Fast Polarization Manipulation

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Research Proposal

Under the supervision of

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Abstract

The generation of a pair of entangled photons from the biexcition-exciton cascade is complicated by the presence of fine structure splitting (FSS)[**Winik2017**] that leads to the degradation of the degree of entanglement. Many methods were implemented to overcome the problem with varying degrees of success, but the problem continues to persist.

This research proposal aims to take a different approach to the problem by implementing a scheme for the restoration of the degree of entanglement of the photon pairs by fast polarization manipulation [**Fognini18**, **Varo2022**].
This scheme can be potentially used as a method for fast photon rerouting in integrated photonics.

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1   Introduction

1.1   Self assembled QDs

Self-assembled quantum dots (QDs) are localized nano-scale semiconductor struc-
tures that creates a three-dimensional(3D) potential well, both in the valence and
conduction bands,which trap charge carriers. Due to their small confinement length
relative to the particle's wavelength, the energy levels of the QD are quantized with
properties similar to atoms which lead them to be described as "Artificial Atoms"
[**Kastner1993**].

In recent years, semiconductor QDs were thoroughly investigated as technology-
compatible single photon sources, providing a quantum source of "flying qubits"
on demand.[**Dekel2000**, **Michler2000**, **Michler2000_1**, **Yuan2002**] Moreover,
recently it has been shown that QDs can emit pair of entangled photons [**Akopian2006**,
Hafenbrak2007] and that an emitted photon can be entangled with the remaining
spin in the QD. [**Pelk2012**, **Schaibley2013**, **Gao2012**] These achievements form
the required building blocks for quantum information processing. [**DiVincenzo1998**,
Duan2001]

In semiconductor QDs, at low temperatures, the basic optical excitation, in which
an electron is optically excited from the full valence band, thereby leaving there a
hole, to the empty conduction band is called a bright exciton(BE). In self-assembled
QDs the BE consists of an electron - heavy-hole pair.This optical excitation pre-
serve the spin orientation of the excited electron and therefore the electron and
hole are said to have anti-parallel spins. The total angular momentum projection
of the BE on the direction of the exciting light is therefore ± 1 (like that of the ab-
sorbed photon), reflecting the orbital momentum difference between the electron

in the valence band to that in the conduction band. If the excited conduction electron's spin projection is in addition opposite to the spin projection of the ground valence band electron the electron and the 2 hole have parallel spins, with total angular momentum projection of ±2. This type of excitation is optically forbidden since the light electric field cannot change the electronic spin and therefore it is called dark exciton (DE).Excitons in the QD can be generated also while the QD contains additional charges, such as a single electron or a single hole. Similarly, many other types of multiple carrier configurations can populate the QD at a given time. For example, a biexciton is two excitons (two electrons and two holes), and a positively (negatively) charged exciton (trion) is an exciton with addition of one hole (electron), just to mention a few basic QD excitations.

1.2　The QD exciton fine structure

Figure 1 presents the four lowest energy configurations of electron-heavy hole pairs (excitons) and describes the energy difference between the parallel and anti-parallel spin configurations. The energy splitting between the DE and the BE is $\triangle_0 \approx 300\mu eV$ due to the isotropic long and short range electron-hole exchange interaction (EHEI). Additional splitting is caused by the anisotropic (mainly long range) EHEI which removes the degeneracy between the two BE eigenstates by $\triangle_2 \cong 30\mu eV$

