Tuning single GaAs quantum dots in resonance with a rubidium vapor

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We study single GaAs quantum dots with optical transitions that can be brought into resonance with the widely used D_2 transitions of rubidium atoms. We achieve resonance by Zeeman or Stark shifting the quantum dot levels. We discuss an energy stabilization scheme based on the absorption of quantum dot photoluminescence in a rubidium vapor. This offers a scalable means to counteract slow spectral diffusion in quantum dots. © *2010 American Institute of Physics*. [doi:10.1063/1.3478232]

Quantum dots (QDs) proved to be efficient sources of single photons.[1,2] However, using different QDs to produce indistinguishable photons, which are a fundamental resource for different quantum information schemes like linear optics quantum computation[3] or the entanglement of remote qubits,[4,5] has been challenging. Only very recently the interference of indistinguishable photons from independent dots was demonstrated.[6] One of the difficulties in interfering photons from independent dots is that the spectra of different dots are not only different but they also fluctuate in time, making it difficult to adjust the energy of two or more QDs in perfect resonance. Some of the processes that cause spectral diffusion have rather slow time constants. This is the case for the energy shifts due to the hyperfine interaction with randomly oriented nuclear spins. In GaAs QDs the effective magnetic field due to the nuclei is a few millitesla, depending on the size of the dot, and evolves on a time scale that can be up to seconds.[7] For these reasons a scalable means to tune different QDs into resonance and actively correct for spectral fluctuations is desirable.

Here we show that GaAs QDs can be brought to resonance with the D_2 transition line of ^{87}Rb (780 nm) by applying an external electric or magnetic field. Rb vapor cells are extensively used as a simple wavelength standard for lasers, are available in micrometer sizes[8,9] and would be suitable to stabilize in energy two independent QDs. The detuning of a photoluminescence (PL) line from the D_2 transitions is determined by measuring the PL transmission through a Rb vapor cell. This direct energy comparison between the optical transitions of a QD and Rb atoms provides a fast and precise measurement of the QD environment. We examine how the transmitted PL can be used as a feedback signal for stabilizing the QD emission energies, we discuss the noise level and the achievable feedback rate.

The QDs we study are GaAs inclusions in an AlGaAs matrix and are fabricated by molecular beam epitaxy in a multistep self-assembly process.[10,11] A scheme of the sample structure is shown in the inset of Fig. 1. The QDs are connected by a GaAs quantum well (QW) whose thickness was optimized so that the QD PL is close to 780 nm.

We studied the optical properties of these QDs at 4.2 K under nonresonant excitation. Figure 1(a) shows PL spectra of a single QD for two orthogonal polarization states. The high energy peak consists of two linearly polarized components [Fig. 1(b)] with a fine structure splitting of 40 μeV and can be identified as the neutral exciton transition. In some of the dots we can also identify the positively charged exciton. The case of indistinguishable photons emitted by two singly charged QDs is of particular interest: the spins of the electrons or holes that are left in the QDs after exciton recombination can be entangled by interfering the emitted photons on a beam splitter as recently demonstrated with atomic systems.[4]

Time resolved PL measurements under pulsed excitation allowed to determine a typical decay time of about 500 ps [Fig. 1(c)]. This time corresponds to a natural linewidth of 1.3 μeV and sets the relevant energy scale within which two

