Electron-photon and electron-electron scattering as dephasing mechanisms in a single quantum emitter

UNIVERSITÄT DUISBURG ESSEN

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CENIDE CENTER FOR NANOINTEGRATION DUISBURG-ESSEN

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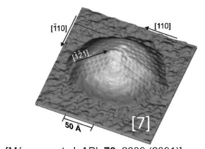
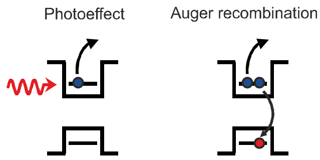
1. Motivation

Excitons in semiconductor **quantum dots** (QDs)

- Promising candidate for quantum information technologies
- **Resonance fluorescence** (RF) is ideal: No generation of electrons/holes in the environment; less dephasing



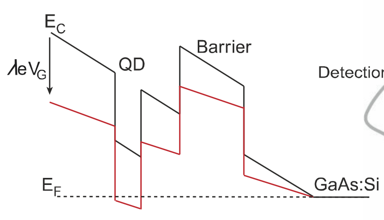
[Márquez, et al. APL **78**, 2309 (2001)]



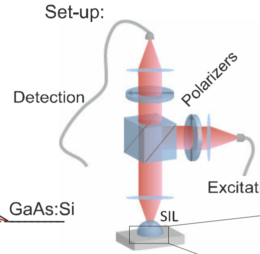
Dephasing mechanisms besides spin and charge noise [1]:

- Electron-photon scattering: Electron emission into the conduction band by the **photoeffect** [2,3]
- Electron-electron scattering, e.g. **Auger recombination** of the trion [4-6]

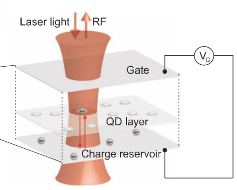
2. Sample and set-up



- Si-doped GaAs as charge reservoir
- 45 nm AlGaAs/GaAs tunneling barrier
- QD can be charged with single charge resolution

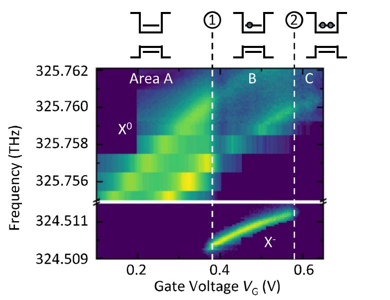


- Resonance fluorescence set-up with linear polarizers to separate laser excitation and QD emission
- 10^7 laser background suppression

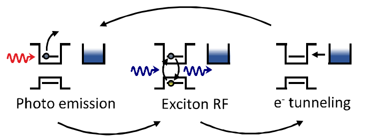


3. Electron-photon scattering - The photoeffect [2,3]

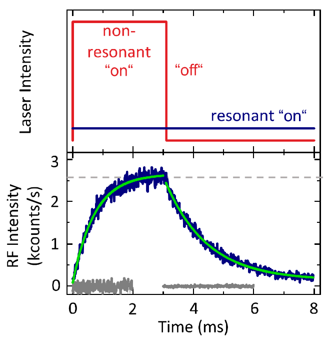
- Resonance fluorescence intensity of the exciton X^0 and trion X^- transition:

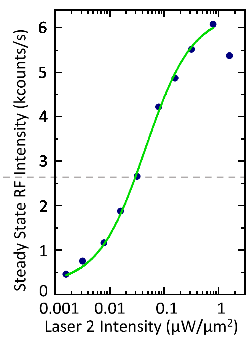


- Schematic representation of the photoemission effect which allows to excite the X_0 in area B of the trion transition:



- Time-resolved two-laser resonant excitation:
  1. Non-resonant in the band gap (photoeffect)
  2. Resonant on the exition transition (read-out)





- Non-resonant laser 2 "on": Increasing exciton intensity by the photoeffect
- Non-resonant laser 2 "off": Electron tunneling quenches the X^0
- The maximum steady-state intensity of the X^0 increases with the non-resonant laser 2 excitation

- The tunneling and electron emssion rate (by the electron-photon scattering) can be obtained by using a rate equation:

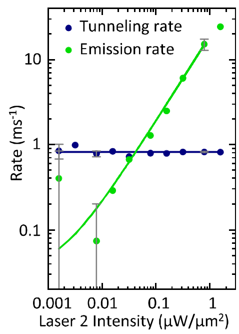
Tunneling rate $\gamma_{In} = (0.82 \pm 0.02)\,\mathrm{ms}^{-1}$

