論 文 の 内 容 の 要 旨

論文題目　Detection of Angular Momentum Transfer from a Single Photon to a Single Electron Spin in a Lateral Double Quantum Dot
(横型二重量子ドットにおける単一光子偏光から単一電子スピンへの角運動量転写の実証)

氏　　名　　藤田　高史

These days quantum interfaces that transform different quantum media to another are focused in the field of quantum information technology to benefit from their different characteristics of coherence. This dissertation focuses on the transfer from single polarized photons, which could send information over long distances, to single electron spins, which are suitable for quantum information storage and processing. One application of this photon-spin interface is a quantum repeater that could extend the existing limit of photon coherence length for long range quantum communication. We especially focused on an interface implemented with GaAs based semiconductor lateral quantum dots (QDs) that are already speculated as a suitable platform for quantum information processing and are also optically active and useful for an interface. We will show the progress towards coherent quantum state transfer to this structure where we have successively detected the incoherent angular momentum transfer from a single photon polarization to a single electron spin.

GaAs based gate defined quantum dots are expected to be platforms for storage and manipulation of electron spin quantum bits (qubits) owing to their relatively long spin coherence time, tunability and scalability of qubits. Especially, compared to other solid state materials for photon - electron spin interfaces,

entanglement of two electron spins has been realized in a lateral double quantum dot. Therefore, by using entangled photon sources it is feasible to further entangle the distant electron spins if coherent transfer from photon to electron spin is realized. Recently, coherent transfer between an ensemble of polarized photons to an ensemble of electron spins was realized in a GaAs based quantum well (QW) structure. To apply this transfer scheme to quantum communication the information carrier has to be a single quanta. Therefore the transfer also needs to be verified between a single quanta. There were several progressed works of single photoelectron trapping in a quantum dot but the spin of single photoelectron was not yet detected. We have been developing controlled trapping and resetting of photoelectrons, meaning the tunneling of photoelectrons are tuned and measured, so we can detect the single electron spin created by a circularly polarized photon and eventually verify the angular momentum transfer.

For the experiment of angular momentum transfer we first prepared a quantum well structure in which a pair of electron and heavy hole can be resonantly excited. Additionally, for our future work of coherent transfer experiments we have designed a g-factor engineered QW. The purpose is to decrease the electron Zeeman splitting such that both the opposite electron spins can be excited simultaneously from the Zeeman split light hole state to realize coherent transfer. Note that the excitation laser bandwidth can cover both electron spin states to create a superposition state. It is known that the g-factor can be tuned by varying the QW well width so we obtained several wafers with different well width and barrier configuration. We performed resistive electron spin resonance measurements on the two dimensional electron systems to evaluate the bare electron g-factor. Then we measured the QD fabricated on these wafers using a conventional electron beam lithography technique. We found that the lifting of Kondo effects and spin blockade remained present for higher magnetic fields compared to the QD devices fabricated on the conventional high mobility wafers. These spin properties are due to the effect of smaller g-factors in the QW. Finally we chose a wafer with well width 7.2 nm and g-factor 0.12.

Next we developed a new spin measurement scheme where spin blockaded electrons are observed in real-time to measure the single spin state in a single-shot manner. We first investigated the real-time inter-dot tunneling of an electron between the (1,1) and (0,2) charge state. We plotted the histogram of the residing time in the (1,1) state and obtained a single exponential histogram for zero magnetic field and a double exponential histogram for finite magnetic field. The two time constants correspond to the two tunneling times of the different spin configurations, parallel and anti-parallel configuration. In the real-time signals we see two regions, repetitive inter-dot tunneling regions between (1,1) and (0,2) states and stable regions at (1,1) state. This shows the distinct regions of the two spin states of anti-parallel and parallel spin configurations and they would have a high distinguishability of the spin states if the time constants are largely different. To investigate the spin properties and to know what restricts the spin detection distinguishability in this Pauli spin blockade scheme we took the magnetic field dependence of the tunneling rates and plotted the ratio between anti-parallel spin tunneling rate and parallel spin relaxation rate (the two time constants seen in the histogram of the (1,1) state residing time). In the end we found that the hyperfine coupling between electron spins and nuclear spins governs the electron spin dynamics at low magnetic field and the relaxation rate has a cutoff due to the spin flipping by spin orbit interaction at high magnetic field. The measurement at 1.65 T normal to the 2DEG plane gave us a high enough distinguishability of spins over 90 %.

