

# Chapter I

## Coherent dynamics of Mn-doped positively charged quantum dots

### I.1 Mn in a II-VI positively charged quantum dot

Cf Optical control of the spin of a magnetic atom in a semiconductor QD, L. Besombes et. al., Sept 2014

#### I.1.1 Spin structure of a positively charged Mn doped quantum dot

Cf XplusMnRes.pptx to detail the e-Mn levels

  Lorem ipsum dolor sit amet, consectetur adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetur id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

  Nam dui ligula, fringilla a, euismod sodales, sollicitudin vel, wisi. Morbi auctor lorem non justo. Nam lacus libero, pretium at, lobortis vitae, ultricies et, tellus. Donec aliquet, tortor sed accumsan bibendum, erat ligula aliquet magna, vitae ornare odio metus a mi. Morbi ac orci et nisl hendrerit mollis. Suspendisse ut massa. Cras nec ante. Pellentesque a nulla. Cum sociis natoque penatibus et

magnis dis parturient montes, nascetur ridiculus mus. Aliquam tincidunt urna. Nulla ullamcorper vestibulum turpis. Pellentesque cursus luctus mauris.

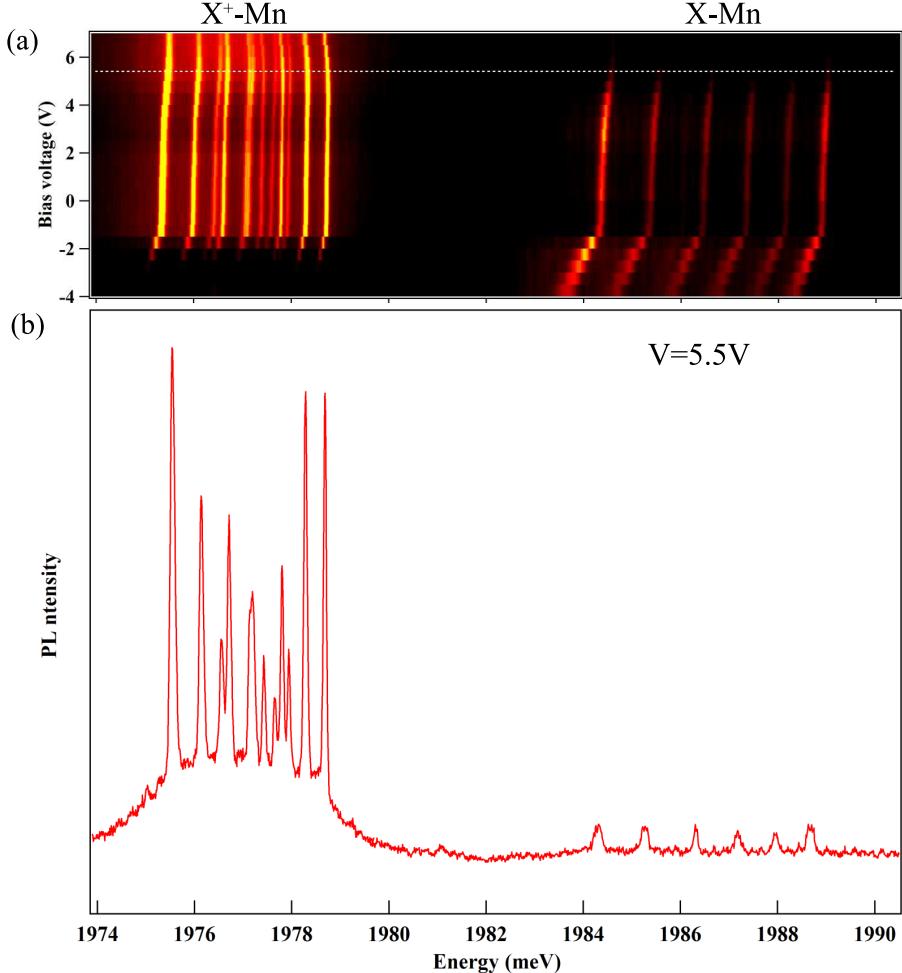


Figure I.1: (a) Color scale plot of the PL intensity of the studied Mn doped QD inserted in Schottky structure showing the emission of the neutral (X-Mn) and positively charged ( $X^+$ -Mn) exciton as a function of energy and bias voltage. (b) PL of the Mn-doped QD under a positive bias voltage of  $V=5.5V$ .

Nulla malesuada porttitor diam. Donec felis erat, congue non, volutpat at, tincidunt tristique, libero. Vivamus viverra fermentum felis. Donec nonummy pellentesque ante. Phasellus adipiscing semper elit. Proin fermentum massa ac quam. Sed diam turpis, molestie vitae, placerat a, molestie nec, leo. Maecenas lacinia. Nam ipsum ligula, eleifend at, accumsan nec, suscipit a, ipsum. Morbi blandit ligula feugiat magna. Nunc eleifend consequat lorem. Sed lacinia nulla

vitae enim. Pellentesque tincidunt purus vel magna. Integer non enim. Praesent euismod nunc eu purus. Donec bibendum quam in tellus. Nullam cursus pulvinar lectus. Donec et mi. Nam vulputate metus eu enim. Vestibulum pellentesque felis eu massa.

Quisque ullamcorper placerat ipsum. Cras nibh. Morbi vel justo vitae lacus tincidunt ultrices. Lorem ipsum dolor sit amet, consectetur adipiscing elit. In hac habitasse platea dictumst. Integer tempus convallis augue. Etiam facilisis. Nunc elementum fermentum wisi. Aenean placerat. Ut imperdiet, enim sed gravida sollicitudin, felis odio placerat quam, ac pulvinar elit purus eget enim. Nunc vitae tortor. Proin tempus nibh sit amet nisl. Vivamus quis tortor vitae risus porta vehicula.

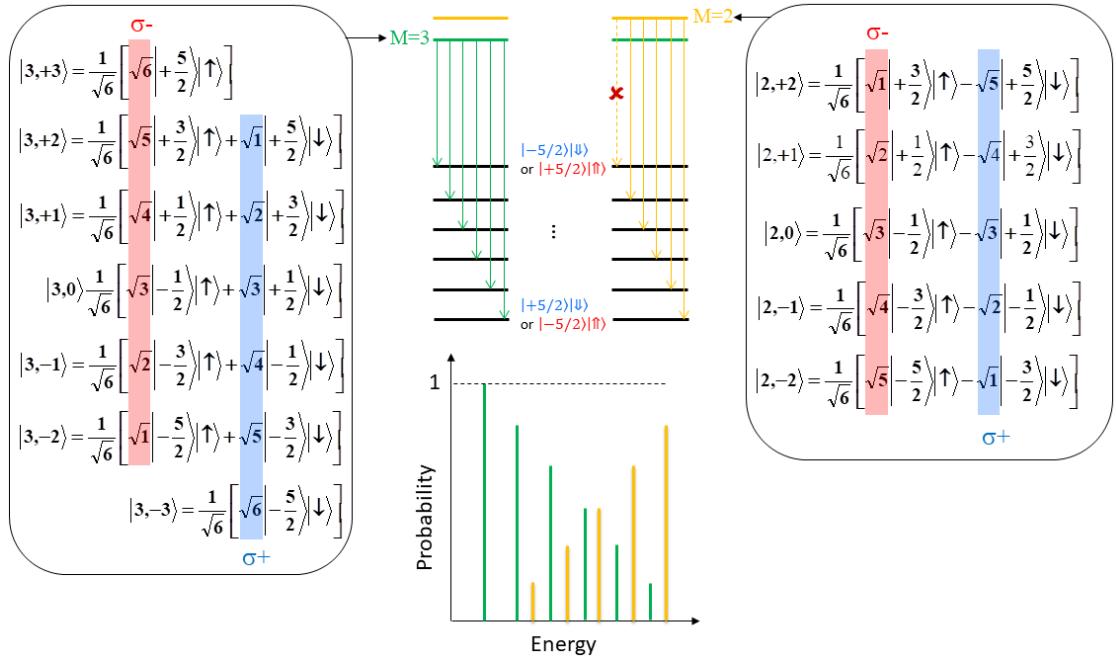


Figure I.2: Electron-Mn spin states for each  $|M, M_z\rangle$ . For each  $M$ , the  $\sigma-$  (red) and  $\sigma+$  (blue) probability is highlighted. This probability is directly linked to the intensity of each peak. In the center, the different possible recombination path for  $M = 3$  and  $M = 2$  are presented. A schema of the resulting spectra is drawn below.

Fusce mauris. Vestibulum luctus nibh at lectus. Sed bibendum, nulla a faucibus semper, leo velit ultricies tellus, ac venenatis arcu wisi vel nisl. Vestibulum diam. Aliquam pellentesque, augue quis sagittis posuere, turpis lacus congue quam, in hendrerit risus eros eget felis. Maecenas eget erat in sapien mattis port-

Table I.1: Values of the parameters used in the model of the positively charged Mn-doped QD presented in Fig. I.1.  $I_{eMn}$ ,  $I_{hMn}$ ,  $\frac{\rho_s}{\Delta_{lh}}$ ,  $\theta$ ,  $\eta$  and  $T_{eff}$  are used to model the linear polarization intensity map of Fig. I.3. The other parameters cannot be extracted from the PL measurements and values for typical Mn-doped QDs are chosen for the calculation of the spin dynamics presented in Sec. I.2 and I.3.

| $I_{eMn}$ | $I_{hMn}$ | $\frac{\rho_s}{\Delta_{lh}}$ | $\theta$ | $\eta$   | $T_{eff}$ | $g_e$ | $g_h$ | $g_{Mn}$ | $D_0$    | $E$      |
|-----------|-----------|------------------------------|----------|----------|-----------|-------|-------|----------|----------|----------|
| $\mu eV$  | $\mu eV$  |                              | $^\circ$ | $\mu eV$ | K         |       |       |          | $\mu eV$ | $\mu eV$ |
| -175      | 345       | 0.09                         | 0        | 30       | 20        | -0,4  | 0.6   | 2        | 7        | 1.5      |

titor. Vestibulum porttitor. Nulla facilisi. Sed a turpis eu lacus commodo facilisis. Morbi fringilla, wisi in dignissim interdum, justo lectus sagittis dui, et vehicula libero dui cursus dui. Mauris tempor ligula sed lacus. Duis cursus enim ut augue. Cras ac magna. Cras nulla. Nulla egestas. Curabitur a leo. Quisque egestas wisi eget nunc. Nam feugiat lacus vel est. Curabitur consectetur.

