Executive Summary

Title: Nitrogen-Vacancy Centers in Diamond – Production by Ion Implantation and Spin Manipulation

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Introduction

Nitrogen-Vacancy centers (NV) in diamond show very interesting properties, which has to lead to their extensive study by many research groups in the recent years. The NV has strong optical transition from its triplet ground state, allowing the detection of single centers even at room temperature (RT). Moreover, the electron and nuclear spin of a single NV can be detected and manipulated (F. Jelezko et al. *Phys. Rev. Lett.* **2004**, 92, 0976401; F. Jelezko et al. *Phys. Rev. Lett.* **2004**, 93, 130501), thus making them ideal candidates for solid state quantum bits as well as for ultra low magnetic field sensors (G. Balasubramanian et al. *Nature*, **2008**, 455, 648; J.R. Maze et al. *Nature*, **2008**, 455, 644). These proof-of-principle experiments were performed on NVs create during the growth of the diamond crystal. For their future implementation in real devices, it is of crucial importance to find a way how to produce and position these centers on demand.

The progress of selected topics over the past five years including your results

J. Meijer et al. found a way how to produce single NVs by implanting low dose of nitrogen ions in diamond (J. Meijer et al. *Appl. Phys. Lett.* **2005**, 87, 261909) and subsequently anneal the sample in vacuum. Later, Rabeau et al. (J.R. Rabeau t al. *Appl. Phys. Lett.* **2006**, 88, 023113) used ^{15}N (natural abundance 0.4 %, nuclear spin I = 1/2) ions for the NV production, since they induce different hyperfine splitting as compared to ^{14}N (I = 1) in the optically detected magnetic resonance spectrum. This method allows unambiguously to distinguish between the implanted NVs and NVs already present in the diamond. Using this procedure Gaebel et al. (T. Gaebel et al. *Nat. Phys.* **2006**, 2, 408) managed to couple a single NV to an interstitial nitrogen atom in its proximity, demonstrating coherent coupling of single spins at RT. The next step towards the NV based quantum computer was to couple two artificially produced single NVs, which was realized by Neumann et al. (P. Neumann et al. *Nat. Phys.* **2010**, 6, 249) using focused nitrogen ion beam. The distance between the NV centers in one pair was about 10 nm, resulting in a coherent coupling of about 40 kHz. Surprisingly, the electron spin coherence time T_2 of these NVs was much shorter ($T_2^{NVA} \approx 110$ μs and $T_2^{NVB} \approx 2$ μs) compared to "natural" NVs ($T_2 \sim 1$ ms). This fact can be explained by the presence of various paramagnetic defects around the implanted NV, which induce decoherence. One way to extend the T_2 of an electron spin surrounded by a spin bath would be to use dynamical decoupling techniques. There have been several reports based on this approach. Naydenov et al. (Naydenov et al. *arXiv* **2010**, 1008.1953v1) used the Carr-Purcell-Meiboom-Gill (CPMG) pulse sequence to increase the T_2 up to the limit posed by the thermal relaxation and demonstrated the detection of low magnetic fields using this method. Similar results have been reported by C. A. Ryan et al. (C. A. Ryan et al. *arXiv* **2010**, 1008.2197v2) and G. de Lange et al. (G. de Lange et al. *Science* **2010**, 330, 60) where they used not only CPMG, but also Uhrig Dynamical Decoupling (UDD) and XY pulse sequences in order to

prolong the coherence time of NV.

An important issue of the NV production is their yield (the ratio of implanted nitrogen ions to the observed single NVs) which varies from 1% - 50 % depending on the ion energy (S. Pezzagna et al. *New J. Phys.* **2010**, 12, 065017). It is very important for all practical applications to have yield as close to 100 % as possible otherwise the device fabrication would be very difficult. Naydenov et al. (Naydenov et al. *Appl. Phys. Lett.* **2010**, 96, 163108) introduced a new method for increasing the yield of implanted NVs by creating additional vacancies using subsequent carbon ion implantation.

Potential application opportunities, if possible (What is the potential impact on ITRS?)

NV can be used as a stable single photon source (R. Brouri et al. *Optics Express*, **2000**, 25, 1294) and there are already commercial devices available on the market. L. Childess et al. (L. Childress et al. *Phys. Rev. Lett.* **2006**, 65, 070504) proposed to use NVs as quantum repeaters for a long distance quantum communication protocol and the first experiments towards this goal have been recently demonstrated (see E. Togan et al. *Nature* **2010**, 466, 730). Another possible candidate for a single photon source emitting in the blue spectral region is the TR12 defect center in diamond, which can be also produced by ion implantation (Naydenov et al. *Appl. Phys. Lett.*, **2009**, 95, 181109). Nano-sized diamonds (ND) containing NVs are very good sensors for ultra low magnetic fields, however their practical application is still limited and more research is required.

The difficult challenges and potential solutions for the next 10 – 15 years

The main challenge in the next years would be to increase the yield of NV production up to 100 %. This could be overcome by two (or more) implanting steps. Another problem is that the small NDs (< 10 nm) usually do not contain NV centers. For the application of ND as magnetic sensors and biological marker, it is necessary create NVs in this small ND, which is not an easy task. Nitrogen ion implantation at low energy (< 1 keV) would possibly solve this problem.

Deterministic ion implantation is the next big challenge on the way to a solid state quantum computer based on NV. Recently W. Schnitzler et al. (W. Schnitzler et al. *Phys. Rev. Lett.* **2009**, 102, 070501) demonstrated a new method for single ion implantation which approaches the Heisenberg limit.

Experts and expertise with references

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