line spends in the energy window then the probability of emitting two or more photons in the same cycle will be small. This method enables the photon output to be clocked at gigahertz frequencies without the need for a pulsed laser.

The sample, grown by molecular beam epitaxy, consists of a layer of low density self-assembled InAs dots above a 12 period GaAs/AlGaAs distributed Bragg reflector. Single dots were isolated by wet etching an array of 4.5 μm diameter pillars to a depth of ~150 nm (just below the level of the quantum dots). An interdigitated Ti/Al transducer with a resonant frequency of ~1 GHz was patterned by electron-beam lithography on an etched area 270 μm away from the pillars as shown in Fig. 1(c). This transducer was used to generate a SAW propagating in the $[1\bar{1}0]$ direction. Dot emission lines from several pillars were studied using micro-photoluminescence (PL) measurements in a liquid helium continuous flow cold-finger cryostat. The emitted light was collected through a microscope objective lens and measured with a grating spectrograph and liquid-nitrogen-cooled charge coupled device (CCD). A continuous wave (cw) HeNe laser was used to excite the sample and rf signals with nominal powers of 1–15 dBm were applied to the SAW transducer.

Figure 2(a) shows the PL spectra of a typical dot with and without a SAW applied. The line structure with no SAW present (blue line) is typical of InAs dots than have been studied previously.[12,13] Fine structure splitting of X and X_2 was observed (not shown)[14,15] but was absent for the charged exciton. This is tentatively assigned to be positively charged since it occurs at higher energy than the neutral exciton as in previous charge tuning studies.[16]

When the SAW is applied, the strain wave causes an approximately sinusoidal modulation of the energy levels causing the dot lines to oscillate around their equilibrium energy. Each emission line spends most time at the maxima and minima of its oscillating emission energy, and peaks are

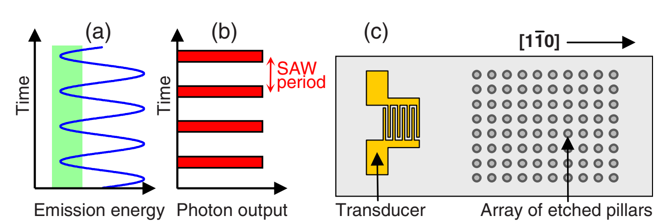

FIG. 1. (Color online) SAW modulated quantum dot. (a) The modulation of the emission energy (blue line) of the quantum dot as a function of time. The green rectangle represents the energy window over which photons are collected. (b) Temporal emission profile. (c) Schematic of the device.

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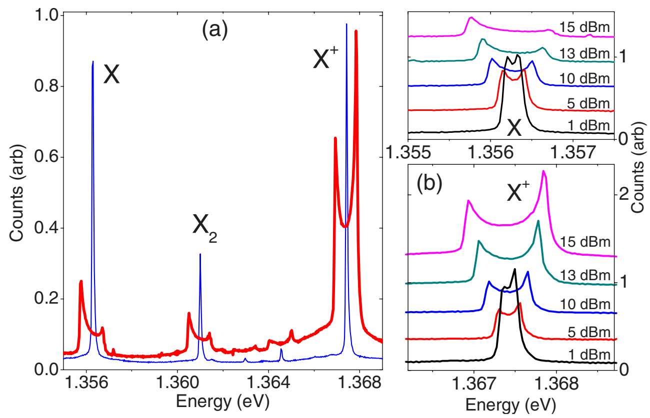

FIG. 2. (Color online) (a) Change in the dot line structure in the presence of a SAW: thin blue line, no SAW present; thick red line, SAW present with 15 dBm applied to the transducer. (b) X and X^+ emission lines as a function of the power applied to transducer. The traces have been offset for clarity.

