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# Spin pumping InAs/GaAs Quantum Dots: controlling linear and circular Polarization

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## 1. Introduction

Quantum dots (QDs) – nanoscale inclusions of one semiconductor embedded within another – are a vital building block for spin-based quantum computing. They can serve as an interface between “flying” photonic qubits, and stationary spin qubits. Carrier spins confined to a quantum dot can have long spin coherence times. Selection rules in the semiconductor convert circular polarization into a spin polarized population of electrons. Similarly, on recombination, the carrier spin is converted into circularly polarized light: this is a method for “reading” and “writing” spins to a QD spin system. Clearly, understanding the connection between spin and light emission is crucial for the development of this field, with applications in quantum information processing and quantum cryptography.

In this work, we investigate a single, positively charged InAs/GaAs QD, optically pumping the spin with circularly polarized light above the band-edge of the GaAs. By collecting the photoluminescence (PL), we analyze the polarization using a rotating quarter wave-plate, completely projecting the degree of polarization onto the fundamental components: the degree of circular polarization (the excess of right-handed circularly polarized light over left-handed circularly polarized light); the degree of linear polarization (the excess of one linear polarization over the orthogonal polarization); and the direction of linear polarization (the angle at which this linear polarization is orientated).

We find that not only the degree of circular polarization is changed, but also the *degree* and *direction* of linear polarization. We suggest this remarkable occurrence arises from the hyperfine polarization of the nuclei.

## 2. Experimental methods

The sample consists of a single layer of p-doped InAs QDs, grown by MBE on a GaAs substrate. The substrate is processed with e-beam lithography and dry etching to produce 1 μm mesas, which allow optical isolation of individual quantum dots. In an empty QD, a single electron-hole pair can be captured, form an exciton ($X^0$) due to the close confinement and recombine. In this sample, the presence of a single hole in a typical QD gives rise to a positively charged exciton ($X^+$). $X^+$ and $X^0$ have radically different spin properties: in the $X^0$ case, the electron and hole spin are unpaired, and thus undergo an exchange interaction. This long-range part of this interaction is enhanced by the asymmetry of the QD, and is known as the Anisotropic Exchange Interaction (AEI). This interaction causes a highly efficient spin relaxation mechanism, and $X^0$ in QDs typically have very short spin lifetimes (~100ps).

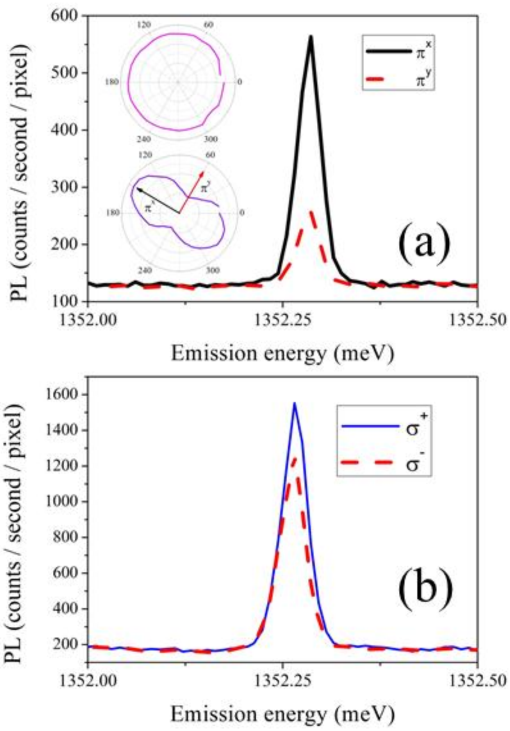


**Fig 1(a)** Linearly **(b)** circularly polarized spectra under linearly, circularly polarized excitation respectively

In the case of X+, however, there are two holes and one electron. The two holes relax to the ground state, where they form a spin singlet. There can be no exchange interaction with the electron, so this dephasing mechanism is absent. Spin lifetimes for X+ can be >1ns, limited by the interaction of the spin unpaired electron with the nuclei in the QD, via the hyperfine interaction [1]. This makes the $X^+$

state of interest for quantum information applications.

