Nitrogen-vacancy center in diamond as a true gift of nature

Mikhail Shalaginov
ECE 695 Quantum Optics and Photonics

1. Introduction

It is well-known that current technologies based on electronics are reaching their limits and scientists are looking for new breakthrough solutions that can greatly advance computing machines. Two of the promising solutions are photonic [1] and quantum computing [2]. Photonic elements can work faster and consume less power in comparison to their electronic counterparts. Quantum nature of computation provides with such unique phenomenon as entanglement which allows information teleportation [3]. Moreover, quantum algorithms based on quantum bits (qubits) can solve problems much faster than traditional computational methods [4]. In addition, the information encrypted in qubits can be safeguarded with the highest available level of security [5].

2. Quantum computing and quantum networking

One of the key problems in quantum computing technologies to be solved is physical realization of quantum bits. Figure 1 shows variety of the implementation approaches, such as superconducting circuits, semiconductor structures, Majorana fermions, color centers in solids, and trapped-ion systems.

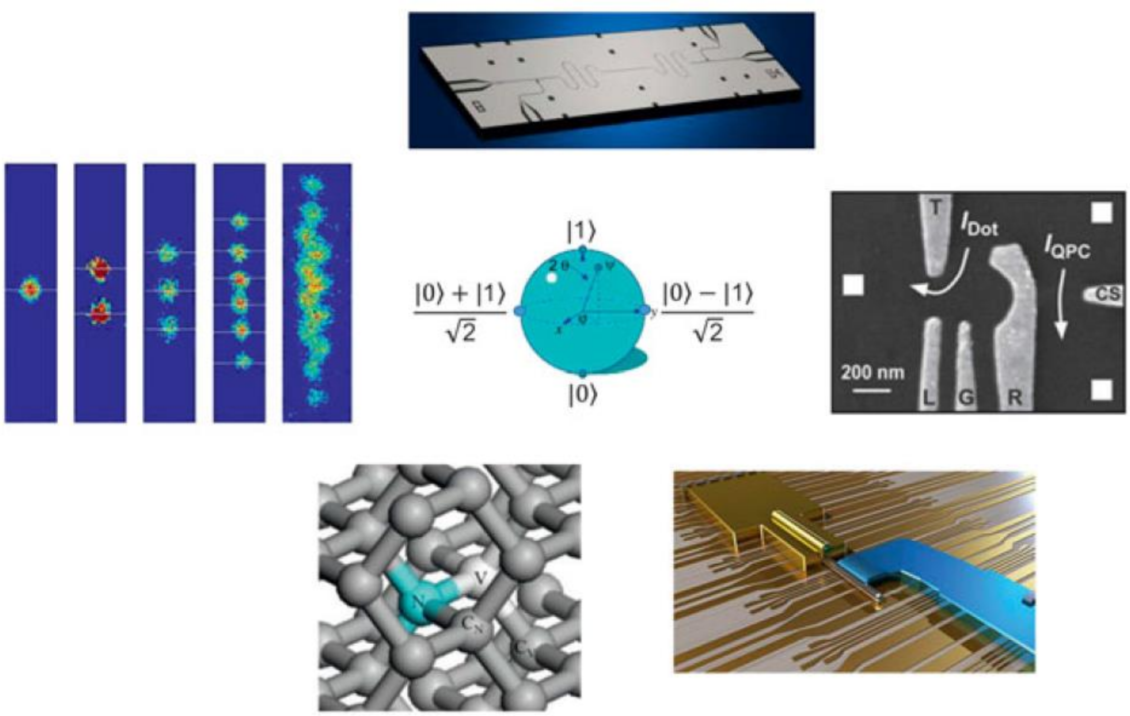

Fig. 1. Physical implementations of a quantum bit [6]. Clockwise from the top: superconducting circuits based on Josephson junctions, semiconductor gate-defined spin structures, Majorana fermions in semiconductor/superconductor nanowire hybrid materials, color centers in crystals, and trapped-ion systems.

Regarding quantum networking, decent carriers of quantum information could be single photons. However, to create these single photons is a big challenge. One of the ways to do is to use a pulsed stabilized laser. Basically, the intensity of the pulse corresponds to number of photons, by attenuation one can achieve on average one photon per pulse. But still, any laser produces a Poisson distribution of photons, and there is some non-zero probability that several photons can be emitted at the same time, which means that they are no longer single or antibunched. This fact does not satisfy requirements of quantum cryptography, dealing with single photons. More fundamental approach is to consider atomic structures that are isolated and emit one photon at the same time. Figure 2 shows the examples of microscopic single-photon sources, such as: trapped ions of barium, single organic dye molecules embedded in crystals, quantum dots and color centers in solids [7]. All the mentioned sources have their strengths and weaknesses. However, our matter of choice is nitrogen-vacancy (NV) center in diamond.

The NV center consists of a vacancy, or missing carbon atom, in the diamond lattice lying next to nitrogen atom, which substituted one of the carbon atoms. It can be formed naturally during diamond growth or artificially using a variety of implantation and annealing techniques.