Suspendisse vel felis. Ut lorem lorem, interdum eu, tincidunt sit amet, laoreet vitae, arcu. Aenean faucibus pede eu ante. Praesent enim elit, rutrum at, molestie non, nonummy vel, nisl. Ut lectus eros, malesuada sit amet, fermentum eu, sodales cursus, magna. Donec eu purus. Quisque vehicula, urna sed ultricies auctor, pede lorem egestas dui, et convallis elit erat sed nulla. Donec luctus. Curabitur et nunc. Aliquam dolor odio, commodo pretium, ultricies non, pharetra in, velit. Integer arcu est, nonummy in, fermentum faucibus, egestas vel, odio.

Sed commodo posuere pede. Mauris ut est. Ut quis purus. Sed ac odio. Sed vehicula hendrerit sem. Duis non odio. Morbi ut dui. Sed accumsan risus eget odio. In hac habitasse platea dictumst. Pellentesque non elit. Fusce sed justo eu urna porta tincidunt. Mauris felis odio, sollicitudin sed, volutpat a, ornare ac, erat. Morbi quis dolor. Donec pellentesque, erat ac sagittis semper, nunc dui lobortis purus, quis congue purus metus ultricies tellus. Proin et quam. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Praesent sapien turpis, fermentum vel, eleifend faucibus, vehicula eu, lacus.

Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Donec odio elit, dictum in, hendrerit sit amet, egestas sed, leo. Praesent feugiat sapien aliquet odio. Integer vitae justo. Aliquam vestibulum fringilla lorem. Sed neque lectus, consectetur at, consectetur sed, eleifend ac, lectus. Nulla facilisi. Pellentesque eget lectus. Proin eu metus. Sed porttitor. In hac habitasse platea dictumst. Suspendisse eu lectus. Ut mi mi, lacinia sit amet, placerat et, mollis vitae, dui. Sed ante tellus, tristique ut, iaculis eu, malesuada ac, dui. Mauris nibh leo, facilisis non, adipiscing quis, ultrices a, dui.

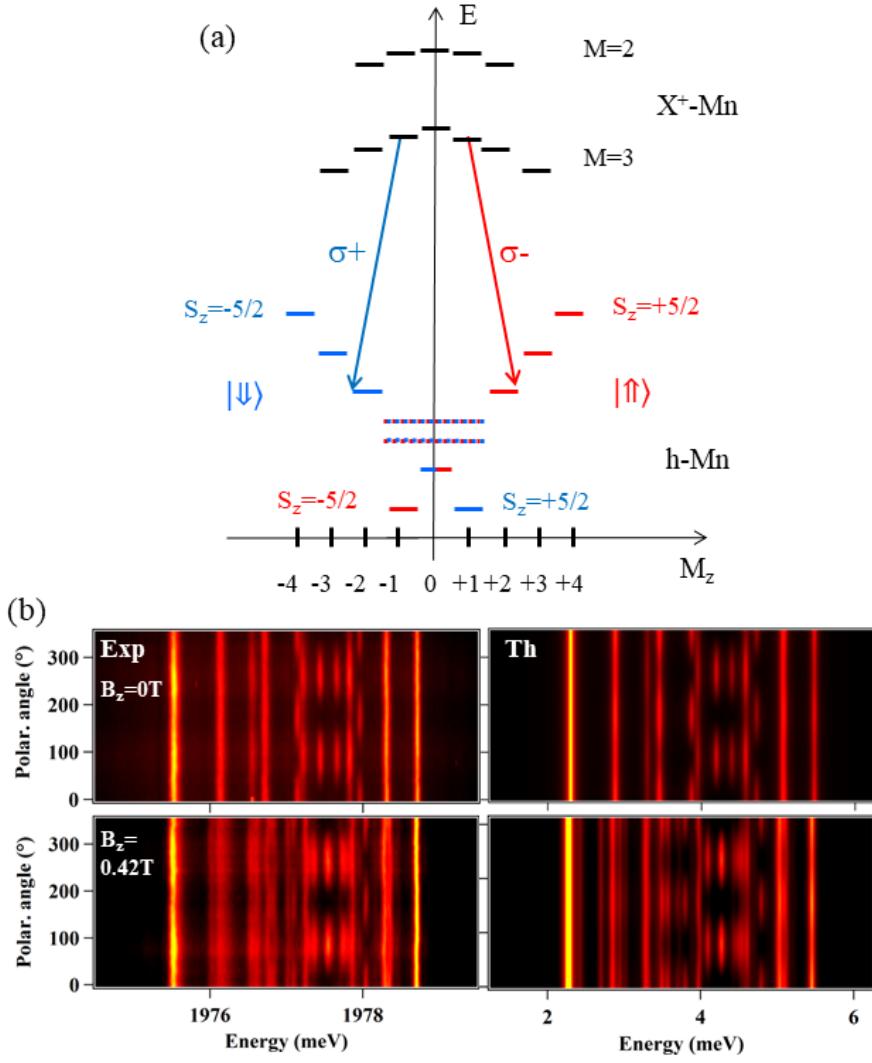


Figure I.3: (a) Energy levels of the ground (h-Mn) and excited ( $X^+$ -Mn) states as a function of their angular momentum ( $M_z$ ). The levels in dotted lines corresponds to the h-Mn states  $| -1/2 \rangle | \uparrow \rangle$  and  $| +1/2 \rangle | \downarrow \rangle$  coupled by the valence band mixing. Optical recombination towards these levels leads to the linearly polarized lines observed in (b). (b) Experimental (left) and calculated (right) color-scale plot of the linear polarization dependence of the PL of  $X^+$ -Mn at  $B = 0$  T (top) and  $B_\perp = 0.42$  T (bottom). The parameters used in the calculation are listed in Table I.1.

### I.1.2 Optical $\Lambda$ -level identification

Sed feugiat. Cum sociis natoque penatibus et magnis dis parturient montes, nascentur ridiculus mus. Ut pellentesque augue sed urna. Vestibulum diam eros, fringilla et, consectetur eu, nonummy id, sapien. Nullam at lectus. In sagittis ultrices mauris. Curabitur malesuada erat sit amet massa. Fusce blandit. Aliquam erat volutpat. Aliquam euismod. Aenean vel lectus. Nunc imperdiet justo nec dolor.

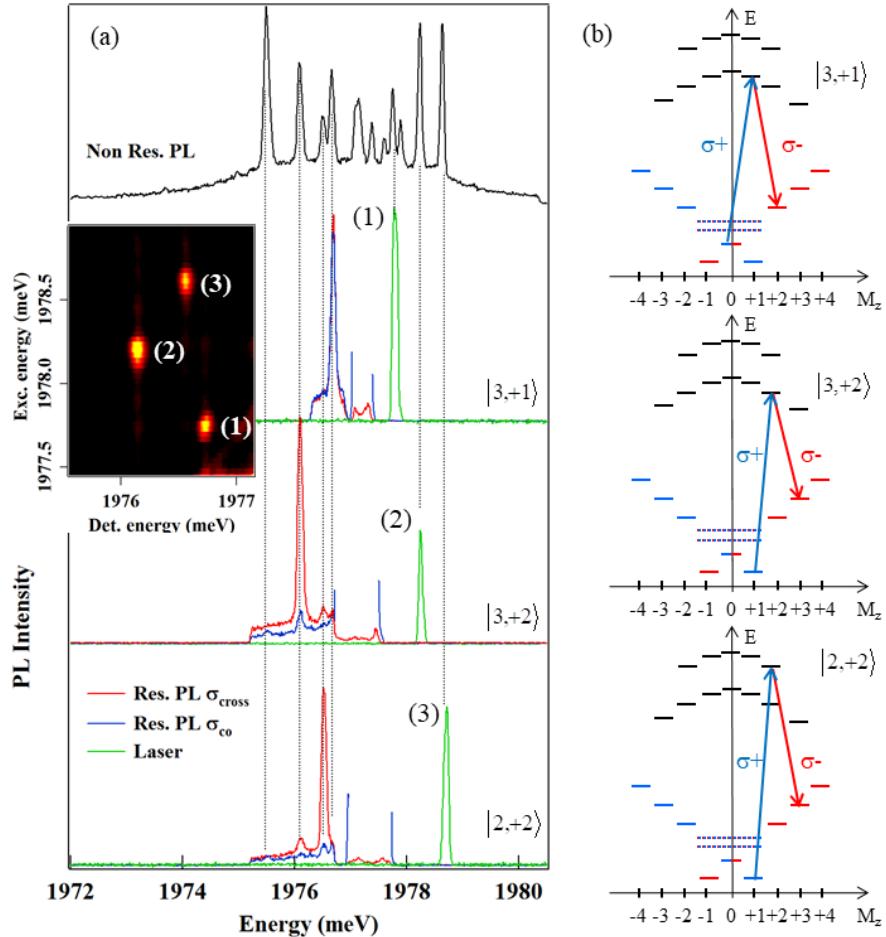


Figure I.4: (a) Non resonant (Non Res.) and resonant (Res.) PL of  $X^+$ -Mn. Co and cross circularly polarized PL spectra are collected for three different energies of the CW resonant laser (green). Inset: intensity map of the cross-circularly polarized PL detected on the low energy side of  $X^+$ -Mn as the CW laser is scanned through the high energy side. (b) Energy levels of  $X^+$ -Mn and identification of the three resonances observed in (a) corresponding to the optical  $\Lambda$  systems associated with the e-Mn states  $|3,+1\rangle$ ,  $|3,+2\rangle$  and  $|2,+2\rangle$ .