⇑ - Heavy Hole
↑ - Electron

Non interacting

Isotropic electron-hole exchange

Anisotropic electron-hole exchange

⇑↓−⇓↑
$\sigma^+ - \sigma^-$
$|a\rangle$

$\updownarrow$ V

Bright Exciton
$\frac{3}{2} - \frac{1}{2} = 1$ $-\frac{3}{2} + \frac{1}{2} = -1$

$\Delta_1 \approx 0.03\text{meV}$

$|s\rangle$ ⇑↓+⇓↑
$\sigma^+ + \sigma^-$

⇑↓ σ^+ ⇓↑ σ^-

⇑↓ ⇓↑

$\leftrightarrow$ H

Energy

⇑↑   ⇓↓

$\Delta_0 \approx 0.3\text{meV}$

$\frac{3}{2} + \frac{1}{2} = 2$ $-\frac{3}{2} - \frac{1}{2} = -2$

Dark Exciton

$|a\rangle$ ⇑↑−⇓↓

⇑↑ ⇓↓

$|s\rangle$ ⇑↑+⇓↓
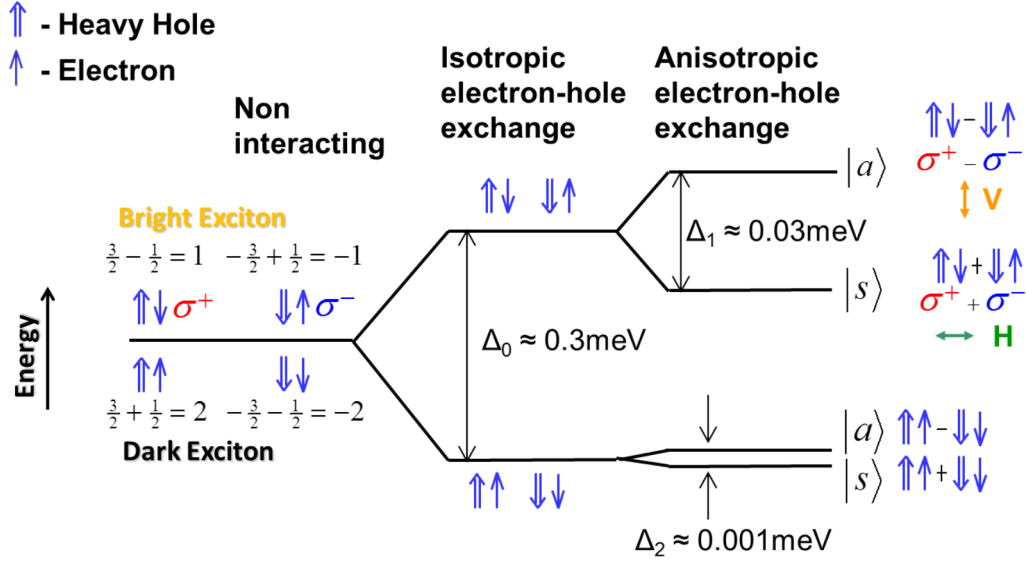
$\Delta_2 \approx 0.001\text{meV}$

Figure 1: Schematic description of the bright and dark exciton energy levels and spin eigenstates. The polarization of light that interacts with the BE eigenstates is marked underneath the corresponding BE eigenstate.

The projection of the spin of the electron on the z-axis (growth axis) of the QD can be either 1/2 or -1/2 while for the heavy hole, the spin projection is either 3/2 or -3/2 such that the two spin states of the bright exciton are $\left|\frac{1}{2}, -\frac{3}{2}\right\rangle$ and $\left|-\frac{1}{2}, \frac{3}{2}\right\rangle$ with a total spin in the z direction of ± 1. While in the case of electron-hole pair with parallel spin, the spin states are $\left|\frac{1}{2}, \frac{3}{2}\right\rangle$ and $\left|-\frac{1}{2}, -\frac{3}{2}\right\rangle$ with a total spin of ± 2. In figure 2 we describe two of the simple configurations that we can have in a QD. We start with empty dot which we denote by $|0\rangle$.
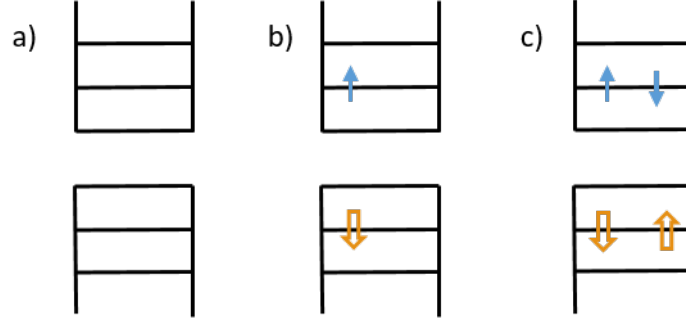
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Figure 2: Schematic of the energy levels in the quantum dot for empty quantum dot (a),exciton (b) and a biexciton (c)

while having two electron-hole pairs falling in the dot a biexciton is formed and we denote it by $|XX_0\rangle$. The total energy of the biexciton differs from twice the energy of the exciton due to the interaction between all the particles.

In an ideal QD, the radiative decay path of the biexciton back to the ground state goes via one path, but due to the anisotropy of the QD, the energy of exciton is split in what is defined as the fine structure splitting (FSS) as seen in figure **??**b. Here we refer to the up (down) spin of the electron as $|\uparrow\rangle$ ($|\downarrow\rangle$) and the up (down) spin of the hole as $|\Uparrow\rangle$ ($|\Downarrow\rangle$) such as the two eigenstates of the exciton are $|\uparrow\Downarrow\rangle$ and $|\downarrow\Uparrow\rangle$,and the decay from these states result in the emission of photons with co-linear polarization. Here we refer to them as horizontal $|H\rangle$ and vertical $|V\rangle$. We can represent these two rectilinear bases using the Bloch sphere where the poles in the sphere are $|H\rangle$ and $|V\rangle$ base.

