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Electrical tuning of the *g* factor of single self-assembled quantum dots

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The *g* factor of a single self-assembled quantum dot is tuned by applying an electrical bias voltage. Individual InGaAs quantum dots embedded in a stripe mesa structure sandwiched by Schottky electrodes are studied by photoluminescence measurements. We find that under applied magnetic field a dot with an asymmetric shift for applied bias voltage shows an increase of the exciton *g*-factor absolute value by about 8%, while most of the dots with relatively symmetric shifts show no significant change. The anomalous *g*-value increase is discussed in terms of the Kondo effect.

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Manipulation of the spin degrees of freedom of electrons is desirable for encoding and processing quantum information. A key quantity for the spin manipulation is the *g* factor, a coefficient connecting magnetic-dipole moments with the spin degrees of freedom. For example, a large *g* factor leading to faster spin-Rabi oscillations is preferable for spin-based quantum computing while near zero *g* factor degeneration of the spin-up and -down states under magnetic field is suitable to design a quantum receiver.[1,2] In particular, modulating the *g*-factor tensor with an electric field enables spin manipulation without a time-dependent magnetic field.[3] One essential requirement for the approach is tuning of the *g* factor through an electric field. Although the *g* factor in a quantum well is varied by displacing the wave function into a region with different material compositions, the method is not effective in quantum dots because of their strong confinement to about 10 nm.

A promising candidate for a basic building unit to realize spin-based quantum information processing in solid-state systems is a self-assembled quantum dot. The strong three-dimensional confinement of carriers[4] provides a long spin lifetime and expected long decoherence time.[5,6] Structural control of the *g* factor of the self-assembled dots has been shown based on eight-band $\mathbf{k}\cdot\mathbf{p}$ calculation.[7–10] Recently, electrical control over the *g* factor has been realized in closely stacked dots where the energy levels of the two dots are optimized to be very close and the relative energy is carefully tuned by a vertical electric field. The *g* factor is changed by the formation of bonding and antibonding molecularlike orbitals.[11]

In this paper, we show electrical tuning of the exciton *g* factor in a single quantum dot embedded in a Schottky depletion region. Our approach does not require carefully selected stacked dots to have very similar energy levels. The observed maximum increase of the *g* factor by about 8% is obtained for the dot embedded near the edge of the mesa stripe or the Schottky electrode.

Our self-assembled InGaAs quantum dots were grown by metalorganic chemical vapor deposition on a GaAs (100) wafer.[7] The dots were sandwiched between a 100-nm GaAs buffer layer and 100-nm GaAs capping layer. To isolate the dots, we fabricated a stripe mesa structure with lateral width of 100 nm by electron-beam lithography and dry etching. The mesa structure was sandwiched by a parallel pair of 150-nm-thick Ti/Au Schottky contacts fabricated subsequently by using a lift-off technique [Figs. 1(a) and 1(b)]. Since the depletion length is of the order of 100 nm or more, all the dots are in the depletion region [Fig. 1(c)]. The lateral device structure allows application of a lateral field and tuning of the dot energy levels with respect to the Fermi energy in the electrode,[12] as in the vertical Schottky diode structures used in many studies for electrical control of quantum dots.[6,13,14] The lateral structure allows optical studies of the dots positioned quite proximately to the electrode.

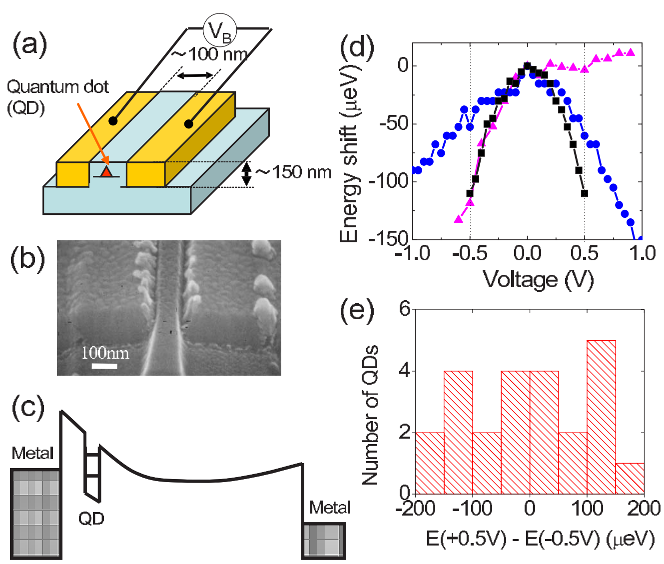

FIG. 1. (Color online) (a) Schematic view and (b) the scanning tunneling microsocope (SEM) picture of our device. A mesa stripe structure in which InGaAs quantum dots are embedded is sandwiched by Ti/Au metal electrodes. (c) Energy and position dependences of the lower conduction band edge under applied a bias voltage when a dot is embedded near an electrode. (d) Spectral shift of the emission energy of various single quantum dots as a function of bias voltage. (e) Number of quantum dots as a function of emission energy difference between the bias voltages of +0.5 V and −0.5 V, which represents the asymmetry of the Stark shifts for the bias voltage.