Etiam euismod. Fusce facilisis lacinia dui. Suspendisse potenti. In mi erat, cursus id, nonummy sed, ullamcorper eget, sapien. Praesent pretium, magna in eleifend egestas, pede pede pretium lorem, quis consectetur tortor sapien facilisis magna. Mauris quis magna varius nulla scelerisque imperdiet. Aliquam non quam. Aliquam porttitor quam a lacus. Praesent vel arcu ut tortor cursus volutpat. In vitae pede quis diam bibendum placerat. Fusce elementum convallis neque. Sed dolor orci, scelerisque ac, dapibus nec, ultricies ut, mi. Duis nec dui quis leo sagittis commodo.

## I.2 Spin dynamics under resonant excitation

Cf article 2016/01

### I.2.1 Cycling and escaping the $\lambda$ -level system

Sed feugiat. Cum sociis natoque penatibus et magnis dis parturient montes, nascentur ridiculus mus. Ut pellentesque augue sed urna. Vestibulum diam eros, fringilla et, consectetur eu, nonummy id, sapien. Nullam at lectus. In sagittis ultrices mauris. Curabitur malesuada erat sit amet massa. Fusce blandit. Aliquam erat volutpat. Aliquam euismod. Aenean vel lectus. Nunc imperdiet justo nec dolor.

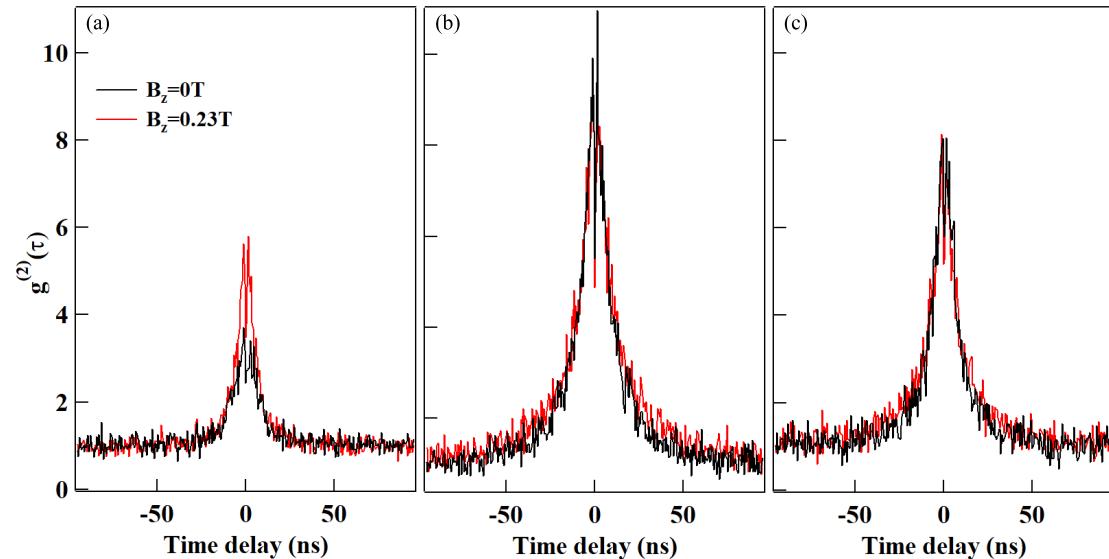


Figure I.5: Auto-correlation of the resonant PL for a cross-circularly polarized excitation and detection of the electron-Mn states (a)  $|3,+1\rangle$ , (b)  $|3,+2\rangle$  and (c)  $|2,+2\rangle$ .

Etiam ac leo a risus tristique nonummy. Donec dignissim tincidunt nulla. Vestibulum rhoncus molestie odio. Sed lobortis, justo et pretium lobortis, mauris turpis condimentum augue, nec ultricies nibh arcu pretium enim. Nunc purus neque, placerat id, imperdiet sed, pellentesque nec, nisl. Vestibulum imperdiet neque non sem accumsan laoreet. In hac habitasse platea dictumst. Etiam condimentum facilisis libero. Suspendisse in elit quis nisl aliquam dapibus. Pellentesque auctor sapien. Sed egestas sapien nec lectus. Pellentesque vel dui vel neque bibendum viverra. Aliquam porttitor nisl nec pede. Proin mattis libero vel turpis. Donec rutrum mauris et libero. Proin euismod porta felis. Nam lobortis, metus quis elementum commodo, nunc lectus elementum mauris, eget vulputate ligula tellus eu neque. Vivamus eu dolor.

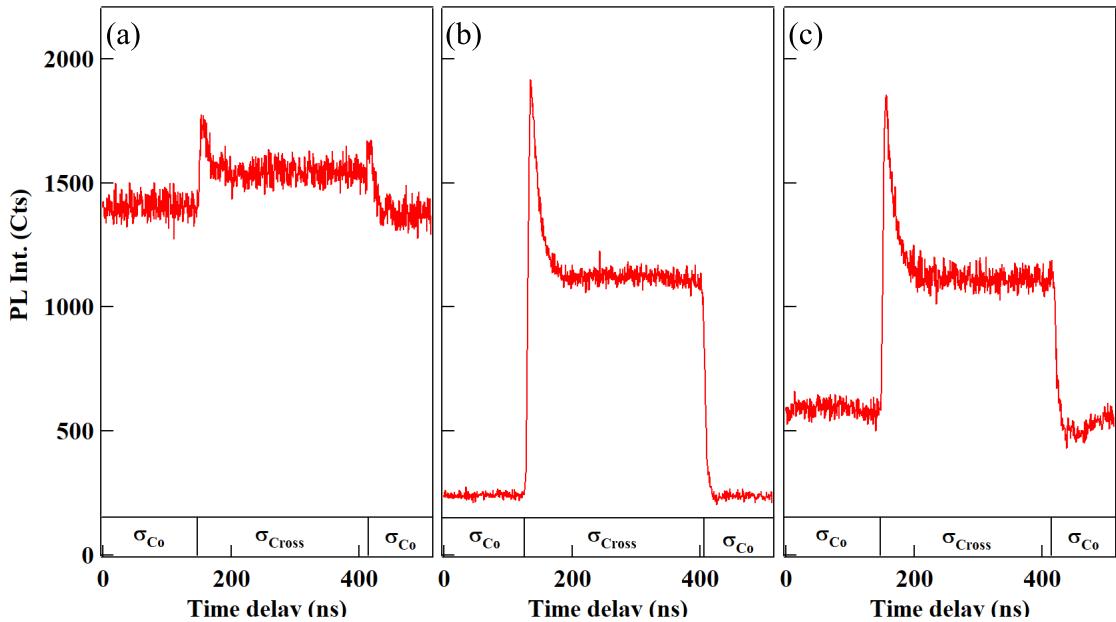


Figure I.6: Resonant optical pumping transients obtained under circular polarization switching of the resonant excitation for (a)  $|3, +1\rangle$ , (b)  $|3, +2\rangle$  and (c)  $|2, +2\rangle$  at zero field.

Nulla mattis luctus nulla. Duis commodo velit at leo. Aliquam vulputate magna et leo. Nam vestibulum ullamcorper leo. Vestibulum condimentum rutrum mauris. Donec id mauris. Morbi molestie justo et pede. Vivamus eget turpis sed nisl cursus tempor. Curabitur mollis sapien condimentum nunc. In wisi nisl, malesuada at, dignissim sit amet, lobortis in, odio. Aenean consequat arcu a ante. Pellentesque porta elit sit amet orci. Etiam at turpis nec elit ultricies imperdiet. Nulla facilisi. In hac habitasse platea dictumst. Suspendisse viverra aliquam risus. Nullam pede justo, molestie nonummy, scelerisque eu, facilisis vel, arcu.

Curabitur tellus magna, porttitor a, commodo a, commodo in, tortor. Donec interdum. Praesent scelerisque. Maecenas posuere sodales odio. Vivamus metus lacus, varius quis, imperdiet quis, rhoncus a, turpis. Etiam ligula arcu, elementum a, venenatis quis, sollicitudin sed, metus. Donec nunc pede, tincidunt in, venenatis vitae, faucibus vel, nibh. Pellentesque wisi. Nullam malesuada. Morbi ut tellus ut pede tincidunt porta. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Etiam congue neque id dolor.

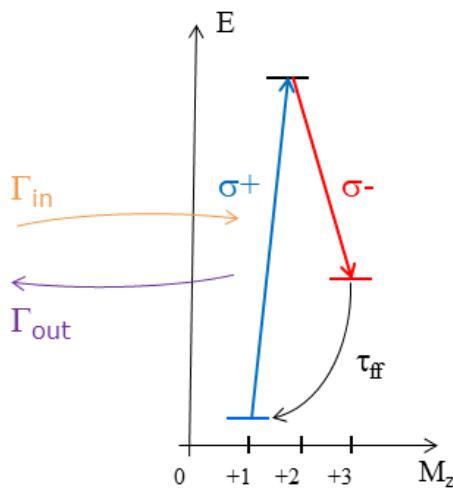


Figure I.7: Schema of the energy levels of the optical  $\Lambda$  system associated with the electron-Mn state  $|3, +2\rangle$  extracted from the full level structure of a positively charged Mn-doped QD (Fig. I.4). The different processes discussed in the section are presented on it.

Donec et nisl at wisi luctus bibendum. Nam interdum tellus ac libero. Sed sem justo, laoreet vitae, fringilla at, adipiscing ut, nibh. Maecenas non sem quis tortor eleifend fermentum. Etiam id tortor ac mauris porta vulputate. Integer porta neque vitae massa. Maecenas tempus libero a libero posuere dictum. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Aenean quis mauris sed elit commodo placerat. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Vivamus rhoncus tincidunt libero. Etiam elementum pretium justo. Vivamus est. Morbi a tellus eget pede tristique commodo. Nulla nisl. Vestibulum sed nisl eu sapien cursus rutrum.