In addition to the rectilinear polarization states, We can define the diagonal

linear and the circular polarization bases:

$$|L\rangle = (|H\rangle + i\,|V\rangle)/\sqrt{2}$$
$$|R\rangle = (|H\rangle - i\,|V\rangle)/\sqrt{2} \tag{1}$$

where $|R\rangle$ and $|L\rangle$ are the left and right circular bases respectively, and:

$$|D\rangle = (|H\rangle + |V\rangle)/\sqrt{2}$$
$$|\bar{D}\rangle = (|H\rangle + |V\rangle)/\sqrt{2} \tag{2}$$

$|D\rangle$ and $|\bar{D}\rangle$ are the diagonal and anti-diagonal bases respectively
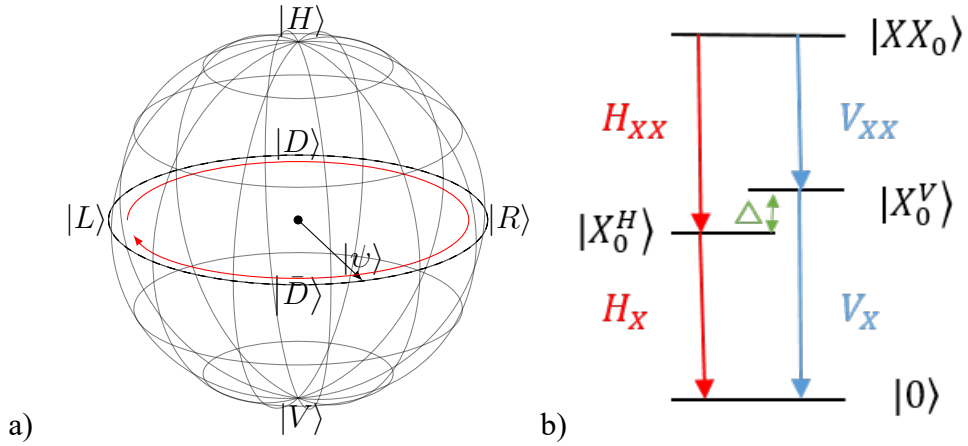

Figure 3: a) A Bloch sphere representation of the spin state. A point on the sphere represents an arbitrarily polarized spin state. b) Decay paths of the biexciton back the ground state where the red arrows represent the emission of a H polarized photon and blue arrows represent the emission of V polarized photon.

When the biexciton spontaneously radiatively decays it emits a photon leaving in the QD an exciton in coherent superposition of its two eigenstates. The optical

selection rules for the biexciton radiative recombination and the lack of informa-
tion by "which path" the recombination proceeds result in entanglement between
the exciton state and the polarization state of the emitted photon. Their mutual
wave function is given by:

$$|\psi_{X^0}\rangle = \frac{1}{\sqrt{2}}(|H_1 H_H^1\rangle + |V_1 V_V^1\rangle) \tag{3}$$

here $|H_1\rangle$ and $|V1\rangle$ are the two rectilinear polarization states of the first (biexciton)
photon. since the two exciton eigenstates are not degenerate, the relative phase
between these eigenstates precesses in time with a period of $T_P = h/\triangle$, where
where h is the Planck constant and $\triangle$ is the exciton FSS [**rwinik2017**]. This
precession is schematically described on the exciton Bloch sphere in figure. $3a$.
The precession "stops" when the exciton recombines and the radiative cascade
is completed with the emission of a second photon. The two photons are thus
entangled. Their mutual wave function depends on the recombination time and is
given by:

$$|\psi_{X^0}\rangle = \frac{1}{\sqrt{2}}(|H_1 H_1\rangle + e^{-i2\pi t/T_P} |V_1 V_2\rangle) \tag{4}$$

where $|H_2\rangle$ and $|V_2\rangle$ are the second (exciton) photon polarization states and
$t = t_{X_0} - t_{XX_0}$ is the time between the emission of the biexciton photon t_{XX_0} and
that of the exciton t_{X_0}.

2 Preliminary Results

3 The Proposal

Appendices

Appendix I

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Appendix 2

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