Micro-photoluminescence (μPL) measurements are per formed on a single InAs/GaAs QD at 4 K. The collected photoluminescence (PL) for $X^+$ is shown in figure 1(a) under linearly polarized excitation. These excitation conditions pump both spin states equally. The PL is strongly linearly polarized, and is analyzed along the orthogonal directions $\pi^x$, $\pi^y$. The degree of linear polarization in this basis is calculated from

$$\Pi_{x,y} = \frac{PL_x - PL_y}{PL_x + PL_y} \qquad (1)$$

where $PL_x$, $PL_y$ are the integrated photoluminescence emission on the basis $\pi^x$, $\pi^y$. The light is ~50% polarized in the direction $x$. The polarization as a function of angle in the laboratory frame is shown as an inset in figure 1(a) (blue) with the basis marked in red. The emission energy does not change as a function of emission angle, demonstrating the absence of exchange interaction. This linear polarization arises from mixing between the heavy holes and light holes in the ground state of the QD (often called VBM, or Valence Band Mixing)[2].

Under circularly polarized excitation, the spectra analyzed in the circular basis are shown in fig.1(b). The PL is polarized in the same helicity as the excitation, demonstrating that spin polarization is preserved on relaxation to the ground state. The degree of circular polarization can be calculated from

$$\Sigma = \frac{PL_{\sigma^+} - PL_{\sigma^-}}{PL_{\sigma^+} + PL_{\sigma^-}} \qquad (2)$$

where $PL_{\sigma+}$,$PL_{\sigma-}$ are the left-hand and right-hand circularly polarized emission. The example spectrum is about 15% circularly polarized.

We measured the degree of polarization of the PL as the excitation power was increased. We found that the circular polarization first increased, then decreased with pump power (see fig.2(a)). At the same time, the degree of linear polarization (fig.2(b)) changed, and the direction of linear polarization rotated(fig.2(c)).

This intriguing effect may be explained in terms of the hyperfine interaction. The electron and nuclear spins are coupled together by the hyperfine interaction. The electron spin polarizes the nuclear spin. In the excitation regime when there is only one electron in the quantum dot, the higher the pump power, the greater fraction of the time the QD is occupied by an electron. This means the nuclei in the QD become more polarized, resulting in a stronger nuclear field exerted on the QD, explaining the initial increase. However, in the higher power regime where there is more than one electron in the QD, the electron-electron spin scattering reduces the degree of spin polarization, and thus the degree of circular polarization.

Nuclear polarization can also interacts with hole spins. We posit that heavy and light holes couple differently to the nuclear field: thus, the degree of heavy - light hole mixing, and the degree and direction linear polarization can be changed.

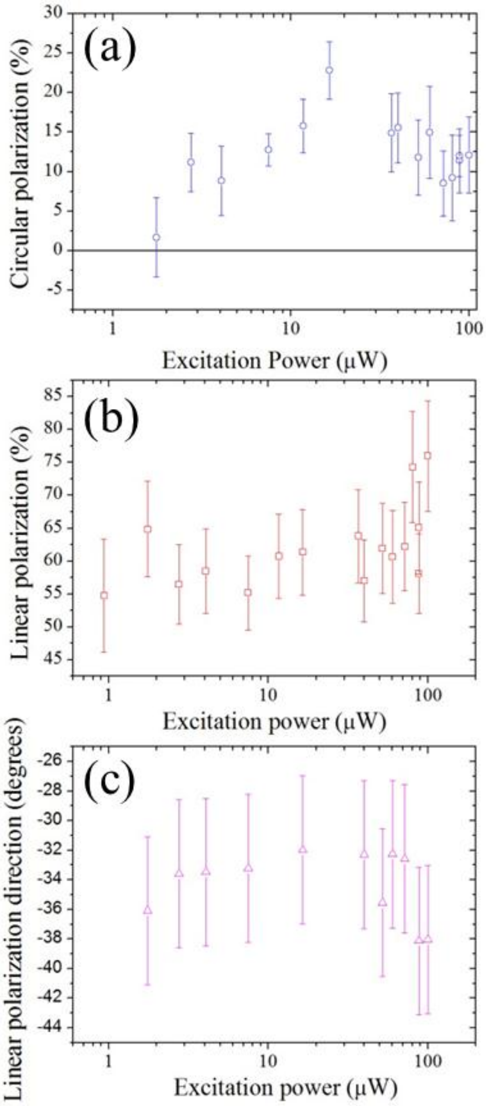


**Fig.2(a)** Circular, **(b)** Linear polarization. **(c)** Direction of linear polarization

## 3. Conclusions

We have used circularly polarized excitation to excite a positively charged exciton in single quantum dot, and controlled the degree and direction of linear polarization by the excitation power. .

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