We studied the electric field dependence of the photoluminescence (PL) from the dots sandwiched between the two contacts by a conventional micro-PL setup using an 850-nm laser to excite the dots. Special care was taken to avoid any heating effects, especially for the 3.5 K measurement, by using a very low excitation density of 0.8 W/cm^2.

The PL spectra from the quantum dots embedded in the Schottky structure are very similar to those of the as-grown unbiased dots except the linewidths of the emission peaks. The linewidths of about 120 μeV broader than the as-grown ones are attributed to spectral diffusion due to space charges in the Schottky depletion region. The magnetic field dependence is also very similar. All measured dots show an almost linear increase of the Zeeman splitting with an exciton g factor of about −3 and quadratic diamagnetic shift with the coefficient of about 10 $\mu eV/T^2$.[7] In contrast, the electric field dependence is quite different from dot to dot even qualitatively.

Figure 1(d) shows typical bias voltage dependences of the emission energies of the single dots. In the measured 24 dots, two dots show a weak almost parabolic energy shift, which is symmetric for the applied bias voltage, while the other dots show a relatively linear energy shift, which is asymmetric for the bias. The parabolic shift is attributed to the rotationally symmetric confinement potential and the electric field applied equally for positive and negative biases. In other words, the dot should be located near the center of the stripe. On the other hand, the asymmetric shift suggests that the quantum dot is embedded near the Schottky interface where the GaAs conduction band is strongly bended even without the external bias. The band bending differs for external positive and negative biases, depending on the charges at the interface. The statistics of the symmetric and asymmetric shifts are shown in Fig. 1(e). The similar number of dots showing the larger shifts at positive and negative bias voltages confirms the position-dependent energy shifts of randomly distributed quantum dots across the mesa.

Figure 2(a) shows a close-up of the Zeeman-split emission lines of a dot (QD A) with almost symmetric electric field dependences [Fig. 2(b)]. There is no measurable significant dependence of the Zeeman splitting magnitude or the g factor on electric field in this dot and also in most of the dots (22/24). The results are in agreement with a calculation based on an eight-band effective mass model[7] including strain, piezoelectric, and excitonic effects[10] assuming uniform lateral electric field. The modeled quantum dot has a square-based pyramid shape with a base length of 16.6 nm based on atomic force microscope (AFM) and cross-sectional SEM measurements. The effective electric field is estimated based on the one-dimensional Poisson model. The details of the calculation procedure are described in Ref. 7. The calculated exciton energy shift with polarizability of 11.8 $\mu eV/(kV/cm)^2$ and calculated exciton g factor of −3.01 for the unbiased dot agree well with the experiment. As shown in Fig. 2(c), the field-induced g-factor variation is less than 2% in both the experiment and calculation. The small decrease of the absolute value of the g factor (g value) is mainly attributed to a reduction of the heavy-hole projection of the hole wave function. Thus, the typical dependences of the emission energy and the g factor on the lateral electric field can be described by our effective mass calculation on single-particle bound states.

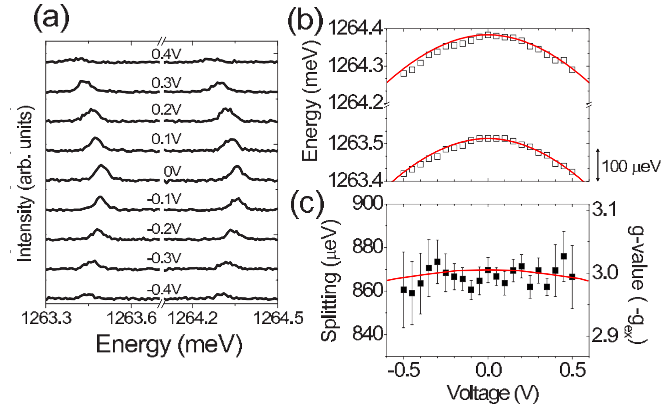

FIG. 2. (Color online) (a) Photoluminescence for various applied bias from a dot located near the center of the mesa stripe under applied magnetic field of 5 T in Faraday configuration. (b) Energy shift of the Zeeman-split peaks. Solid lines give the calculated emission energy (shifted vertically by about 10 meV for comparison). (c) Experimental and calculated energy splitting or corresponding exciton g value as a function of applied voltage.

