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Phonon-Assisted Efficient Spin Injection in InGaAs Quantum Well-Quantum Dot Tunnel-Coupled Structures

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Abstract

Time-resolved optical spin orientation measurement was performed on an $In_{0.1}Ga_{0.9}As$ quantum well (QW)-$In_{0.5}Ga_{0.5}As$ quantum dot (QD) tunnel-coupled structure. Fast electron spin injection has been observed, with an injected initial spin polarization of 48 % at QD excited states (ES) at 6 K. With rising temperature, the initial polarization of electron spin exhibits thermal stability. Such temperature-insensitivity is found as due to both an enhanced phonon scattering rate and relatively much longer spin relaxation time in QW ground state (GS).

1. Introduction

III-V quantum dots (QDs) are one of the most promising nanostructured materials for harnessing both prominent photonic and spin properties at same time. This is enabled by the fact that QD's potential results in discrete electronic states with large oscillator strength, which gives rise to atom-like sharp transitions with high optical yield. On the other hand, confinement of carrier motion inside QD markedly suppresses the spin relaxation event, leading to a long-lived spin lifetime. Therefore, QDs are regarded as potential candidate for spin light-emitting/laser diode (spin LED/LD) and spin quantum computer.

By growing a quantum well (QW) beside QDs, a tunnel-injector forms, where QW functions as spin reservoir and allows fast spin transfer into QDs via quantum-tunneling process. Though spin injection time ranging from several to several tens of picoseconds has been reported by previous work [1] at cryogenic range based on different barrier thickness, the information about spin injection dynamics and efficiency at higher temperature is incomplete. This is complicated by the fact that rising temperature can not only activate non-radiative recombination centers but also cause carrier thermalization via enhanced phonon scattering that further influences spin-flip time in QW and QDs. All these effects contribute to spin injection process and are important for practical devices operating at high temperature. Therefore, to clarify these issues, we employed time-resolved optical spin orientation spectroscopy to investigate the temperature-dependent spin injection in InGaAs QW-QD coupled structures. We show a faster injection time with increasing temperature and thermal-stable injection efficiency, which are governed by intense phonon coupling and relatively long spin flip time in QW GS.

2. Experimental procedure

Crystal growth of InGaAs QW-QD coupled structure

The coupled structures were grown by molecular-beam-epitaxy (MBE) on (001) GaAs substrate. A 400 nm-thick GaAs buffer layer was deposited first, followed by 20 nm-thick $In_{0.1}Ga_{0.9}As$ QW grown at 580 ^{o}C. Then GaAs barrier of 8nm thickness is deposited on top, with subsequent growth of $In_{0.5}Ga_{0.5}As$ QD layer at 480 ^{o}C. Finally, 50nm-thick GaAs capping layer covers the QD ensemble.

Time-resolved optical orientation measurement

Time-resolved optical orientation measurement was performed using Ti: Sapphire pulsed laser as excitation source. Circular-polarized laser was tuned slightly above QW GS transition to excite spin-polarized electrons and holes. The subsequent circular photoluminescence (PL) dynamics from QW GS and QDs are differentiated by quarter-wave-plate and linear polarizer and detected by streak camera. Since hole spins are easily depolarized in QW and QDs due to stronger spin-orbit interaction and intra-heavy and light hole valence band relaxation [2], electron spins are the only species determining PL circularity and can be derived from PL circular polarization degree (*CPD*), via:

$$CPD = (I^{\sigma^+} - I^{\sigma^-}) / (I^{\sigma^+} + I^{\sigma^-}) \tag{1}$$

where I^{σ^+} (I^{σ^-}) is PL intensity of σ^+ (σ^-)-polarized component, respectively.

3. Results and discussion

Fig. 1 (a) shows the representative circular-polarized PL spectrum from coupled structure at 6K. Under σ^+ quasi-resonant excitation, spin-down (up) electrons (holes) are generated, which undergo fast relaxation to QW GS and result in strongly σ^+-polarized PL emission at 1.41eV. Since QW is tunnel-coupled with QDs, the carrier spins at QW GS can be immediately transferred into QDs and relaxed down to QD ES by phonon scattering. This gives rise to a QD ES PL which is predominantly σ^+-polarized within energy range 1.32-1.38 eV. The sharply dropped PL Intensity below 1.32 eV is caused by the insufficient spectral responsivity of our detector and therefore limits the resolution of QD GS emission. Owing to the spin-conserving tunneling process, highly efficient electron spin injection is obtained.

