

Introduction

Constructing a quantum computer is one of the challenge of this century. The core component of this computer is the *qbit*, quantum bits. Instead of regular bits, that can take the states (values) $|0\rangle$ and $|1\rangle$, the *qbits*, being quantum devices, can also be in a superposition of states, $\alpha|0\rangle + \beta|1\rangle$. There is therefore a need of two level quantum systems that can be easily prepared and controlled, with a lifetime longer than the calculation time of the computer (a few tens of picoseconds).

One promising system is the quantum dots (QDs): small islands, with a characteristic size of a few nanometers, of semiconductor embedded in a semiconductor of wider gap. Carriers can be injected in the QD, were they are confined in three dimensions. This confinement leads to a quantization of the carriers energy, akin to the energy level of the electrons in an isolated atom. For this reason, they are dubbed "artificial atom". It has been shown that these structures can be used to control electrically or optically the spin of the injected carriers [1, 2]. The coherence time of the spin of the carriers in a quantum dot is of hundreds of picoseconds [3]. This can be enough for the calculation. However, it is too short for stocking information between two operations.

In order to get a longer coherence time, NV centers [3] or atomic spins directly inserted in the semiconductors [4] can be used. However, in those systems, the spins are harder to control than the spins of carriers in QDs.

Another approach arises from the Diluted Magnetic Semiconductors. It was shown that, in such materials, there was a strong interaction between the carriers and the magnetic atoms' spins. Inserting magnetic atoms in QD, it is possible to use this interaction to control their spins with the injected carriers. In this thesis, the reasoning goes to its limit, inserting a single magnetic atom in a QD, and controlling it optically. Such individual spins are promising for the implementation of emerging quantum information technologies in the solid state [5–8]. Magnetic dopants in conventional semiconductors present many desirable features, such as reproducible quantum properties, stability, and potential scalability for further applications [9]. Thanks to their point-like character, a longer spin coherence time (compared to carriers' spins) can also be expected at low temperature, making them potentially good systems to store quantum information.

Table 1: List of different possible transition metals and their key properties in the context of our study.

Inserted atom	V^{2+}	Cr^{2+}	Mn^{2+}	Fe^{2+}	Co^{2+}	Ni^{2+}	Cu^{2+}
d -shell	d^3	d^4	d^5	d^6	d^7	d^8	d^9
Electronic spin	$3/2$	2	$5/2$	2	$3/2$	1	$1/2$
Nuclear spin	$7/2$	0	$5/2$	0	$7/2$	0	$3/2$

The control of the spin state of individual [10–15] or pairs [16, 17] of magnetic atoms has been demonstrated. The spin of a magnetic atom in a QD can be prepared by the injection of spin polarized carriers and its state can be read through the energy and polarization of the photons emitted by the QD [18–20]. The insertion of a magnetic atom in a QD where the strain or the charge states can be controlled also offers degrees of freedom to tune the properties of the localized spin such as its magnetic anisotropy responsible for the spin memory at zero magnetic field [21].

Tab. 1 lists the different magnetic atoms that can be inserted in a semiconductor lattice. Each of those atoms has a unique set of electronic spin, nuclear spin and orbital momentum. Those properties changes the behaviour of the magnetic atom inserted in the semiconductor matrix, and it is therefore interesting to have a large choice. Mn was the first atom to be successfully inserted and optically probed in CdTe/ZnTe QDs, in 2004 [10]. Since then, several other magnetic atoms have been embedded in II-VI QDs and studied: Co (2014) [22] and Fe (2016) [23].

In this thesis, I propose to study two systems that are promising for the realization of spin *qbit* coupled to strains: the hole-Mn hybrid spin and the spin of a Cr atom in a QD. Growth of the Mn-doped QDs were grown in Grenoble, in the INAC-CNRS joined team NPSC, by Hervé Boukari. The Cr-doped QDs were grown in Tsukuba, in the team of Pr. Shinji Kuroda, by Hayato Ustumi, Masahiro Sunaga and myself. I studied the dots in Grenoble, with the help of Lucien Besombes.

This thesis is organized as follows:

Chapter I I present in this chapter the system we will study as well as the main theoretical tools one needs to understand it. It presents the main theory we need to describe the semiconductor matrix and the quantum dot. We then propose a model for the interaction between the carrier and the magnetic, and apply it to the Mn and the Cr. Finally, we look at how the semiconductor matrix modify the Mn and Cr spin structure.

Chapter II I discuss in this chapter the growth of the quantum dots. Donec a nibh ut elit vestibulum tristique. Integer at pede. Cras volutpat varius