Nulla non mauris vitae wisi posuere convallis. Sed eu nulla nec eros scelerisque pharetra. Nullam varius. Etiam dignissim elementum metus. Vestibulum faucibus, metus sit amet mattis rhoncus, sapien dui laoreet odio, nec ultricies nibh augue a enim. Fusce in ligula. Quisque at magna et nulla commodo consequat. Proin accumsan imperdiet sem. Nunc porta. Donec feugiat mi at justo. Phasellus facilisis ipsum quis ante. In ac elit eget ipsum pharetra faucibus. Maecenas viverra nulla in massa.

## I.2.2 Relaxation mechanism

Nulla ac nisl. Nullam urna nulla, ullamcorper in, interdum sit amet, gravida ut, risus. Aenean ac enim. In luctus. Phasellus eu quam vitae turpis viverra pellentesque. Duis feugiat felis ut enim. Phasellus pharetra, sem id porttitor sodales, magna nunc aliquet nibh, nec blandit nisl mauris at pede. Suspendisse risus risus, lobortis eget, semper at, imperdiet sit amet, quam. Quisque scelerisque dapibus nibh. Nam enim. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Nunc ut metus. Ut metus justo, auctor at, ultrices eu, sagittis ut, purus. Aliquam aliquam.

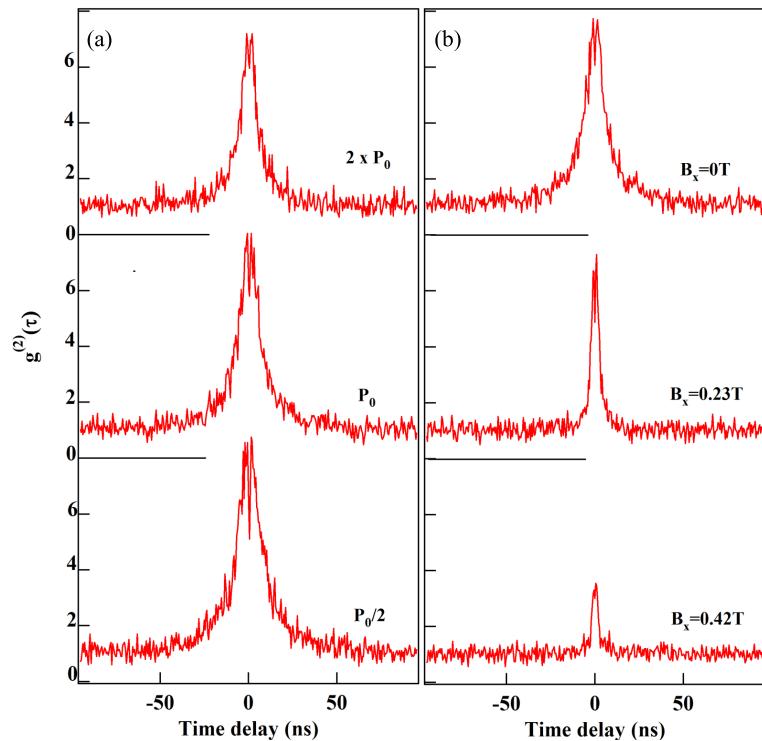


Figure I.8: Excitation power dependence (a) and transverse magnetic field dependence (b) of the auto-correlation of the resonant PL obtained for an excitation on the high energy branch of the  $\Lambda$  level system associated to the e-Mn state  $|2, +2\rangle$ .

Etiam suscipit aliquam arcu. Aliquam sit amet est ac purus bibendum congue. Sed in eros. Morbi non orci. Pellentesque mattis lacinia elit. Fusce molestie velit in ligula. Nullam et orci vitae nibh vulputate auctor. Aliquam eget purus. Nulla auctor wisi sed ipsum. Morbi porttitor tellus ac enim. Fusce ornare. Proin ipsum enim, tincidunt in, ornare venenatis, molestie a, augue. Donec vel pede in lacus sagittis porta. Sed hendrerit ipsum quis nisl. Suspendisse quis massa ac nibh

pretium cursus. Sed sodales. Nam eu neque quis pede dignissim ornare. Maecenas eu purus ac urna tincidunt congue.

Donec et nisl id sapien blandit mattis. Aenean dictum odio sit amet risus. Morbi purus. Nulla a est sit amet purus venenatis iaculis. Vivamus viverra purus vel magna. Donec in justo sed odio malesuada dapibus. Nunc ultrices aliquam nunc. Vivamus facilisis pellentesque velit. Nulla nunc velit, vulputate dapibus, vulputate id, mattis ac, justo. Nam mattis elit dapibus purus. Quisque enim risus, congue non, elementum ut, mattis quis, sem. Quisque elit.

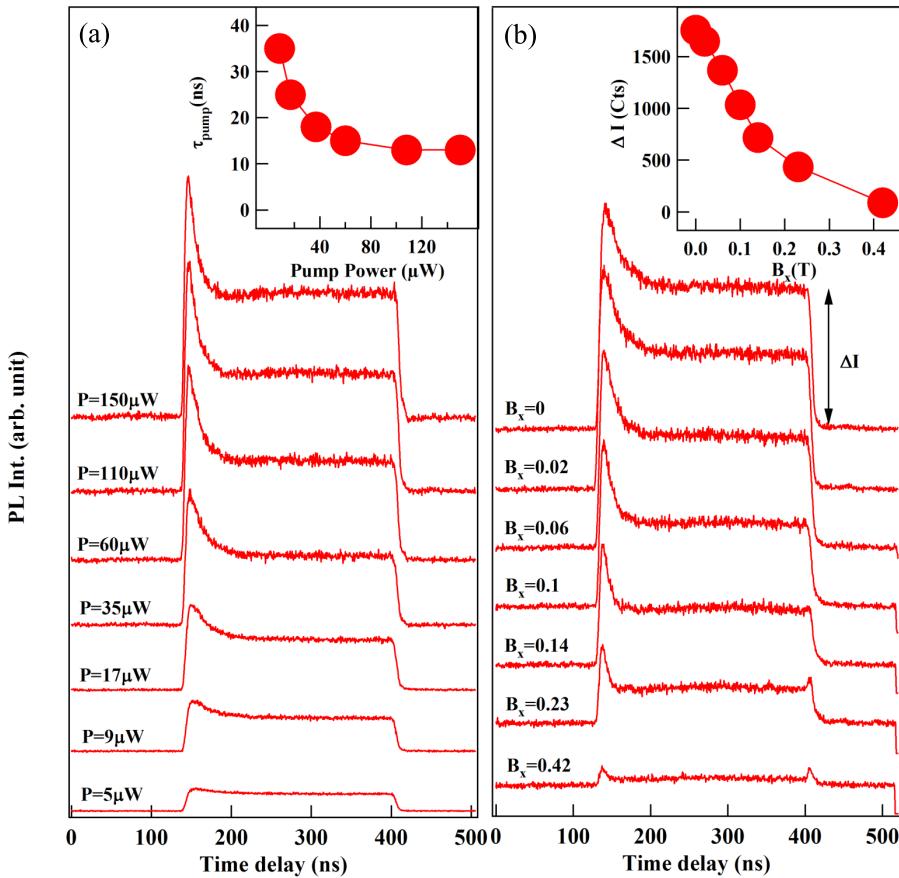


Figure I.9: Excitation power dependence (a) and transverse magnetic field dependence (b) of the optical pumping signal obtained for a resonant excitation on  $|3, +2\rangle$ . Insets: excitation power dependence of the pumping time and transverse magnetic field dependence of the difference of resonant PL intensity between a  $\sigma_{cross}$  and a  $\sigma_{co}$  excitation.

Maecenas non massa. Vestibulum pharetra nulla at lorem. Duis quis quam id lacus dapibus interdum. Nulla lorem. Donec ut ante quis dolor bibendum condi-

mentum. Etiam egestas tortor vitae lacus. Praesent cursus. Mauris bibendum pede at elit. Morbi et felis a lectus interdum facilisis. Sed suscipit gravida turpis. Nulla at lectus. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Praesent nonummy luctus nibh. Proin turpis nunc, congue eu, egestas ut, fringilla at, tellus. In hac habitasse platea dictumst.

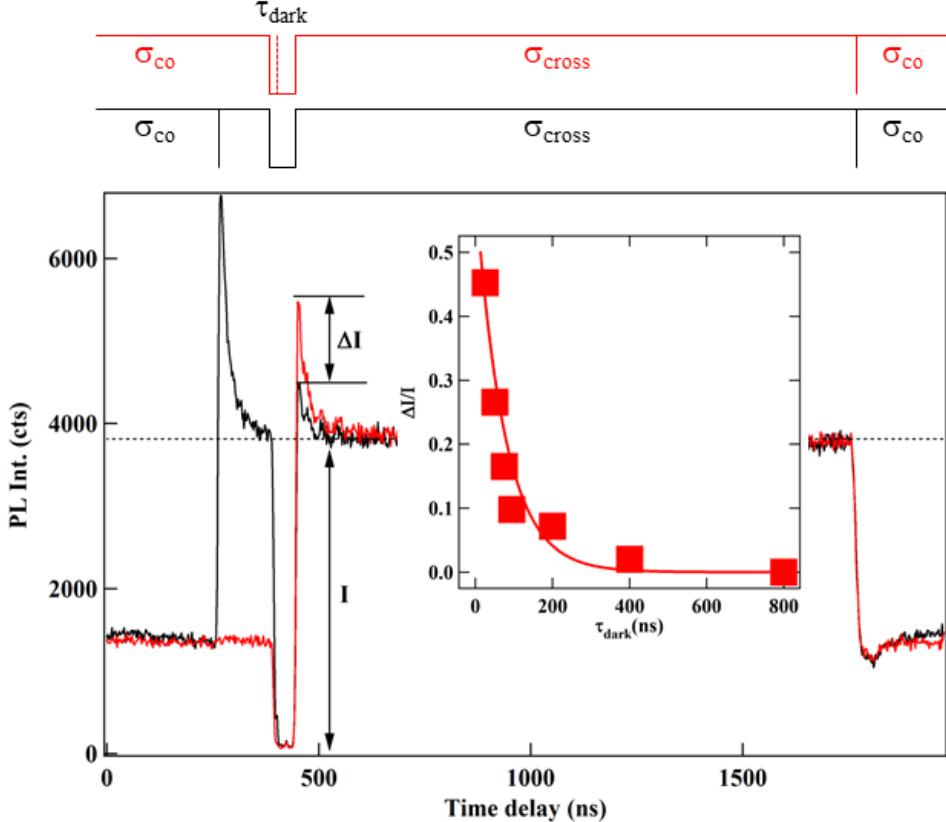


Figure I.10: Optical pumping experiment for an excitation of  $|3,+2\rangle$  with modulated circular polarization. A dark time ( $\tau_{\text{dark}} = 50\text{ns}$ ) is introduced either before (black) or during (red) the change of circular polarization. The black and red diagrams present the corresponding resonant excitation sequences. The inset presents the variation of the ratio  $\Delta I/I$  as a function of  $\tau_{\text{dark}}$ . The solid line is an exponential fit with  $\tau_{\text{relax}} = 80\text{ns}$ .