Emission rate $\gamma_{Emission} = [(18.8 \pm 0.3) \cdot I_{Laser}]\,\frac{\mathrm{ms}^{-1}}{\mu\mathrm{W}/\mu\mathrm{m}^2}$

- Rate equations:

$$P_0 = \gamma_{In} P_0 + \gamma_{Emission} P_1$$
$$P_0 + P_1 = 1$$
$$P_0(0) = 0$$

P_0 ≙ QD unoccupied
P_1 ≙ QD occupied with 1 electron

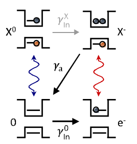


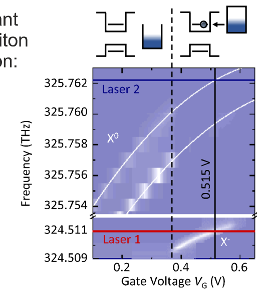
- Follows the occupation probability of the exciton state:

$$P_0(t) = \frac{\gamma_{Emission}}{\gamma_{In} + \gamma_{Emission}}(1 - \exp(-(\gamma_{In} + \gamma_{Emission})t))$$

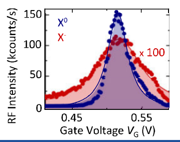
5. Electron-electron scattering - The Auger effect [4-6]

- Two-laser resonant excitation on exciton and trion transition:





- Exciton and trion visible at the same gate voltage, due to the Auger effect:



- Electron tunneling vs. the Auger recombination
  1. Excitation on the trion transition: Auger effect
  2. Excitation on the exciton transition: Electron tunneling into the dot

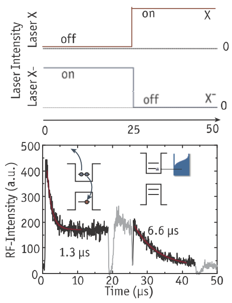
- Rate equation yields: Probability for the fluorescent trion state:

$$P_f(t) = \frac{\gamma_{In} + n\gamma_a e^{-\gamma_m t}}{\gamma_{In} + n\gamma_a}$$

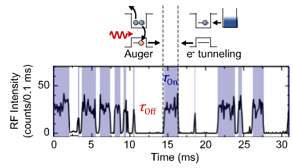
Relaxation rate: $\gamma_m = \gamma_{In} + n\gamma_a$

Tunneling rate: $\gamma_{In} = 0.2\,\mu s^{-1}$

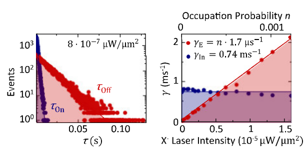
Auger rate: $\gamma_a = 2.3\,\mu s^{-1}$



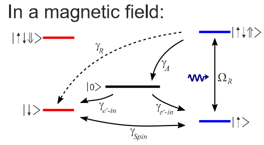
- Real-time measurement of every Auger recombination event:



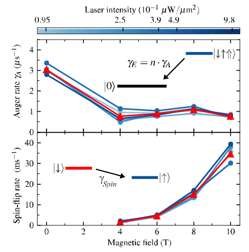
- Waiting time distribution:



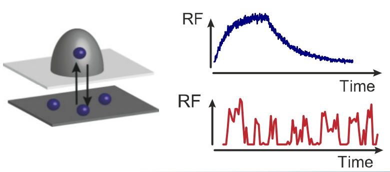
- In a magnetic field:



- Suppression the Auger effect:



6. Conclusion



Two important dephasing mechanisms, even in resonant excitation of a quantum emitter:

- The internal photoeffect can emit an electron/hole from the conduction/band into the continuum
- The Auger effect as an electron-electron scattering event that has a negative influence on the trion
- Suppression by magnetic field or band structure engineering (reduction of the final states in the continuum)

Further reading

[1] Kuhlmann et al., Nature Phys. **9**, 570 (2013).
[2] Kurzmann et al., Nano Lett.**16**, 3367 (2016).
[3] Lochner et al, Nano Lett. **20**, 1631 (2020).
[4] Kurzmann et al., Appl. Phys. Lett. **108**, 263108 (2016).
[5] Lochner et al., Phys. Rev. B **103**, 075426 (2021).
[6] Mannel et al., preprint: arXiv:2110.12213 (2021).

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