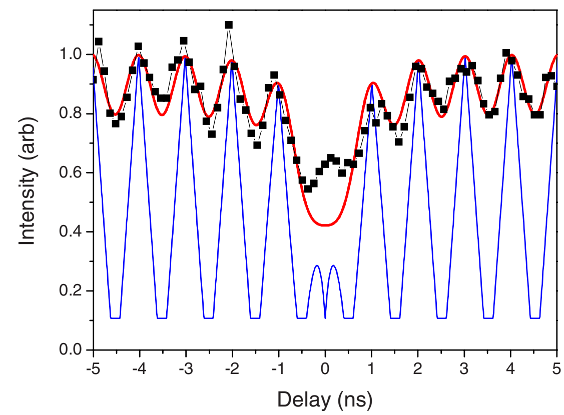

FIG. 4. (Color online) Correlation measurement of the SAW modulated source: black data points, experimental data; thin blue line, predicted ideal correlation function with lifetime $X^+=1.51$ ns (measured); lifetime $X_2^+=0.76$ ns (estimated as half X^+); probability of capturing exciton onto the dot within one cycle=1.05 (free parameter); background emission=15% of the area under each peak (assumed to be unmodulated by SAW); SAW period=1.006 ns (measured); and the time the dot energy spends within the filter bandwidth, each cycle=0.4 ns; thick red line, predicted correlation function after convolution with the system response.

observed in the time-averaged spectra at these points.

In addition to broadening the lineshapes, the SAW changes the intensities and relative shapes of the different emission lines. The initially narrow linewidths of the quantum dot emission enable the shape changes to be clearly resolved. Figure 2(b) shows that the relative intensity of the line identified with the recombination of X^+ increases with SAW power while the intensities of the X (and X_2 not shown) lines decrease. Also visible in Fig. 2(b) is an asymmetry in the high and low energy peaks of the SAW broadened dot lines. The high energy side of X^+ is most intense whereas for X and X_2 the low energy sides are brightest. These effects were seen in all of the dots studied here and could offer an alternative method of identifying differently charged emission lines from self-assembled quantum dots.

We used time resolved techniques to study the temporal dependence of the light emission from different parts of a spectrally broadened emission line to confirm that the spectral shape was caused by oscillation of the energy levels. A grating monochromator was used to select emission at a particular wavelength and this was then detected using an avalanche photodiode (APD) and time correlated counting electronics. The counter was started on detection of a photon and stopped on a signal derived from the rf generator. Figure 3 shows the emission as a function of time at three different energies. These measurements were taken using the X^+ emission line (the strongest line at high SAW power). It can be seen that there are oscillations in the light emission at each position as the SAW moves the dot line in and out of the energy range considered. The emission at the highest and

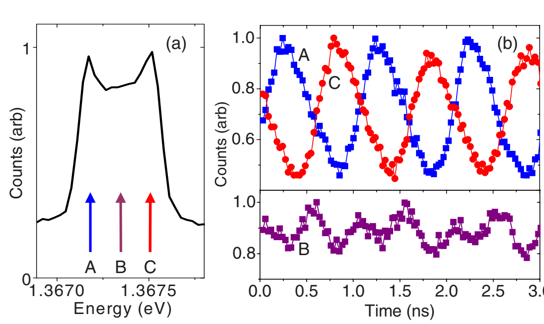

FIG. 3. (Color online) (a) SAW broadened X^+ line (15 dBm). (b) Time resolved PL at the energies marked by the correspondingly colored arrows.

lowest energies is seen to be π out of phase as expected. At a central energy the emission shows evidence of oscillations at twice the frequency of the SAW since the dot line moves past this energy twice per SAW cycle.[17] The visibility of the oscillations [particularly those of ~2 GHz shown in Fig. 3(b), energy B] is limited by the jitter of the APD (~300 ps).

We performed an autocorrelation measurement of the X^+ line using a Hanbury Brown–Twiss detection scheme with cw excitation from a HeNe laser. Initially the measurement was performed without a SAW. A clear dip was observed at zero time delay to $g^{(2)}(\tau=0)$ of 0.67, indicating that emission from the quantum dot is antibunched. The measurement was then repeated with the SAW present. The slits on the monochromator were adjusted so that ~40% of the SAW broadened X^+ emission line was collected. The result of the measurement is shown by the black points in Fig. 4. In addition to suppression at $\tau=0$, oscillations are seen due to the pulsed output from the device.

