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# High-frequency electron-spin manipulation in semiconductor artificial atoms and molecules

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## 1. 研究のねらい

The aim of the project is high-frequency (GHz) electron-spin manipulation in semiconductor few-electron quantum dots. The main motivation of this proposal is formed by the possible application of electron spins as basic building blocks for quantum logic.
One concrete aim is to rotate a single-electron spin in a few-electron quantum by means of a locally generated electron spin resonance (ESR) field. A key experiment that still needs to be done is the determination of the single-electron spin decoherence time $T_2$ in a semiconductor environment. The next logical step after studying single dots is to look at double dot systems. The entanglement of two electron spins using tunnel-coupled quantum dots is of great importance for the realization of the XOR (or controlled-NOT) gate operation.

## 2. 研究成果と考察

### 2.1. Few-electron quantum dot devices for single electron spin resonance

We have fabricated vertical few-electron quantum dot (QD) devices with an integrated high-frequency line to generate an ac magnetic field in the vicinity of the QD. This ac magnetic field is intended for realizing single electron spin resonance (ESR) and measuring the single-electron coherence time $T_2$. The effective $g$-factor in our GaAs dot is derived and microwave experiments show the importance of photon assisted tunneling (PAT) and pumping.

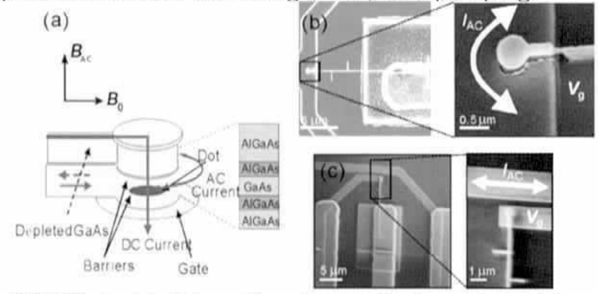

*FIGURE 1. (a) Schematic of a vertical quantum dot with a ring gate used for generating an ac magnetic field $B_{ac}$. (b) and (c) Scanning electron micrographs of our ESR devices.*

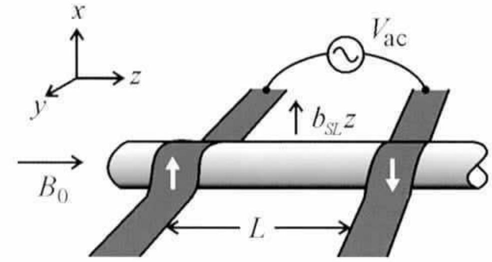

*FIGURE 2. Model of a 1D QD in a slanting Zeeman field. The spin in the dot is controlled by applying an oscillating voltage $V_{ac}$ between the two ferromagnetic gates.*

Examples of our ESR devices are shown in Fig. 1. Ideally, a single electron is confined in the QD and its discrete orbital energy level is Zeeman split due to a static magnetic field $B_0$ by $\Delta E_Z = g_{dot}\mu_B B_0$ with $g_{dot}$ the $g$-factor in the dot and $\mu_B$ the Bohr magneton. A microwave magnetic field, $B_{ac}$, (generated by an ac current through a microstripline) in a plane perpendicular to $B_0$ and in resonance with the precession rate, causes coherent oscillations between the states $|\uparrow\rangle$ and $|\downarrow\rangle$ (electron spin resonance: ESR).

Since $g_{dot}$ is expected to differ significantly from the value in bulk GaAs we first independently determined $g_{dot}$, using excited state spectroscopy. We derive $|g_{dot}| = 0.23 \pm 0.02$, which is smaller than that of bulk GaAs ($|g_{GaAs}| = 0.44$), probably due to the effect of electron confinement and the influence of the $Al_{0.3}Ga_{0.7}As$ barriers (bulk $g$-factor +0.4). Our microwave results indicate that instead of generating only an AC magnetic field, we also create a significant AC electric field near the dot. We have not been able to confirm ESR in our system, hampered by the spurious electric ac field.

As an alternative for the above strategy, we have described a general concept for realizing a solid-state quantum two-level system, based on a single electron in a quantum dot (Fig. 2), which combines ease of manipulation with long coherence times. An ac voltage is applied to let an electron in a QD oscillate under a *static* slanting Zeeman field. This effectively provides the electron spin with the necessary time-dependent magnetic field. Note the analogy with the Stern-Gerlach experiment, where the spin and orbital degrees of freedom are coupled by employing an inhomogenous magnetic field. A robust single pseudo-spin system is obtained that can be controlled by voltage only, without the need for an external time-dependent magnetic field or spin-orbit coupling. This unique and important feature is expected to considerably facilitate experimental realization of qubits based on single electrons. It is shown that both single qubit rotations and the C-NOT operation can be realized, thereby providing a universal set of gates for quantum computation. Using this approach it is also possible to determine the intrinsic single electron spin coherence time in the system.

### 2.2. Electron-phonon Coupling in a Double Quantum Dot

Electron-phonon coupling often leads to dissipation and decoherence problems in nanoelectronic devices. The decoherence in a tunable two-level quantum system (qubit), such as a double quantum dot (DQD), is of particular interest in the recent light of quantum computation and information. In analogy to quantum states in natural atoms – which dominantly couple to, and are successfully controlled by photons – the electronic states in solid state systems may be controlled by phonons, taking advantage of the strong electron-phonon coupling. We have observed non-adiabatic transport through a double quantum dot under irradiation of surface acoustic waves generated on-chip. At low excitation powers, absorption and emission of single and multiple phonons is observed. At higher power, sequential phonon assisted tunneling processes excite the double dot in a highly non-equilibrium state. The present system is attractive for studying electron-phonon interaction with piezoelectric coupling.