We moved on to the photon irradiation measurements to trap a single photoelectron in the double dot. We developed a novel method of single-shot laser pulse irradiation on the lateral QD in a dilution refrigerator using Ti:Sapphire laser with a laser scanning system. and measured the charge sensor current in real-time to see the photo-response after pulse irradiation. What differs for the double dot is that we observed the subsequent inter-dot tunneling of the photoelectron after the trapping. The signal is seen as a repetitive inter-dot tunneling signal right after irradiation. We have investigated the irradiation to double dots in both conventional high mobility wafers (irradiation of bulk GaAs) and QW wafers. For both types of wafers we observed characteristic signals of one and two or more photoelectron trapping, i.e. showing the photoelectron detection before a complete escape to the reservoir meaning non-destructive photon detection. A QW would show a wavelength dependence of the absorption rate so we measured the single photoelectron trapping rate in different incident photon wavelength. The QW sample showed a peak at 885 nm excitation wavelength with a peak efficiency of ~1% consistent with band calculations. Here we have demonstrated the energy selective excitation and trapping of single photoelectrons.

To measure the single photoelectron spins we combined the scheme of non-destructive single photoelectron trapping with the real-time observation of spin blockade by starting from a (0,1) state with the (1,1), (0,2) excited states on resonance. We always observed an inter-dot tunneling of photoelectrons at zero magnetic field but at finite magnetic fields we also observed a blocked signal after irradiation. The two types of signals already indicate the spin detection of trapped photoelectrons but at low magnetic field where the Zeeman splitting is comparable to the electron temperature the initialization is not complete due to the thermal distribution of the prepared spin. We raised the magnetic field and observed that the blocked time of the photoelectron also increased with field obeying the relaxation rate dependencies measured in dark. Finally we did the photoelectron spin measurements in 1.65 T in a condition mentioned previously in the real-time blockade section. Here we irradiated polarized photons by varying the lambda/4 plate angle and for each polarization we took over 1000 single-shots to obtain the statistics of the measured spins. From the single-shot signals two types of signals were extracted where fast inter-dot tunneling or blocked inter-dot tunneling was observed after pulse irradiation. Each signal indicates down spin or up spin detection depending on which sign of magnetic field was applied to initialize the prepared spin. We plotted the spin-blockaded probabilities as a function of lambda/4 plate angle and obtained a cosine like dependence of the probability as expected from the selection rules. The visibility of the circular polarization to electron spin conversion was limited to 60 % in our experiment. This still indicates that the spin preparation is affected by thermal contribution. According to our calculation the polarization of photons are not distorted before it reaches the quantum dot and the extracted electron temperature from the polarization dependence gives 150 mK which is consistent with our measurement setup. Here we have shown that the angular momentum of the circularly polarized photon (+-1) was successfully transferred to a single electron spin (-+1/2) by the excitation of a valence electron of the heavy hole band (-+3/2).

As a conclusion, we measured in a single-shot manner the spin state of photoelectron spins trapped in a double QD and achieved the angular momentum transfer between single photons and single electrons for the first time. Our spin detection scheme would be further improved in efficiency to apply for the coherent transfer experiments where an in-plane high magnetic field would be applied to make the splitting of the light hole states larger. This measurement of photoelectron spins is a breakthrough in lateral quantum dots that would lead to verification of coherent transfer and spin manipulation subsequent to the conversion that are indispensable ingredients in constructing a quantum repeater for long range quantum communication.