Duis aliquet dui in est. Donec eget est. Nunc lectus odio, varius at, fermentum in, accumsan non, enim. Aliquam erat volutpat. Proin sit amet nulla ut eros consectetur cursus. Phasellus dapibus aliquam justo. Nunc laoreet. Donec consequat placerat magna. Duis pretium tincidunt justo. Sed sollicitudin vestibulum quam. Nam quis ligula. Vivamus at metus. Etiam imperdiet imperdiet pede. Aenean

turpis. Fusce augue velit, scelerisque sollicitudin, dictum vitae, tempor et, pede. Donec wisi sapien, feugiat in, fermentum ut, sollicitudin adipiscing, metus.

Donec vel nibh ut felis consectetur laoreet. Donec pede. Sed id quam id wisi laoreet suscipit. Nulla lectus dolor, aliquam ac, fringilla eget, mollis ut, orci. In pellentesque justo in ligula. Maecenas turpis. Donec eleifend leo at felis tincidunt consequat. Aenean turpis metus, malesuada sed, condimentum sit amet, auctor a, wisi. Pellentesque sapien elit, bibendum ac, posuere et, congue eu, felis. Vestibulum mattis libero quis metus scelerisque ultrices. Sed purus.

Table I.2: Material (CdTe or ZnTe) [1] and QD parameters used in the calculation of the coupled hole and Mn spin relaxation time.

| CdTe                            |               |      |                   |
|---------------------------------|---------------|------|-------------------|
| Deformation potential constants | b             | -1.0 | eV                |
|                                 | d             | -4.4 | eV                |
| Longitudinal sound speed        | $c_l$         | 3300 | m/s               |
| Transverse sound speed          | $c_t$         | 1800 | m/s               |
| Density                         | $\rho$        | 5860 | kg/m <sup>3</sup> |
| ZnTe                            |               |      |                   |
| Deformation potential constants | b             | -1.4 | eV                |
|                                 | d             | -4.4 | eV                |
| Longitudinal sound speed        | $c_l$         | 3800 | m/s               |
| Transverse sound speed          | $c_t$         | 2300 | m/s               |
| Density                         | $\rho$        | 5908 | kg/m <sup>3</sup> |
| Quantum dot                     |               |      |                   |
| Hole Mn exchange energy         | $I_{hMn}$     | 0.35 | meV               |
| hh-lh exciton splitting         | $\Delta_{lh}$ | 15   | meV               |
| Hole wave function widths:      |               |      |                   |
| - in plane                      | $l_\perp$     | 3.0  | nm                |
| - z direction                   | $l_z$         | 1.25 | nm                |

Donec molestie, magna ut luctus ultrices, tellus arcu nonummy velit, sit amet pulvinar elit justo et mauris. In pede. Maecenas euismod elit eu erat. Aliquam augue wisi, facilisis congue, suscipit in, adipiscing et, ante. In justo. Cras lobortis neque ac ipsum. Nunc fermentum massa at ante. Donec orci tortor, egestas sit amet, ultrices eget, venenatis eget, mi. Maecenas vehicula leo semper est. Mauris vel metus. Aliquam erat volutpat. In rhoncus sapien ac tellus. Pellentesque ligula.

Sed mattis, erat sit amet gravida malesuada, elit augue egestas diam, tempus scelerisque nunc nisl vitae libero. Sed consequat feugiat massa. Nunc porta, eros in eleifend varius, erat leo rutrum dui, non convallis lectus orci ut nibh. Sed lorem massa, nonummy quis, egestas id, condimentum at, nisl. Maecenas

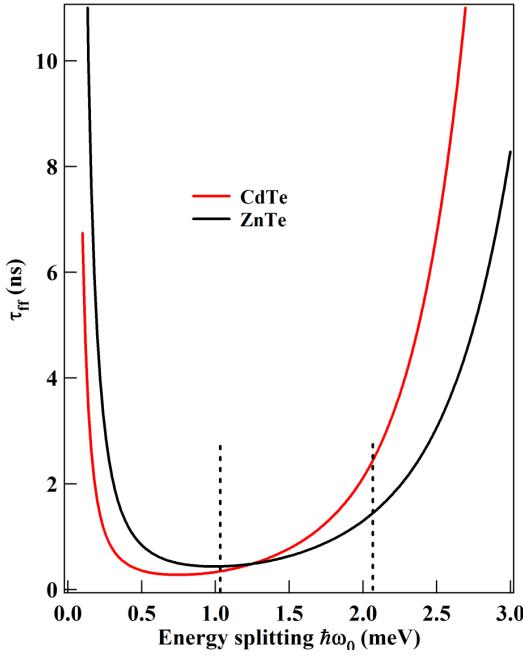


Figure I.11: Relaxation rates between the two h-Mn ground states of the  $\Lambda$  system  $\tau_{ff}$  calculated with the material and QD parameters listed in table I.2 and a temperature  $T=7\text{K}$ . The vertical lines show the energy splitting of the hole-Mn states involved in the optical  $\Lambda$  systems identified in Fig. I.4.

at nibh. Aliquam et augue at nunc pellentesque ullamcorper. Duis nisl nibh, laoreet suscipit, convallis ut, rutrum id, enim. Phasellus odio. Nulla nulla elit, molestie non, scelerisque at, vestibulum eu, nulla. Ut odio nisl, facilisis id, mollis et, scelerisque nec, enim. Aenean sem leo, pellentesque sit amet, scelerisque sit amet, vehicula pellentesque, sapien.

Phasellus id magna. Duis malesuada interdum arcu. Integer metus. Morbi pulvinar pellentesque mi. Suspendisse sed est eu magna molestie egestas. Quisque mi lorem, pulvinar eget, egestas quis, luctus at, ante. Proin auctor vehicula purus. Fusce ac nisl aliquam ante hendrerit pellentesque. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Morbi wisi. Etiam arcu mauris, facilisis sed, eleifend non, nonummy ut, pede. Cras ut lacus tempor metus mollis placerat. Vivamus eu tortor vel metus interdum malesuada.

Nullam eleifend justo in nisl. In hac habitasse platea dictumst. Morbi nonummy. Aliquam ut felis. In velit leo, dictum vitae, posuere id, vulputate nec, ante. Maecenas vitae pede nec dui dignissim suscipit. Morbi magna. Vestibulum id purus eget velit laoreet laoreet. Praesent sed leo vel nibh convallis blandit. Ut rutrum. Donec nibh. Donec interdum. Fusce sed pede sit amet elit rhoncus ultrices. Nullam at enim vitae pede vehicula iaculis.

Nulla malesuada risus ut urna. Aenean pretium velit sit amet metus. Duis iaculis. In hac habitasse platea dictumst. Nullam molestie turpis eget nisl. Duis a

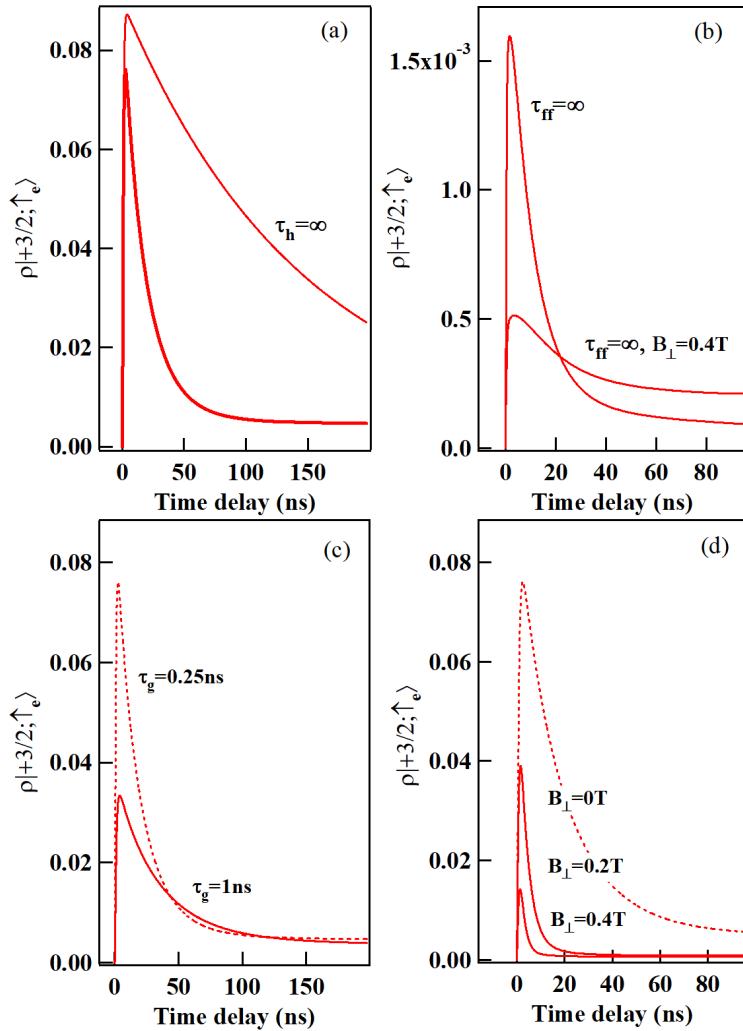


Figure I.12: (a) Calculated time evolution of  $\rho|+3/2, \uparrow\rangle_e(t)$  with the QD parameters listed in Table I.1 and (unless specified)  $\tau_r=0.3\text{ns}$ ,  $\tau_{Mn}=5\text{ }\mu\text{s}$ ,  $\tau_h=10\text{ns}$ ,  $\tau_g=0.25\text{ ns}$ ,  $\tau_{ff}=1.5\text{ ns}$ ,  $T_2^{hMn}=5\text{ ns}$ ,  $T_2^{eMn}=0.5\text{ ns}$ ,  $T=10\text{K}$  and  $B_\perp=0$ . (b) (c) and (d) illustrate the influence of, respectively,  $\tau_{ff}$ ,  $\tau_g$  and  $B_\perp$  on  $\rho|+3/2, \uparrow\rangle_e(t)$ .