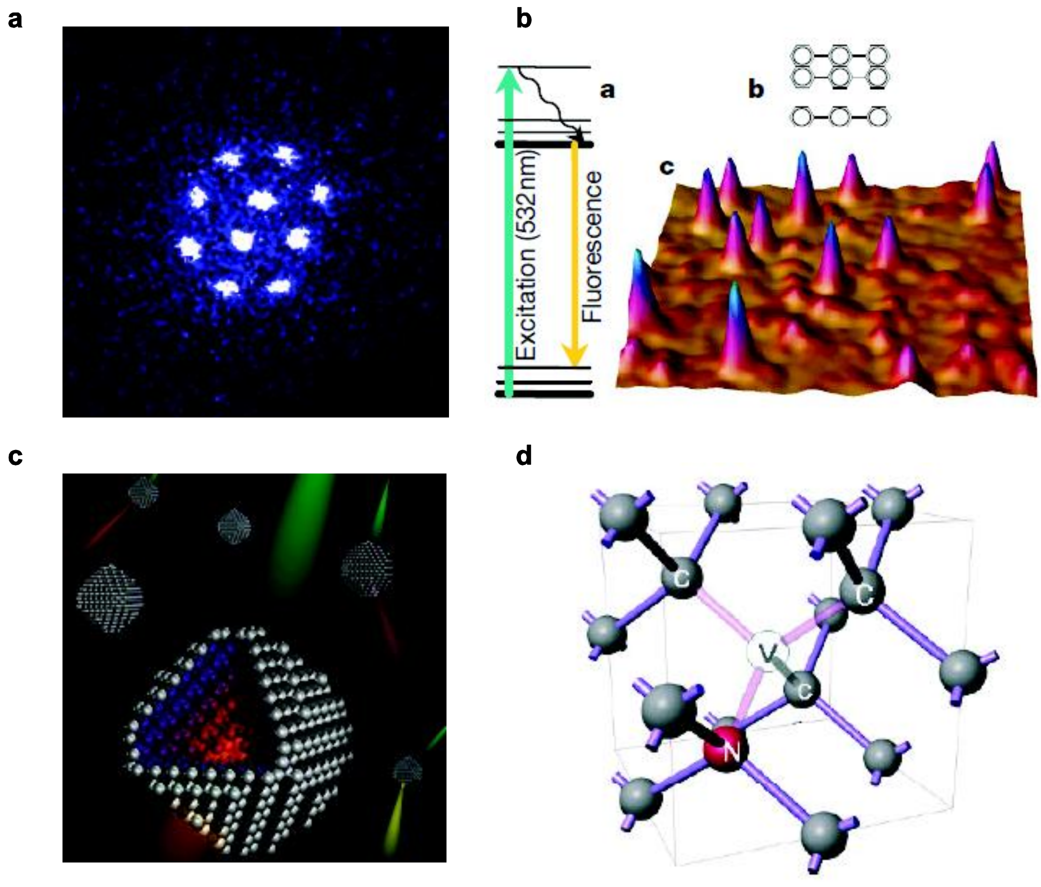

Fig. 2. Available microscopic single-photon sources [7]: (a) trapped atoms/ions, (b) single molecules embedded in a crystal, (c) CdSe/ZnSe quantum dots, (d) color centers in solids.

3. Historical facts about NV centers research

Fig. 3. Left: schematic of the nitrogen-vacancy (NV) center embedded in diamond lattice. Right: Jorg Wrachtrup is the head of the research team that has, for the first time, detected the optical signal of a single defect center.

NV centers have a long history of study which started about fifty years ago. In 1970s, the microscopic model and most optical properties of ensembles of the NV centers were well established. Research tools of that time were mostly based on optical measurements combined with uniaxial stress [8] and on the electron paramagnetic resonance [9]. In 1997 appeared the work by Dr. Wrachtrup et al [10] which sparked the tremendous research interest in NV centers as potentially important system for emergent quantum technologies. In that paper, the authors demonstrated that at room temperature NV centers produce perfectly photostable emission that can be detected by fluorescence microscopy. In addition, it was shown that NV centers exhibit optically detected magnetic resonance (ODMR). Nowadays, this research direction still remains very active.

4. Electronic structure and emission spectrum

The simplified electronic structure (see Fig. 4, left panel) of an NV center consists of a spin-triplet ground and excited state $^3A_2$ and ^3E and metastable spin singlet state $^1A_1$. Due to lattice strain, the ground state $^3A_2$ has the spin-triplet structure with approximately 2.87 GHz splitting between the m_s= 0 and ±1 spin sublevels. The excited state also has a fine structure with zero field splitting of 1.42 GHz similar to the ground state at room temperature.