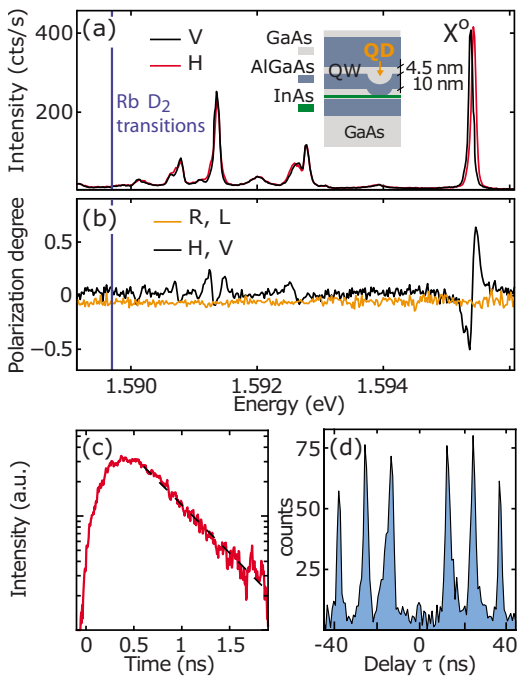

FIG. 1. (Color online) (a) PL intensity for two orthogonal linear polarizations, horizontal (H), and vertical (V). (b) Degree of polarization, $(I_{R(H)}-I_{L(V)})/(I_{R(H)}+I_{L(V)})$, for right and left (R, L) circularly polarized light and for horizontally and vertically polarized light. I_j is the PL intensity for polarization j. (c) Time resolved PL intensity from a single transition. (d) Intensity autocorrelation measurement for a QD transition under pulsed excitation.

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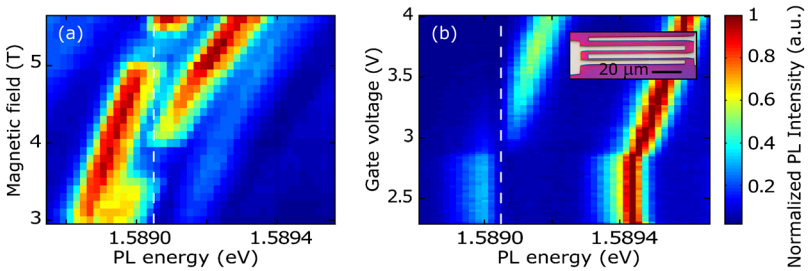

FIG. 2. (Color online) (a) Zeeman split PL line from a single QD as a function of magnetic field. The PL is filtered by a Rb cell before entering the spectrometer. Pronounced absorption at the D_2 transitions is visible around 1.58905 eV (vertical line). (b) Stark shift is used to tune another QD in resonance with Rb transitions. The inset shows metallic gates on the sample surface.

dots need to be tuned in order to achieve a large degree of photon indistinguishability.

Figure 1(d) shows a photon antibunching measurement performed on a PL line within tuning range from the D_2 transitions. The dot was excited by absorption in the QW of picosecond laser pulses with a repetition time of 13.2 ns and the PL was sent to an intensity interferometer equipped with avalanche photodiodes (APDs). Background correlation events due to dark counts of the APDs were subtracted. The single photon nature of our source is clearly shown by the almost complete absence of correlation counts at zero delay.

Without additional sample processing, we can tune the QD emission in resonance with the D_2 transition of Rb by applying an external magnetic field. Figure 2(a) shows a Zeeman split PL line from a single QD. The PL from the dot is sent, in a collimated beam, through a 7.5 cm long Rb vapor cell at a temperature of 134 °C. As the magnetic field is increased to 3.8 T one of the two branches of the Zeeman split line becomes resonant with the D_2 transitions of rubidium and is absorbed in the vapor cell resulting in a dip in the detected PL intensity. The other branch can also be brought into resonance with the D_2 transitions, at magnetic fields around 5.2 T.

In order to have local and fast control on the optical transitions of a quantum dot we used metallic gates on the surface of the sample (Fig. 3, inset) allowing to create a mostly in-plane electric field in the dot region. Figure 2(b) shows two Zeeman split PL lines (B=8T) which are Stark shifted as a function of gate voltage. The PL line at lower energy is tuned in resonance with Rb D_2 transitions for a gate voltage of about 3 V. The PL transitions do not show visible changes for low gate voltages. Similar to Ref. 12, we attribute this observation to background doping, which limits the extension of the depletion regions associated to the Schottky contacts.

In order to use a feedback system to lock an emitter at a given energy, the feedback signal should change sharply as the emitter is detuned from resonance by its natural linewidth. This is the case for the PL intensity transmitted through a Rb cell, because the Doppler broadening of 2.5 μeV, at room temperature, is comparable to the exciton natural linewidth. The stabilization method proposed here is schematically shown in the inset to Fig. 3. Part of the PL emitted from the QD is sent to a Rb cell and the transmitted intensity is measured.

The characteristic time for energy stabilization based on absorption in a Rb vapor depends essentially on the time Δt, required to measure the PL energy with the desired precision. We calculated the feedback signal [Fig. 3(a)] and the corresponding uncertainty in PL energy, ΔE, as follows.