massa id pede dapibus ultricies. Sed eu leo. In at mauris sit amet tortor bibendum varius. Phasellus justo risus, posuere in, sagittis ac, varius vel, tortor. Quisque id enim. Phasellus consequat, libero pretium nonummy fringilla, tortor lacus vestibulum nunc, ut rhoncus ligula neque id justo. Nullam accumsan euismod nunc. Proin vitae ipsum ac metus dictum tempus. Nam ut wisi. Quisque tortor felis, interdum ac, sodales a, semper a, sem. Curabitur in velit sit amet dui tristique sodales.

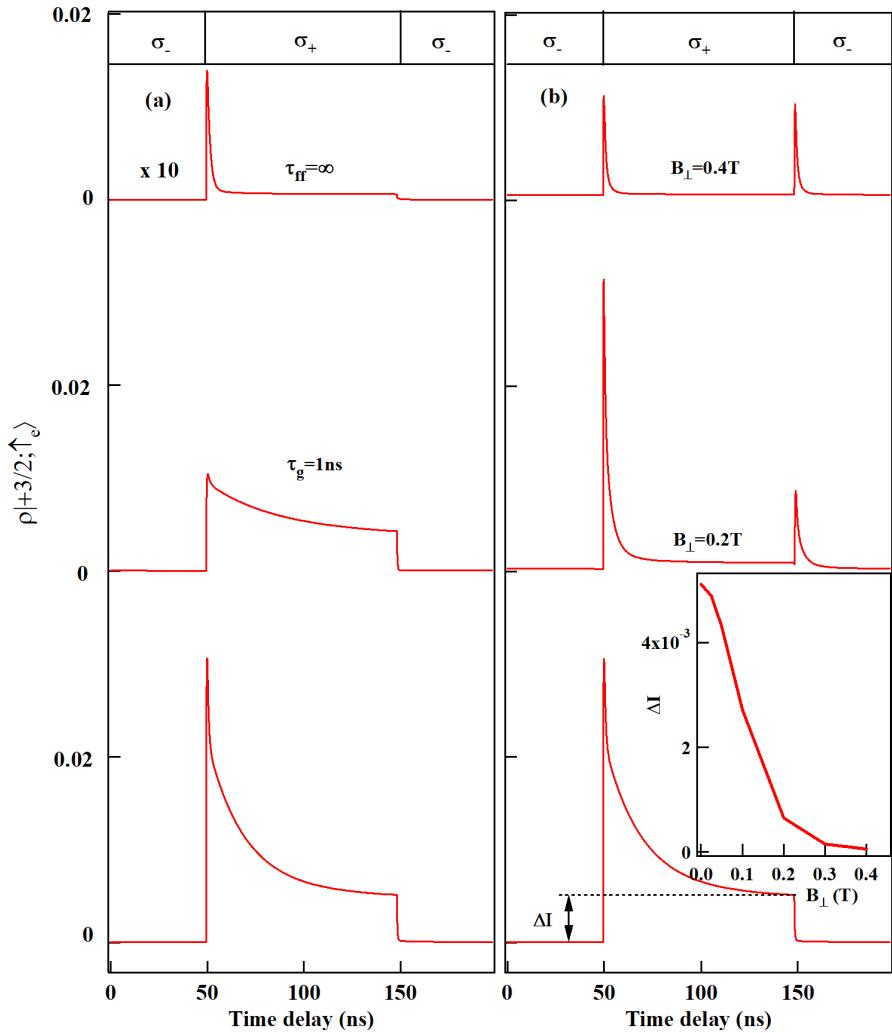


Figure I.13: Resonant optical pumping transients detected in  $\sigma-$  polarization under excitation with modulated circular polarization of  $|3,+2\rangle$  and  $|3,-2\rangle$  calculated with the QD parameters listed in Table I.1 and  $\tau_r=0.3\text{ns}$ ,  $\tau_{Mn}=5\ \mu\text{s}$ ,  $\tau_h=10\text{ns}$ ,  $T_2^{hMn}=5\ \text{ns}$ ,  $T_2^{eMn}=0.5\ \text{ns}$ ,  $\tau_{ff}=1.5\ \text{ns}$ ,  $T=10\text{K}$  and  $\tau_g=0.25\text{ns}$ . (a) Influence of a variation of  $\tau_g$  and  $\tau_{ff}$ . (b) Influence of a transverse magnetic field  $B_\perp$ . The inset presents the magnetic field dependence of the difference of population for a  $\sigma+$  or a  $\sigma-$  excitation.

Vivamus mauris pede, lacinia eget, pellentesque quis, scelerisque eu, est. Aliquam risus. Quisque bibendum pede eu dolor.

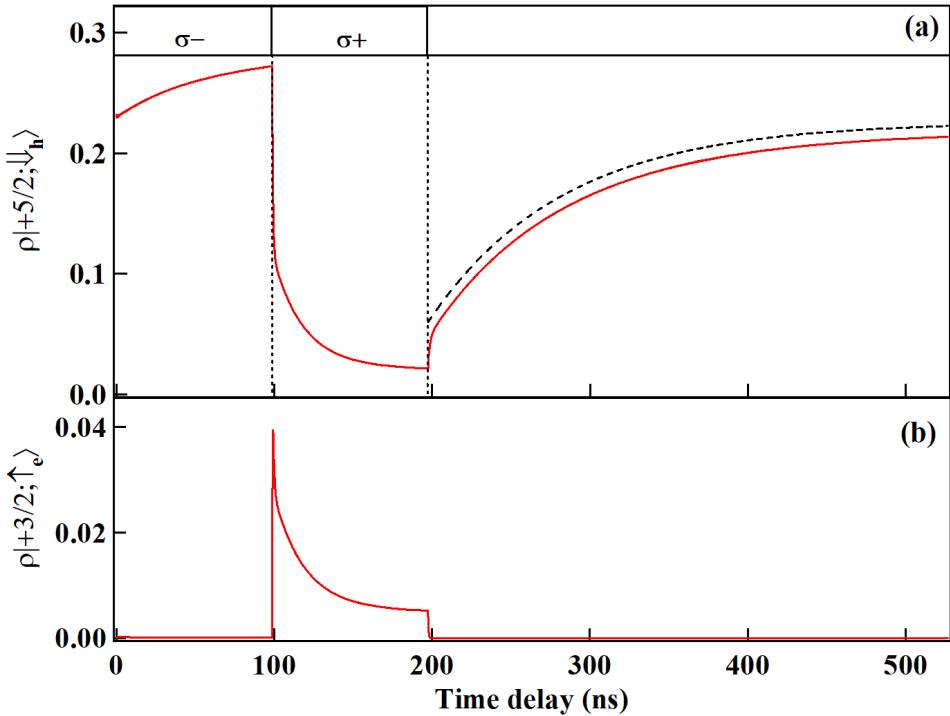


Figure I.14: (a) Calculated time evolution in the dark of the population of the hole-Mn state  $| + \frac{5}{2}, \downarrow_h \rangle$  initialized by a sequence of  $\sigma-$ / $\sigma+$  resonant excitation of  $| 3, -2 \rangle$  and  $| 3, +2 \rangle$ . The dashed black line (shifted for clarity) is an exponential fit with a characteristic time  $\tau_{\text{relax}}=85$  ns. (b) Corresponding calculated time evolution of the population  $| + \frac{3}{2}, \uparrow_e \rangle$ .

### I.3 Influence of the strain anisotropy

Fusce suscipit cursus sem. Vivamus risus mi, egestas ac, imperdiet varius, faucibus quis, leo. Aenean tincidunt. Donec suscipit. Cras id justo quis nibh scelerisque dignissim. Aliquam sagittis elementum dolor. Aenean consectetur justo in pede. Curabitur ullamcorper ligula nec orci. Aliquam purus turpis, aliquam id, ornare vitae, porttitor non, wisi. Maecenas luctus porta lorem. Donec vitae ligula eu ante pretium varius. Proin tortor metus, convallis et, hendrerit non, scelerisque in, urna. Cras quis libero eu ligula bibendum tempor. Vivamus tellus quam, malesuada eu, tempus sed, tempor sed, velit. Donec lacinia auctor libero.