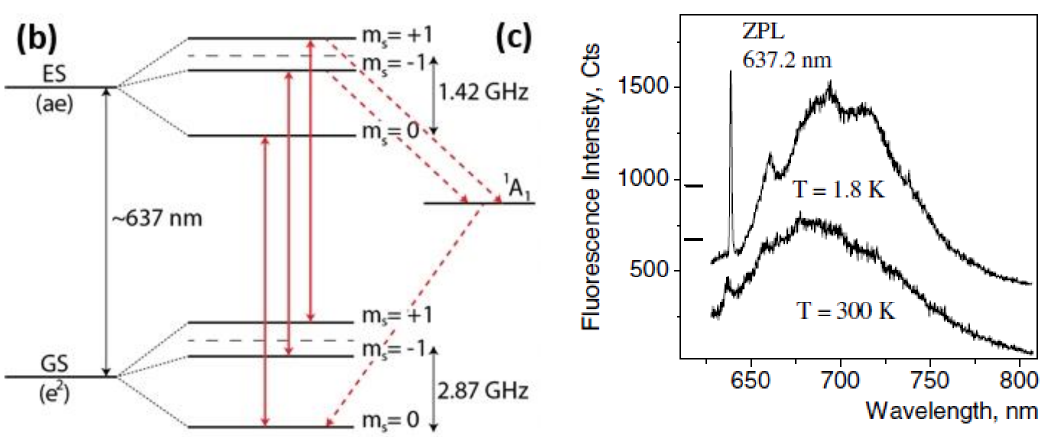

Fig. 4: Left: simplified electronic structure of NV center (courtesy of Jason Petta's group). Right: Photoluminescence spectrum of NV center at 300 K and 1.8 K [11].

5. Properties

Properties of the NV center that make it an ideal component of quantum networking applications are the single photon emission characteristics. It has also been observed that NV centers are photostable in that they do not photobleach despite several hours of usage. This property of negligible photobleaching helps NV centers to be used as a robust material for several quantum and biological sensing applications. Also, the negligible non-radiative relaxation from the excited state to ground state gives rise to the excellent single photon nature of NV centers.

The emission spectrum of NV center is broad and consists of zero-phonon line (ZPL) and phonon sideband. Fig. 4 (right panel) shows the photoluminescence spectrum of the center with a ZPL at 637 nm and a characteristic broad phonon side band extending from 650nm to 800 nm [11].

In addition, the NV center has been explored for several magneto-optical properties. The optical spin-polarization of the center's ground state is one of its most remarkable properties. The mechanism responsible for the single spin-readout property originates from the fact that the fluorescence from the $m_s = \pm 1$ states is significantly lower than the fluorescence of the $m_s = 0$ state. Optical excitation can polarize the electron into the $m_s = 0$ state, from there it can be coherently driven between the ms = 0 and ±1 states, using microwaves. It has also been observed that the NV center can be addressed optically and can exhibit electron spin coherence lifetimes of more than 1 ms at room temperature [12].

6. Conclusion

This essay covers brief information about nitrogen-vacancy (NV) center as a unique system to find potential applications in emerging quantum information technologies. In particular, the main advantage of NV centers as single-photon sources is the ability to generate stable, broadband, and anti-bunched emission at room temperature . Also importantly, NV-center can serve as a as a key component in a spin-based qubit, which is able to store quantum information for a significant amount of time and be read out optically. The efficiency of the NV center both as a single-photon generator and an element of a qubit is directly related to its emission rate, which can be engineered by various structures including hyperbolic metamaterials.

References

1. A. D. McAulay, *Optical Computer Architectures: The Application of Optical Concepts to Next Generation Computers* (Wiley-Interscience, 1991).

2. A. Steane, "Quantum computing," Reports Prog. Phys. **61**, 117–173 (1998).

3. S. Takeda, T. Mizuta, M. Fuwa, P. van Loock, and A. Furusawa, "Deterministic quantum teleportation of photonic quantum bits by a hybrid technique.," Nature **500**, 315–8 (2013).

4. D. Deutsch and R. Jozsa, "Rapid solution of problems by quantum computation.," Proc. R. Soc. London. Ser. A Math. Phys. Sci. **439**, 553–558 (1992).

5. N. Gisin, G. Ribordy, and H. Zbinden, "Quantum cryptography," arXiv Prepr. quant-ph/0101098 (2001).

6. J. N. Eckstein and J. Levy, "Materials issues for quantum computation," MRS Bull. **38**, 783–789 (2013).

7. B. Lounis and M. Orrit, "Single-photon sources," Reports Prog. Phys. **68**, 1129–1179 (2005).

8. G. Davies and M. F. Hamer, "Optical studies of the 1.945 eV vibronic band in diamond.," Proc. R. Soc. London. A. Math. Phys. Sci. **348**, 285–298 (1976).

9. H. Search, C. Journals, A. Contact, M. Iopscience, and I. P. Address, "Electron spin resonance in the study of diamond," **1201**, (n.d.).

10. a. Gruber, "Scanning Confocal Optical Microscopy and Magnetic Resonance on Single Defect Centers," Science (80-.). **276**, 2012–2014 (1997).

11. F. Jelezko and J. Wrachtrup, "Single defect centres in diamond: A review," Phys. Status Solidi **203**, 3207–3225 (2006).

12. G. Balasubramanian, P. Neumann, D. Twitchen, M. Markham, R. Kolesov, N. Mizuochi, J. Isoya, J. Achard, J. Beck, J. Tissler, V. Jacques, P. R. Hemmer, F. Jelezko, and J. Wrachtrup, "Ultralong spin coherence time in isotopically engineered diamond.," Nat. Mater. **8**, 383–7 (2009).