This is reflected by a nearly constant *CPD* (green line) value between higher ES in QD and QW GS, i.e. 1.38-1.41eV. The decreasing CPD below 1.38 eV is due to accelerated

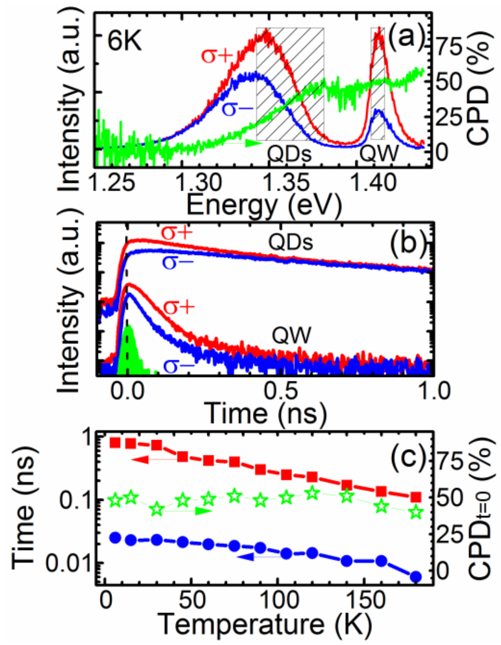

Figure 1. (a) Circular-polarized PL spectrum at 6K, (b) circular-polarized PL transients from QW GS and QD ES, the pulsed laser is given as filled curved, and (c) temperature dependence of phonon relaxation time τ_{rlx} (solid dot), electron spin relaxation time τ_s^{QW} (solid square) at QW GS and initial *CPD*, $CPD_{t=0}$ (open star).

spin flip-induced carrier relaxation [3], which leads to full occupation of spin levels at QD GS.

The circular-polarized PL dynamics from QW and QDs are summarized in Fig. 1 (b), which are spectrally integrated over the range indicated by shaded area in Fig. 1 (a). Electron spin tunnel-injection dynamics is characterized by the fast decay dominating QW GS PL transients in Fig. 1 (b), yielding a time constant of 25 ps at 6 K. We plot the temperature dependence of spin tunnel-injection time as solid dot in Fig. 1 (c), which decreases continually to 7ps at 180 K. The shortening of time is indicative of enhanced phonon scattering at elevated temperature [4] and highly favorable for fast spin injection. By looking at PL decay of QD ES, initial electron spin polarization after injection can be derived from *CPD* value at time origin (dashed line in Fig. 1 (b)) i.e. $CPD_{t=0}$. At 6 K, the QD ES features a sizable $CPD_{t=0}$ of 48 % (open star in Fig. 1 (c)), which is also reflected from σ^+-dominated PL traces at beginning of decay. The temperature dependence of $CPD_{t=0}$ exhibits an almost invariance, with its value slightly decreased to 40% at 180 K. Such T-insensitive $CPD_{t=0}$ implies a thermally stable electron spin feeding from QW GS to QD ES, which are closely associated with two factors, (1) fast phonon-assisted relaxation time τ_{rlx} (2) relatively persistent electron spin flip time τ_s^{QW} at QW GS. The former has been proven efficient with temperature as shown in Fig. 1 (c). To corroborate the latter, a reference QW sample under same growth condition was measured, the resulting τ_s^{QW} of which is shown as solid square in Fig. 1 (c). τ_s^{QW} shows monotonous decrease with temperature, as determined by the well-known D'yakonov-Perel mechanism. However, it's still longer than τ_{rlx} by one order of magnitude. This ensures the preservation of spin state at QW GS and following efficient spin transfer to QD ES. The present results also point out ways for further optimization of spin injection performance, which are (1) enhancing phonon scattering rate by tuning the energy gap between QW GS and QD ES in resonance with longitudinal-optic (LO) phonon in QD and (2) growing (110) QW where spin relaxation along injection axis is suppressed and electron spin preservation is prolonged.

3. Conclusions

We have demonstrated fast and efficient electron spin injection in InGaAs QW-QD coupled structure, where thermally stable transfer of electron spin polarization of ~48% has been observed. This is contributed by the combined effects of accelerating phonon relaxation time (< 25 ps) at elevated temperature and a relatively longer spin-flip time at QW GS.

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