Figure 3 shows an example of the asymmetric shift at 5 T for the applied bias voltage. In the quantum dot (QD B), the energy shift in the positive bias region is much stronger than the shift in the negative region. The asymmetric shift is observed both at 3.5 K and 10 K. We find that the strong linear shift in the positive-bias region follows an increase of the Zeeman splitting at 3.5 K. The increase of the splitting is directly seen in a close-up of the PL spectra [Fig. 3(c)] plotted as a function of the energy separation between the Zeeman-split peaks. With increasing the bias voltage, the Zeeman splitting increases by about 80 μeV at 3.5 K. In contrast, surprisingly, the Zeeman splitting is nearly unchanged at 10 K. Similar behavior is observed also in another dot where a Zeeman splitting increase by about 50 μeV is observed in negative voltages.

In order to compare the result with the calculation, the variations of the g values are plotted as a function of the Stark shift or the estimated effective electric field in Fig. 4. In the small Stark shift range below 100 μeV, the g-value variations are small in all cases. The small variation is consistent with the calculation. With increasing the Stark shift above 100 μeV, the g value of the QD B at 3.5 K starts to deviate from the theoretical value and increases up to 8% while the increase at 10 K is less than 2%. Although we have also calculated g value for various electric fields including vertical electric field (along the growth direction) and nonuniform fields expected for the bended energy band near the Schottky interface, they do not reproduce the experimental g-value increase as a function of the Stark shift. For example, the vertical electric field decreases the g value by less than 0.3% for the corresponding Stark shift range.

Several mechanisms which can increase the electron g value have been proposed in two-dimensional electron gas systems. They are an effective spin-orbit magnetic field imposed on the drift velocity of the carriers[16] and wave-

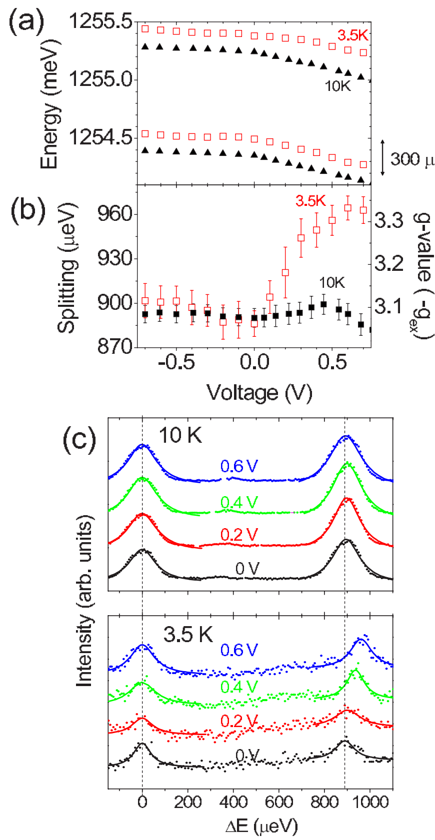

FIG. 3. (Color online) (a) Emission energy shift and (b) the splitting magnitude of the Zeeman-split peaks at 5 T in a dot located near the electrode. (c) Photoluminescence spectra of the Zeeman-split peaks, plotted as a function of the energy separation measured from the lower peak. The spectra are shifted to line up the lower peak to show the splitting increase clearly. The PL spectra at 10 K were measured at excitation density of 4 W/cm^2 because no essential power dependence was observed at the temperature.

function modification by an electric field that determines the confinement.[17] However, both effects are negligible in the self-assembled quantum dots confined by the surrounding semiconductors with a higher band gap. The strong three-dimensional confinement results in almost no center-of-mass motion and very small modifications of the electron and hole wave functions for the electric field. Thermal effects on the *g*-value change are also negligible in our experimental condition. We have confirmed that the *g* values of the unbiased InGaAs dots are unchanged within the resolution in the temperature range of 3.5–20 K.

One possible cause for the anomalous increase of the *g* value is a tunnel coupling to the electrode or Kondo-like effect, as described by the tunneling term of the Anderson Hamiltonian.[14,18,19] Since our dot showing the *g*-value increase is embedded close to the electrode, the electronic states can couple to the delocalized states of the electrode directly by tunneling or via the delocalized states of the wetting layer that surrounds the base of the dot. The tunneling coupling occurs when the electron energy level is close to the Fermi energy, which depends on the bias voltage.