The blue line in Fig. 4 shows a model of the expected emission statistics measured with ideal detectors. The model correlation estimates the probability of detecting a photon in one detector conditional on a photon having been detected at the other detector some time τ earlier. This is found by considering the probability of the dot emitting a pair of photons with this temporal separation, $P_e(\tau)$, multiplied by the probability of such a pair of photons both being detected, $P_d(\tau)$, following the spectral filter. $P_e(\tau)$ can be estimated from a three-state rate-equation model[18] assuming that the SAW does not alter the dynamics of the emission. If the natural linewidth of the dot is small relative to the collected portion of the SAW-induced energy modulation, the photon output probability can be described by a top hat function of width equal to the time the dot spends within the energy window in each cycle. The pair-detection-probability $P_d(\tau)$ will be the correlation of two trains of such top hat functions, resulting in a series of triangles spaced by the SAW period. The thin blue line shows the expected shape of the correlation function predicted by this model $g^{(2)}(\tau) \propto P_e(\tau)P_d(\tau)$ and the red line after convolution with the system response (taken here to be Gaussian with a width of ~650 ps).

Away from the central peak this model (red line) provides a good description of the shape of the correlation function. However, the size of the central peak predicted by the model is smaller than the measured peak. The discrepancy between the data and the model is probably due to the presence of some time-varying background emission. This could be partly due to emission from a nearby dot state (seen in the PL spectra), which is periodically modulated by the SAW or some modulation of the wetting layer emission intensity by the SAW. In addition to this, the X_2^+ and X^+ lifetimes used in the model may be affected by the SAW, perhaps in a time-varying way, changing the shape of the correlation dip.

A measure of the suppression of multiphoton output can be obtained from the ratio of the area under the central peak of the experimental data to the average area under the peaks at finite delays. Due to the finite time resolution of the correlation system (~650 ps), resolution of the peaks is limited. If the peaks are assumed to be Gaussian, this ratio predicts suppression of multiphoton emission to ~0.6 of the Poissonian level. This includes a contribution from uncorrelated background emission estimated to be 10%–15% of the total intensity and a contribution from refilling of the dot.

The blue line in Fig. 4 represents the expected device correlation measured with ideal detectors. The area under the central peak is ~25% that of the peaks at finite time delay once the background has been subtracted. This area represents the contribution from refilling in the same SAW cycle leading to the emission of two photons in the same energy window. This effect could be reduced by narrowing the energy window or by decreasing the laser power used to excite the dot to reduce the probability of the dot refilling within the time the emission energy is within this window.

Another way to improve the suppression of multiphoton periods would be to increase the operating frequency. SAWs with frequencies up to 3 GHz are routinely used on GaAs, and by positioning the energy window in the center of the quantum dot oscillation rather than at the edge, a repetition rate of 6 GHz could be generated from a 3 GHz SAW. Lowering the temporal width of the detection window in this way would reduce the probability of the source emitting two photons within one time window. For an ideal 6 GHz source of this type with all other parameters kept constant and maintaining 40% of the emission passed by the spectral filter, the area under the central peak is predicted to be less than 3% of that at finite times (less than 1% estimated with a spectral filter set to pass 10% of the emission with all other parameters unchanged). Residual multiphoton periods arising from re-excitation could be eliminated altogether by combining with a resonant excitation scheme.[19]

In conclusion, we have studied the change in the line structure of self-assembled InAs dots in the presence of SAWs. The dot energy levels oscillate giving rise to a characteristic broadening of the time-averaged emission spectra. The lineshape offers a way to distinguish emission from neutral and charged excitonic complexes. We have demonstrated that a SAW can be used to control the emission times from the system containing a single quantum dot at gigahertz frequencies without the need for a pulsed laser. This technique could be used to create a high-frequency (multiple-gigahertz) source of single photons.