The coupling of light to the Rb vapor is determined by the optical susceptibility $\chi = A\Sigma_j g_j/(\omega - \omega_j + i\gamma_j)$, where A is the total resonance strength, proportional to the density of Rb atoms, and the $g_j's$ account for the different strengths of each transition at frequencies $\omega_j/2\pi$ with linewidths of $2\gamma_j$. We took into account the Doppler broadening by convoluting the susceptibility χ with a 2.5 μeV wide Gaussian and we assumed the QD luminescence to be a Lorentzian with a width of 1.3 μeV.

In the case of continuous wave excitation the noise of the transmitted PL intensity is Poissonian and determines the uncertainty on the PL energy that we wish to control. This uncertainty depends on the PL energy (the working point of the feedback) and is proportional to $1/\sqrt{N}$, with N the number of counts that would be measured for zero absorption in a time interval Δt. In calculating ΔE we approximated the feedback signal linearly around each working point. The best working point is marked by a vertical line in Fig. 3(a), where N is set to 100.

The relevant quantity in view of producing indistinguishable photons is the ratio between the energy uncertainty ΔE and the exciton natural linewidth. This ratio is plotted in color in Fig. 3(b) as a function of the resonance strength A, and of the number of counts N. From this plot we can see that if two transitions need to be tuned at the same energy within 20% of their linewidth, about 220 counts are neces-

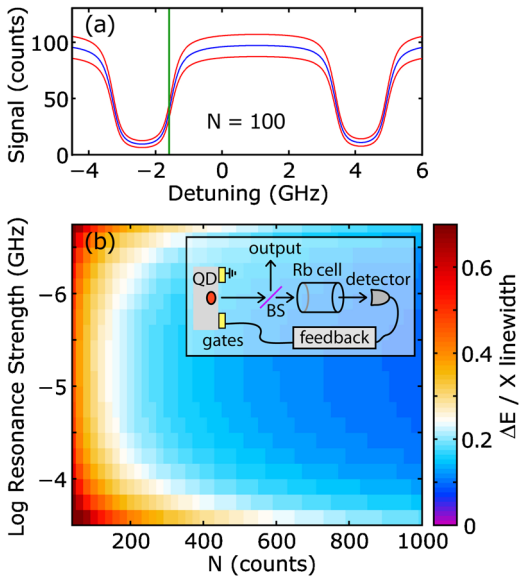

FIG. 3. (Color online) Estimation of the characteristic time for an energy stabilization system based on absorption by a Rb vapor. (a) Transmitted PL intensity (counts) for a QD transition with a Lorentzian lineshape set by the decay time. The top and bottom curves represent the Poissonian error range (plus and minus one standard deviation). (b) Uncertainty in the measurement of the detuning of the QD transition, as a function of the coupling to the Rb vapor and of the PL intensity measured in counts. The inset is a sketch of the proposed feedback scheme.

sary. For a typical intensity $I=N/\Delta t$ of 3000 counts/s the characteristic time, Δt, for the proposed feedback is less than 0.1 s. The same type of QDs presented here were embedded in an optical microcavity[13] and intensities of about 10^5 counts/s were measured. For those QDs, the characteristic feedback time would be about 2 ms.

For most applications a source of indistinguishable photons needs to be triggered[14,15] and the collection efficiency needs to be high.[16] These conditions can be satisfied by the QDs described here, provided that the dots are excited resonantly and that the collection efficiency is improved. It should be noted that in that case a well defined number of photons can be generated, giving sub-Poissonian noise for the transmitted PL intensity. The error shown in Fig. 3, should therefore, be considered as an upper limit.

In conclusion, we have demonstrated that optical transitions of single GaAs quantum dots can be tuned to resonance with transitions in rubidium atoms, by means of an external electric or magnetic field. This fact can be exploited for the energy stabilization of independent quantum dots and we discussed here the characteristic time of this tuning technique. Further improvements on the case discussed here would be the tuning of GaAs dots in microcavities and the triggered emission of photons. Both improvements would make the Rb vapor an even better energy reference due to sub-Poissonian noise in the feedback signal.

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