Sed gravida lectus ut purus. Morbi laoreet magna. Pellentesque eu wisi. Proin turpis. Integer sollicitudin augue nec dui. Fusce lectus. Vivamus faucibus nulla nec lacus. Integer diam. Pellentesque sodales, enim feugiat cursus volutpat, sem mauris dignissim mauris, quis consequat sem est fermentum ligula. Nullam justo

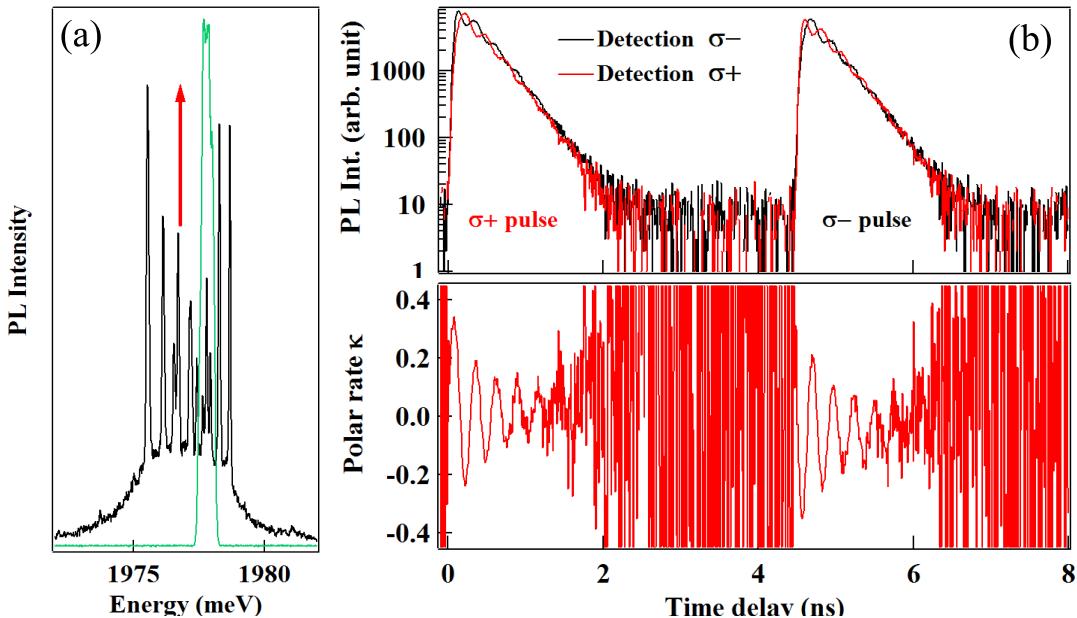


Figure I.15: (a) Configuration of the time resolved PL experiment for an excitation of  $|3, +1\rangle$  (pulsed laser in green). (b) Top panel: Time resolved resonant PL of  $|3, +1\rangle$  with a  $\sigma+/ \sigma-$  sequence of laser pulses and a detection in  $\sigma+$  and  $\sigma-$  polarization. Bottom panel: corresponding time dependence of the circular polarization rate  $\kappa = (\sigma_- - \sigma_+)/(\sigma_- + \sigma_+)$ .

lectus, condimentum sit amet, posuere a, fringilla mollis, felis. Morbi nulla nibh, pellentesque at, nonummy eu, sollicitudin nec, ipsum. Cras neque. Nunc augue. Nullam vitae quam id quam pulvinar blandit. Nunc sit amet orci. Aliquam erat elit, pharetra nec, aliquet a, gravida in, mi. Quisque urna enim, viverra quis, suscipit quis, tincidunt ut, sapien. Cras placerat consequat sem. Curabitur ac diam. Curabitur diam tortor, mollis et, viverra ac, tempus vel, metus.

Quisque consectetur. In suscipit mauris a dolor pellentesque consectetur. Mauris convallis neque non erat. In lacinia. Pellentesque leo eros, sagittis quis, fermentum quis, tincidunt ut, sapien. Maecenas sem. Curabitur eros odio, interdum eu, feugiat eu, porta ac, nisl. Curabitur nunc. Etiam fermentum convallis velit. Pellentesque laoreet lacus. Quisque sed elit. Nam quis tellus. Aliquam tellus arcu, adipiscing non, tincidunt eleifend, adipiscing quis, augue. Vivamus elementum placerat enim. Suspendisse ut tortor. Integer faucibus adipiscing felis. Aenean consectetur mattis lectus. Morbi malesuada faucibus dolor. Nam lacus. Etiam arcu libero, malesuada vitae, aliquam vitae, blandit tristique, nisl.

Maecenas accumsan dapibus sapien. Duis pretium iaculis arcu. Curabitur ut

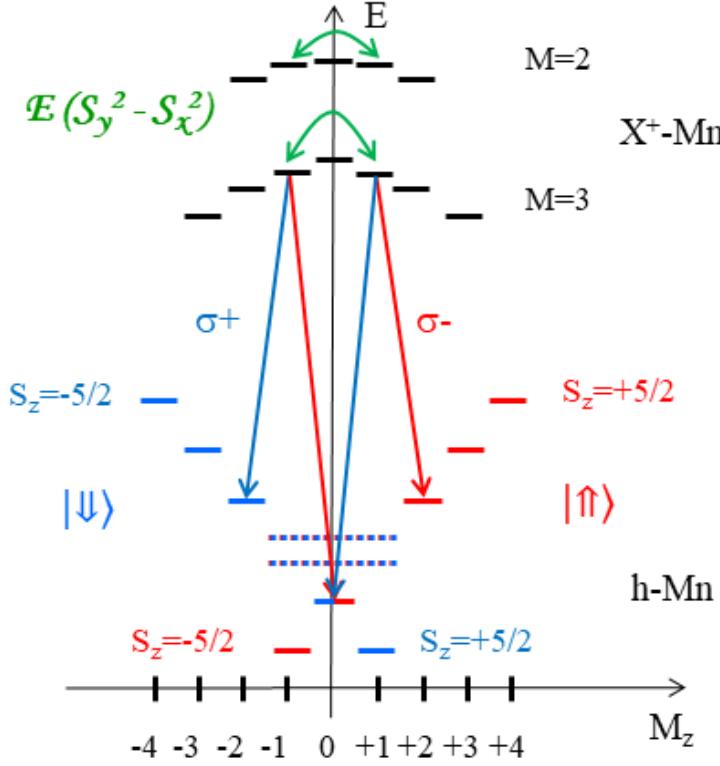


Figure I.16: Energy levels of the ground (h-Mn) and excited ( $X^+$ -Mn) states as a function of their angular momentum ( $M_z$ ). The e-Mn states  $|3, +1\rangle$  and  $|3, -1\rangle$ , as well as  $|2, +1\rangle$  and  $|2, -1\rangle$ , are coupled by the strain anisotropy  $E(S_y^2 - S_x^2)$ . Optical  $\Lambda$  systems associated with  $|3, +1\rangle$  and  $|3, -1\rangle$  are presented.

lacus. Aliquam vulputate. Suspendisse ut purus sed sem tempor rhoncus. Ut quam dui, fringilla at, dictum eget, ultricies quis, quam. Etiam sem est, pharetra non, vulputate in, pretium at, ipsum. Nunc semper sagittis orci. Sed scelerisque suscipit diam. Ut volutpat, dolor at ullamcorper tristique, eros purus mollis quam, sit amet ornare ante nunc et enim.

Phasellus fringilla, metus id feugiat consectetur, lacus wisi ultrices tellus, quis lobortis nibh lorem quis tortor. Donec egestas ornare nulla. Mauris mi tellus, porta faucibus, dictum vel, nonummy in, est. Aliquam erat volutpat. In tellus magna, porttitor lacinia, molestie vitae, pellentesque eu, justo. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Sed orci nibh, scelerisque sit amet, suscipit sed, placerat vel, diam. Vestibulum nonummy vulputate orci. Donec et velit ac arcu interdum semper. Morbi pede orci, cursus ac, elementum non, vehicula ut, lacus. Cras volutpat. Nam vel wisi quis libero

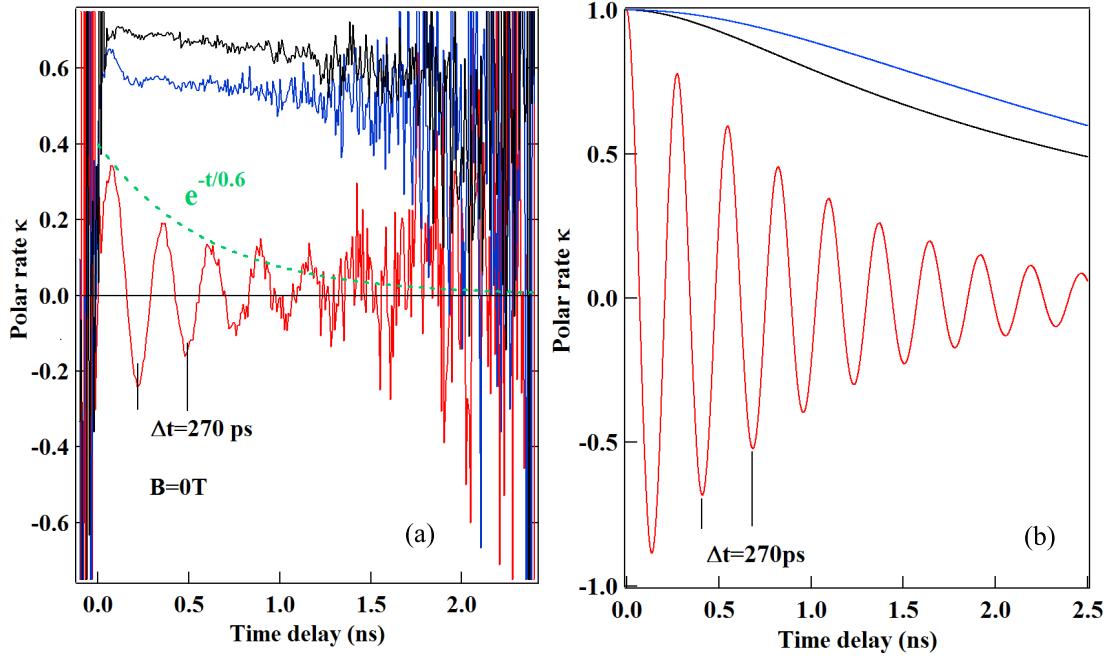


Figure I.17: (a) Time dependence of the circular polarization rate of the resonant PL of the states  $|3,+1\rangle$  (red),  $|3,+2\rangle$  (black) and  $|2,+2\rangle$  (blue). (b) Corresponding polarisation rates calculated with  $D_0 = 7\mu\text{eV}$  [2],  $T_2^{eMn} = 0.6\text{ns}$ ,  $E = 1.8\mu\text{eV}$ , a radiative lifetime  $T_r = 0.3\text{ns}$  and the parameters listed on Table I.1.

venenatis placerat. Aenean sed odio. Quisque posuere purus ac orci. Vivamus odio. Vivamus varius, nulla sit amet semper viverra, odio mauris consequat lacus, at vestibulum neque arcu eu tortor. Donec iaculis tincidunt tellus. Aliquam erat volutpat. Curabitur magna lorem, dignissim volutpat, viverra et, adipiscing nec, dolor. Praesent lacus mauris, dapibus vitae, sollicitudin sit amet, nonummy eget, ligula.