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[1]G. Lindner, J. Phys. D **41**, 123002 (2008).
[2]K. Sritharan, C. J. Strobl, M. F. Schneider, A. Wixforth, and Z. Guttenberg, Appl. Phys. Lett. **88**, 054102 (2006).
[3]V. I. Talyanskii, J. M. Shilton, M. Pepper, C. G. Smith, C. J. B. Ford, E. H. Linfield, D. A. Ritchie, and G. A. C. Jones, Phys. Rev. B **56**, 15180 (1997).
[4]C. H. W. Barnes, J. M. Shilton, and A. M. Robinson, Phys. Rev. B **62**, 8410 (2000).
[5]J. M. Shilton, V. I. Talyanskii, M. Pepper, D. A. Ritchie, J. E. F. Frost, C. J. B. Ford, C. G. Smith, and G. A. C. Jones, J. Phys.: Condens. Matter **8**, L531 (1996).
[6]J. A. H. Stotz, R. Hey, P. V. Santos, and K. H. Ploog, Nat. Mater. **4**, 585 (2005).
[7]C. Bödefeld, J. Ebbecke, J. Toivonen, M. Sopanen, H. Lipsanen, and A. Wixforth, Phys. Rev. B **74**, 035407 (2006).
[8]J. R. Gell, M. B. Ward, A. J. Shields, P. Atkinson, S. P. Bremner, D. Anderson, M. Kataoka, C. H. W. Barnes, G. A. C. Jones, and D. A. Ritchie, Appl. Phys. Lett. **91**, 013506 (2007).
[9]M. Cecchini, G. De Simoni, V. Piazza, F. Beltram, H. E. Beere, and D. A. Ritchie, Appl. Phys. Lett. **85**, 3020 (2004).
[10]P. V. Santos, F. Alsina, J. A. H. Stotz, R. Hey, S. Eshlaghi, and A. D. Wieck, Phys. Rev. B **69**, 155318 (2004).
[11]F. Alsina, P. V. Santos, and R. Hey, Phys. Rev. B **65**, 193301 (2002).
[12]R. M. Thompson, R. M. Stevenson, A. J. Shields, I. Farrer, B. E. Kardynal, C. J. Lobo, K. Cooper, N. S. Beattie, D. A. Ritchie, M. L. Leadbeater, and M. Pepper, Phys. Rev. B **64**, 201302(R) (2001).
[13]D. J. P. Ellis, A. J. Bennett, A. J. Shields, P. Atkinson, and D. A. Ritchie, Appl. Phys. Lett. **88**, 133509 (2006).
[14]R. M. Stevenson, R. M. Thompson, A. J. Shields, I. Farrer, B. E. Kardynal, D. A. Ritchie, and M. Pepper, Phys. Rev. B **66**, 081302(R) (2002).
[15]R. J. Young, R. M. Stevenson, A. J. Shields, P. Atkinson, K. Cooper, D. A. Ritchie, K. M. Groom, A. I. Tartakovskii, and M. S. Skolnick, Phys. Rev. B **72**, 113305 (2005).
[16]R. J. Warburton, C. Schäflein, D. Haft, F. Bickel, A. Lorke, K. Karrai, J. M. Garcia, W. Schoenfeld, and P. M. Petroff, Nature (London) **405**, 926 (2000).
[17]F. Alsina, P. V. Santos, R. Hey, A. Garcia-Cristobal, and A. Cantarero, Phys. Rev. B **64**, 041304 (2001).
[18]C. Kurtsiefer, S. Mayer, P. Zarda, and H. Weinfurter, Phys. Rev. Lett. **85**, 290 (2000).
[19]C. Brunel, B. Lounis, P. Tamarat, and M. Orrit, Phys. Rev. Lett. **83**, 2722 (1999).