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Bibliography

- ¹A. Greilich, D. R. Yakovlev, A. Shabaev, A. L. Efros, I. A. Yugova, R. Oulton, V. Stavarache, D. Reuter, A. Wieck, and M. Bayer, “Mode locking of electron spin coherences in singly charged quantum dots”, [Science 313, 341–345 \(2006\)](#).
- ²D. Press, T. D. Ladd, B. Zhang, and Y. Yamamoto, “Complete quantum control of a single quantum dot spin using ultrafast optical pulses”, [Nature 456 \(2008\)](#).
- ³G. D. Fuchs, G. Burkard, P. V. Klimov, and D. D. Awschalom, “A quantum memory intrinsic to single nitrogen–vacancy centres in diamond”, [Nature Physics 7 \(2011\)](#).
- ⁴M. Pierre, R. Wacquez, X. Jehl, M. Sanquer, M. Vinet, and O. Cueto, “Single-donor ionization energies in a nanoscale cmos channel”, [Nature Nanotechnology 5 \(2009\)](#).
- ⁵J. R. Petta, A. C. Johnson, J. M. Taylor, E. A. Laird, A. Yacoby, M. D. Lukin, C. M. Marcus, M. P. Hanson, and A. C. Gossard, “Coherent manipulation of coupled electron spins in semiconductor quantum dots”, [Science 309, 2180–2184 \(2005\)](#).
- ⁶M. Veldhorst, C. H. Yang, J. C. C. Hwang, W. Huang, J. P. Dehollain, J. T. Muhonen, S. Simmons, A. Laucht, F. E. Hudson, K. M. Itoh, A. Morello, and A. S. Dzurak, “A two-qubit logic gate in silicon”, [Nature 526 \(2015\)](#).
- ⁷K. Saeedi, S. Simmons, J. Z. Salvail, P. Dluhy, H. Riemann, N. V. Abrosimov, P. Becker, H.-J. Pohl, J. J. L. Morton, and M. L. W. Thewalt, “Room-temperature quantum bit storage exceeding 39 minutes using ionized donors in silicon-28”, [Science 342, 830–833 \(2013\)](#).
- ⁸N. Bar-Gill, L. Pham, A. Jarmola, D. Budker, and R. Walsworth, “Solid-state electronic spin coherence time approaching one second”, [Nature Communications 4 \(2013\)](#).
- ⁹P. M. Koenraad and M. E. Flatte, “Single dopants in semiconductors”, [Nature Materials 10 \(2011\)](#).

- ¹⁰L. Besombes, Y. Léger, L. Maingault, D. Ferrand, H. Mariette, and J. Cibert, “Probing the spin state of a single magnetic ion in an individual quantum dot”, *Phys. Rev. Lett.* **93**, 207403 (2004).
- ¹¹C. Le Gall, A. Brunetti, H. Boukari, and L. Besombes, “Optical stark effect and dressed exciton states in a Mn-doped CdTe quantum dot”, *Phys. Rev. Lett.* **107**, 057401 (2011).
- ¹²A. Kudelski, A. Lemaître, A. Miard, P. Voisin, T. C. M. Graham, R. J. Warburton, and O. Krebs, “Optically probing the fine structure of a single mn atom in an inas quantum dot”, *Phys. Rev. Lett.* **99**, 247209 (2007).
- ¹³O. Krebs, E. Benjamin, and A. Lemaître, “Magnetic anisotropy of singly mn-doped inas/gaas quantum dots”, *Phys. Rev. B* **80**, 165315 (2009).
- ¹⁴E. Baudin, E. Benjamin, A. Lemaître, and O. Krebs, “Optical pumping and a nondestructive readout of a single magnetic impurity spin in an InAs/GaAs quantum dot”, *Phys. Rev. Lett.* **107**, 197402 (2011).
- ¹⁵J. Kobak, T. Smolenski, M. Goryca, M. Papaj, K. Gietka, A. Bogucki, M. Koperski, J.-G. Rousset, J. Suffczynski, E. Janik, M. Nawrocki, A. Golnik, P. Kossacki, and W. Pacuski, “Designing quantum dots for solotronics”, *Nature Communications* **5**, 3191 (2014).
- ¹⁶L. Besombes, C. L. Cao, S. Jamet, H. Boukari, and J. Fernández-Rossier, “Optical control of the spin state of two Mn atoms in a quantum dot”, *Phys. Rev. B* **86**, 165306 (2012).
- ¹⁷O. Krebs and A. Lemaître, “Optically induced coupling of two magnetic dopant spins by a photoexcited hole in a mn-doped InAs/GaAs quantum dot”, *Phys. Rev. Lett.* **111**, 187401 (2013).
- ¹⁸L. Besombes, H. Boukari, C. L. Gall, B. Brunetti, C. Cao, S. Jamet, and B. Varghese, “Optical control of the spin of a magnetic atom in a semiconductor quantum dot”, *Nanophotonics* **4**, 75 (2015).
- ¹⁹D. E. Reiter, V. M. Axt, and T. Kuhn, “Optical signals of spin switching using the optical stark effect in a mn-doped quantum dot”, *Phys. Rev. B* **87**, 115430 (2013).
- ²⁰M. Goryca, T. Kazimierczuk, M. Nawrocki, A. Golnik, J. A. Gaj, P. Kossacki, P. Wojnar, and G. Karczewski, “Optical manipulation of a single Mn spin in a CdTe-based quantum dot”, *Phys. Rev. Lett.* **103**, 087401 (2009).
- ²¹J. C. Oberg, M. Reyes Calvo, F. Delgado, M. Moro-Lagares, D. Serrate, D. Jacob, J. Fernandez-Rossier, and C. F. Hirjibehedin, “Control of single-spin magnetic anisotropy by exchange coupling”, *Nature Nanotechnology* **9** (2013).

²²J. Kobak, T. Smoleński, M. Goryca, M. Papaj, K. Gietka, A. Bogucki, M. Koperski, J.-G. Rousset, J. Suffczyński, E. Janik, M. Nawrocki, A. Golnik, P. Kossacki, and W. Pacuski, “Designing quantum dots for solotronics”, *Nat. Comm.* **5**, 3191 (2014).

²³T. Smoleński, T. Kazimierczuk, J. Kobak, M. Goryca, A. Golnik, P. Kossacki, and W. Pacuski, “Magnetic ground state of an individual Fe²⁺ ion in strained semiconductor nanostructure”, *Nat. Comm.* **7**, 10484 (2016).