Kondo physics in electrons or excitons of self-assembled

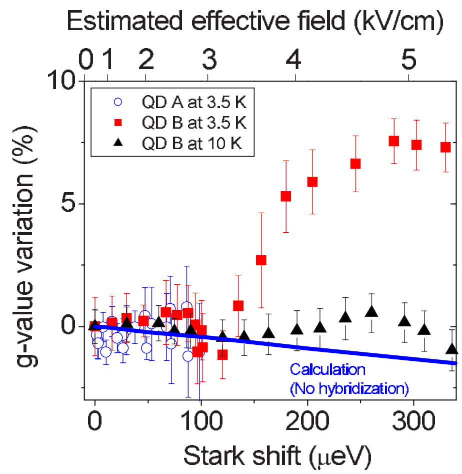

FIG. 4. (Color online) Experimental and theoretical *g*-value variations as a function of the corresponding Stark shift. The experimental *g*-value variations are shown for quantum dots with the symmetric (QD A) and the asymmetric (QD B) energy shifts for the external bias voltage. The experimental Stark shift is measured from the emission energy at the bias voltage which corresponds to the zero effective electric field (Ref. 15).

dots has been recently studied both experimentally[13,20,21] and theoretically.[14,18,19] A Kondo-like effect in excitons allows a hybridization of an exciton state with the charged state where one electron is added via the Fermi sea of the electrode.[14] Using a zero-bandwidth model, the exciton wave function of the hybridized exciton state can be written as $|X_{hyb}\rangle = A_1|X^0+e\rangle + A_2|X^-\rangle$. The state $|X^0+e\rangle$ corresponds to the neutral exciton coupled with the delocalized electron, which screens the electron spin of the dot. The state $|X^-\rangle$ corresponds to the singly charged exciton. The ratio of the wave-function amplitude is given by $A_1/A_2 = (\Delta + \sqrt{\Delta^2+8V^2})/\sqrt{8}V$, where Δ is the energy separation between X^0 and X^-, and V is the tunneling energy between the electron ground state of the dot and the Fermi sea.

The hybridization can increase the *g* value because of the slightly larger *g* value of the charged exciton[22–24] and the contribution from the amplitude of the wave function in the barrier between the dot and the electrode. The *g* factor of the hybridized exciton is given by $g_{hyb} = \langle X_{hyb}|g(r)|X_{hyb}\rangle = |A_1|^2 g_{X^0+e} + |A_2|^2 g_{X^-} + 2A_1A_2 g_{\text{barrier}}$, where $g(r)$ is a position-dependent *g* factor, and $g_{\text{barrier}} = \langle X^0+e|g(r)|X^-\rangle$ gives the contribution from the barrier. The *g*-value difference between the neutral exciton and the singly charged exciton is about 5% in the InGaAs self-assembled dots reported in Ref. 22 although the difference should depend on the size and shape of the dot. When the tunneling energy is comparable to the PL linewidth,[25] the admixture of the charged state $|A_2|^2$ is about 4%. In this case, for *g* values[26] in our sample the hybridization increases the exciton *g* value by about 3%. Thus, this simple hybridization model roughly explains the *g*-value increase.

A confirmation of our interpretation is the suppression of the anomalous *g*-value increase at 10 K. The Kondo-like tunneling processes leading to the exciton hybridization occur only around or below the Kondo temperature because one essential requirement to cause the hybridization is that the emission initial state be in the Kondo singlet state (or many-body ground state).[14] The Kondo temperature corresponds to the binding energy of the Kondo singlet state. Above the temperature, the hybridization should diminish rapidly because the exciton states are independent without the formation of the Kondo singlet state. The sample temperature of 3.5 K at which the g-value increase is observed is lower than a theoretical Kondo temperature.[27] A Kondo temperature T_K as high as 10 K in a self-assembled dot has been shown theoretically[14] and experimentally.[21]

In summary, we report a voltage-dependent g value of a quantum dot exciton near a Schottky electrode. The g value is tuned up to 8%. The results suggest to utilize the lateral Schottky structure with quantum dots as a device for electrical g-factor tuning. The mechanism is attributed to a hybridization of the exciton with the charged state due to a Kondo-like interaction between a localized electron in the quantum dot and a delocalized electron in the Schottky electrode.

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[25] We have taken $\Delta = 1$ meV and $V = 150$ μeV. The tunneling energy corresponds to tunneling time of 4 ps. Using the WKB approximation, the barrier width between the electrode and the dot is estimated to be 5 nm.

[26] We have used $g_{X^0+e} \approx g_{X^0} = -3.1$ and $g_{X^-} \approx 1.05 g_{X^0}$. The contribution from the barrier g_{barrier} should be represented by the bulk electron g factor of the barrier layer which strongly depends on the composition [e.g., g_e(GaAs)$=-0.44$ while g_e(InAs)$=-15$]. We have taken $g_{\text{barrier}} \approx -1$ as a phenomenological parameter because the degree of In-Ga mixing around the dot is unknown.

[27] It may be noted that both the sample temperature and the Kondo temperature are higher compared to the electron Zeeman splitting of 72 μeV (0.8 K) at 5 T, obtained using the calculated electron g factor of -0.25 in our dot.