In hac habitasse platea dictumst. Proin at est. Curabitur tempus vulputate elit. Pellentesque sem. Praesent eu sapien. Duis elit magna, aliquet at, tempus sed, vehicula non, enim. Morbi viverra arcu nec purus. Vivamus fringilla, enim et commodo malesuada, tortor metus elementum ligula, nec aliquet est sapien ut lectus. Aliquam mi. Ut nec elit. Fusce euismod luctus tellus. Curabitur scelerisque. Nullam purus. Nam ultricies accumsan magna. Morbi pulvinar lorem sit amet ipsum. Donec ut justo vitae nibh mollis congue. Fusce quis diam. Praesent tempus eros ut quam.

Donec in nisl. Fusce vitae est. Vivamus ante ante, mattis laoreet, posuere eget, congue vel, nunc. Fusce sem. Nam vel orci eu eros viverra luctus. Pellentesque sit

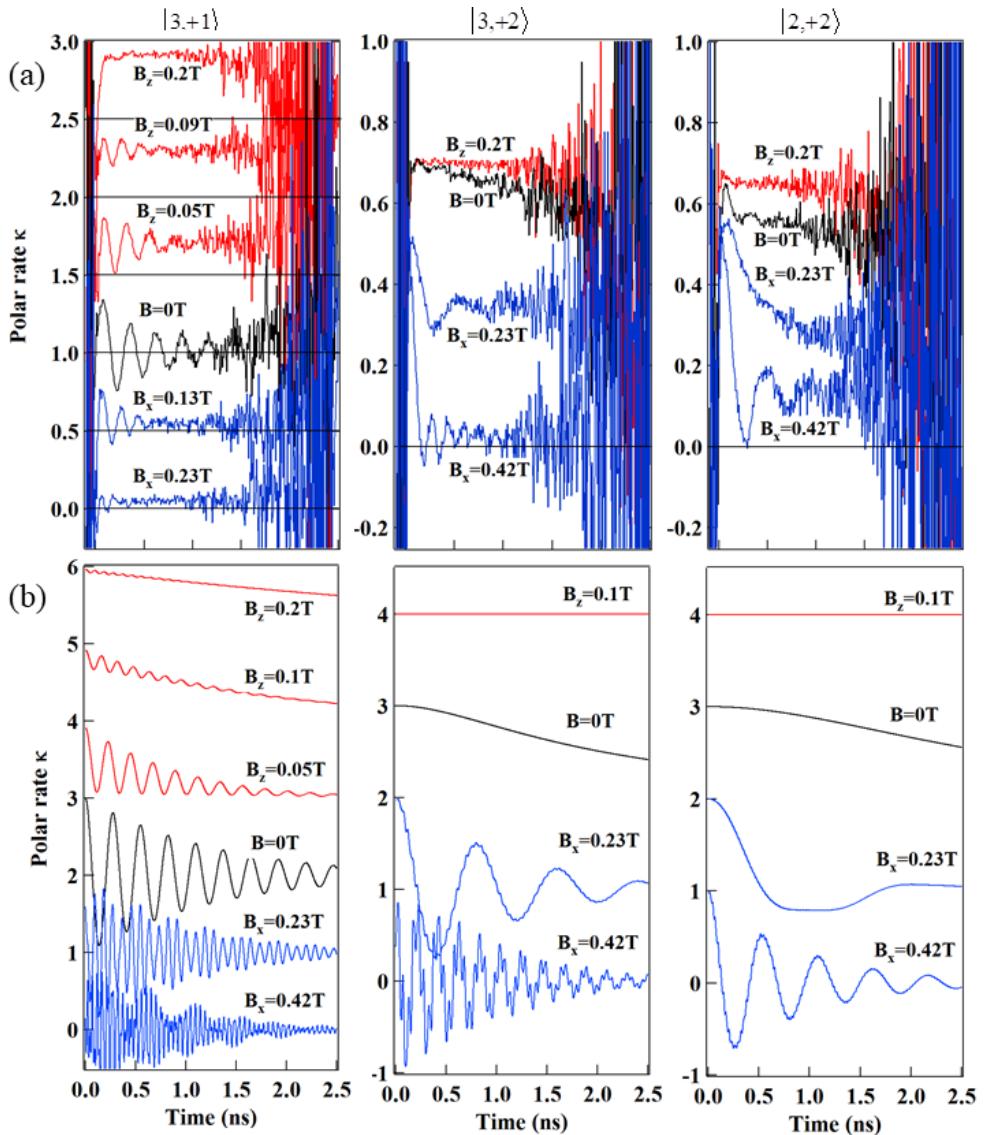


Figure I.18: (a) Influence of a longitudinal ( $B_z$ , red) and a transverse ( $B_x$ , blue) magnetic field on the time dependence of the circular polarization rate  $\kappa = (\sigma_- - \sigma_+)/(\sigma_- + \sigma_+)$  of the resonant PL of  $|3,+1\rangle$ ,  $|3,+2\rangle$  and  $|2,+2\rangle$ . On the top left panel, curves are shifted by 0.5 for clarity. (b) Corresponding time dependence of the circular polarization rate calculated with  $g_{Mn} = 2$ ,  $g_e = -0.4$ ,  $g_h = 0.6$  [2], and the parameters listed on Table I.1. The curves are shifted by 1 for clarity.

amet augue. Nunc sit amet ipsum et lacus varius nonummy. Integer rutrum sem eget wisi. Aenean eu sapien. Quisque ornare dignissim mi. Duis a urna vel risus

pharetra imperdierit. Suspendisse potenti.

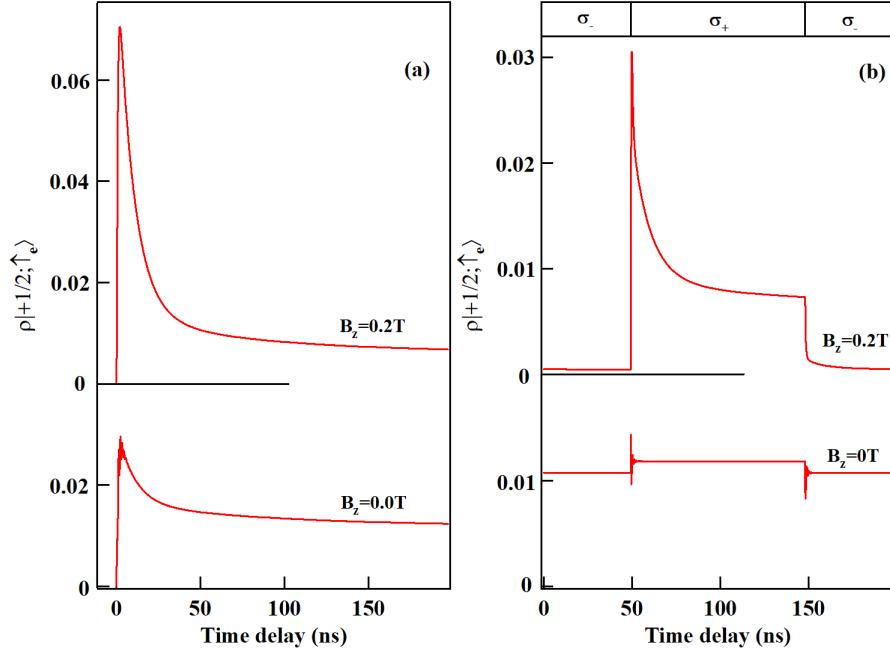


Figure I.19: (a) Calculated time evolution of  $\rho_{|+\frac{3}{2},+e}(t)$  for a resonant excitation of  $|3,+1\rangle$  and  $|3,-1\rangle$  with the QD parameters listed in Table I.1 without and with a longitudinal magnetic field. (b) Corresponding calculated optical pumping transients under excitation with modulated circular polarization.

Morbi justo. Aenean nec dolor. In hac habitasse platea dictumst. Proin non-ummy porttitor velit. Sed sit amet leo nec metus rhoncus varius. Cras ante. Vestibulum commodo sem tincidunt massa. Nam justo. Aenean luctus, felis et condimentum lacinia, lectus enim pulvinar purus, non porta velit nisl sed eros. Suspendisse consequat. Mauris a dui et tortor mattis pretium. Sed nulla metus, volutpat id, aliquam eget, ullamcorper ut, ipsum. Morbi eu nunc. Praesent pretium. Duis aliquam pulvinar ligula. Ut blandit egestas justo. Quisque posuere metus viverra pede.

# Bibliography

<sup>1</sup>S. Adachi, “Properties of group IV, II-V and II-VI semiconductors”, in, edited by Wiley (2005) Chap. 8, p. 178.

<sup>2</sup>B. Varghese, H. Boukari, and L. Besombes, “Dynamics of a Mn spin coupled to a single hole confined in a quantum dot”, [Phys. Rev. B 90, 115307 \(2014\)](#).