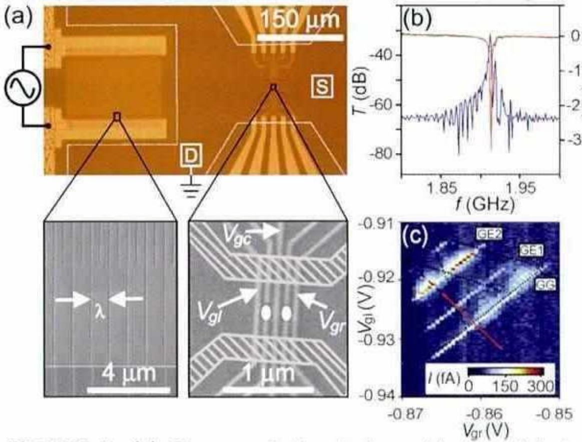

*FIGURE 3. (a) Picture of the device with interdigital transducer (IDT, left) and double quantum dot (DQD, right). The electrodes of the IDT are separated by $\lambda$ = 1.4 $\mu$m. (b) Transmission T (blue curve) and reflection R (red and green curves) at room temperature of two IDTs similar to the one used in the experiments. (c) Color scale plot of the DQD current vs. gate voltages $V_{gl}$ and $V_{gr}$ at source drain voltage $V_{SD}$ = 500 $\mu$V without SAWs.*

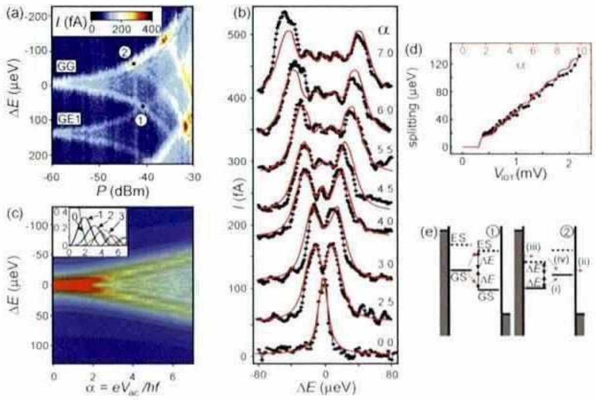

*FIGURE 4. (a) Color scale plot of the DQD current versus $\Delta E$ and microwave power P. (b) Experimental (black dots) and calculated (red curves) current spectra for different microwave powers. (c) Calculated DQD current versus $\Delta E$ and $\alpha = eV_{ac}/hf$ in the non-adiabatic limit. Inset: squared Bessel functions. (d) Splitting of the current peaks as function of the amplitude of the microwave voltage $V_{IDT}$ applied to the IDT for the experimental data (black data points and axes), and current peak splitting derived from the calculated spectra in (c) as function of $\alpha$ (red curve and axes). By matching the experimental and calculated curves, the conversion between P and $\alpha$ is found. (e) Schematic energy level diagrams for the positions 1 and 2 indicated in (a).*

Our device is described in Fig. 3. We observe broadening and splitting of the resonant tunneling peaks only at the IDT resonant frequency, $f_{SAW}$ = 1.9446 GHz. The resonance frequency corresponds very well to that of the GaAs reference sample of Fig. 3(b).

The microwave power dependence of the current spectra is presented in Fig. 4(a). The peak splitting increases with microwave power P. In Fig. 4(d) the splitting is plotted (black dots) as function of the IDT microwave voltage, $V_{IDT}$, confirming the linear dependence. The calculation in Fig. 4(c) shows additional structure in between the split peaks. This structure originates from the phonon satellite peaks that should be individually resolvable at $\Delta E = nhf_{SAW}$ if the peak width is smaller than the phonon energy. In our case, however, the peak width exceeds $hf_{SAW}$. We find good agreement between the calculated current spectra and the experimental data at finite microwave power as shown in Fig. 4(b), where we have applied the $\alpha$-PdBm conversion derived in Fig. 4(d). Our data thus reveal clear quantum behavior, even when we cannot resolve individual phonon satellites. Quantum behavior is also observed in multiple excitation processes between excited states at higher power [Fig. 4(e)].

The current spectra reflect the amplitude of the local piezoelectric potential. The lowest power at which we can resolve peak splitting is −58 dBm, corresponding to $V_{pe}$ = 24 $\mu$V, which is several orders of magnitude smaller than the power used to induce dynamical quantum dots and to induce lattice displacements measurable by optical interferometry. We find that the DQD can be employed as a very sensitive SAW detector and is promising for studying electron-phonon interaction.

## 3. 主な論文

[1] W. G. van der Wiel *et al.*, Rev. Mod. Phys. **75**, 1 (2003). **[146 times cited]**
[2] T. Kodera, W.G. van der Wiel, K. Ono, S. Sasaki, T. Fujisawa and S. Tarucha, Physica E **22**, 518 (2004).
[3] T. Kodera, W.G. van der Wiel, T. Maruyama, Y. Hirayama and S. Tarucha, in *Realizing controllable quantum states*, H. Takayanagi, J. Nitta (eds.), pp. 445-450, World Scientific Publishing, Singapore (2005).
[4] Y. Tokura, W.G. van der Wiel, T. Obata and S. Tarucha, Phys. Rev. Lett., in press; cond-mat/0510411 (2005).
[5] W.J.M. Naber, T. Fujisawa, H.W. Liu and W.G. van der Wiel, submitted to Physical Review Letters; cond-mat/0601158 (2006).

## 4. その他

2005 chair of the 2005 Gordon Research Conference on Quantum Information Science, Ventura CA, USA