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Engineering platform for electric readout of NV spin center in diamond for magnetic field detection

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Abstract

Sensing devices used in (aero)space are constrained by energy consumption, mass, volume and environmental compatibility. Although quantum sensors offer potentially better sensitivity than classical sensors, they are bulky and often require cooling to cryogenic temperatures or operation in vacuum. Here we propose a technical realization of a quantum sensor for magnetic field detection based on nitrogen-vacancy (NV) centers in diamond, which is compatible with miniaturization and offers potential sub-picotesla sensitivity. The miniaturization is based on recently developed electric readout of the NV center electron spin resonance. Our engineering platform allows to use diamond chip as a portable magnetic field sensor. We have designed and tested a miniaturized prototype and describe all key components for technical miniaturization. We achieved a power consumption down to 3.5 W, a weight of the fully integrated sensor of only 27g and small dimensions of 45 x 25 x 25 mm including all driving and readout components. We have proved the chip functionality in vacuum and explored its thermal behavior. The system will be further used for on-board stratospheric balloon experiment. The miniaturized sensor we developed has potential applications in a wide range of fields including navigation, bio-signal measurement, material analysis or space weather monitoring and planetary observation.

Keywords: Diamond, NV centers, magnetometry, quantum sensing, Photocurrent Detection of Magnetic Resonance, miniaturization

1. Introduction

Space industry imposes strict criteria for “on-board” measurement devices in terms of energy consumption, mass, volume, environmental compatibility, etc. The main advantages of sensors operating on basis of quantum principles is their higher sensitivity and spatial resolution in comparison to classical sensors, which are fundamentally limited. However, the most quantum sensors are bulky or require cryogenic temperatures [1, 2] and are difficult to miniaturize. One of the promising candidates to solve this issue is the nitrogen-vacancy (NV) center [3]. NV is a point defect found in diamond and it has been shown that NV centers can serve as highly sensitive quantum magnetic field sensors [4,5,6]. The key advantages of NV magnetometers are wide operating temperature range (from low temperature to above room temperature), temporal stability, sensitivity to magnetic fields in picotesla range and the possibility to perform vector magnetometry [4,5,6]. The biggest obstacles for translating the NV potential into functional miniaturized magnetometer are the efficiency of methods classically used for the readout of NV spin ensembles and its integration with peripheral electronics. The commonly used readout technique, called optical detection of magnetic resonance (ODMR), is based on photon detection [4,5,6]. This method requires rather complex optics to efficiently collect photons and its implementation for miniaturized devices is challenging.

Recently, a novel detection method based on photoelectric readout of magnetic resonance (PDMR) of NV centers has been proposed [7]. The PDMR method uses electrodes fabricated on the diamond surface to collect the electrons generated by NV ionization. The collection efficiency surpasses the optical detection [7] and moreover, PDMR provides possibility of a direct electrical spin readout. Therefore, there is no more need for photon collection optics and the whole miniaturization process is greatly simplified. In this work we have developed a miniaturized system with all the key components for successful PDMR measurement integrated on the chip.

We believe that our miniaturized sensors have future potential for interesting and innovative applications as illustrated in Figure 1. For example, a compact diamond sensor is of interest for navigation, material analysis, biomedical, space weather and space exploration applications.

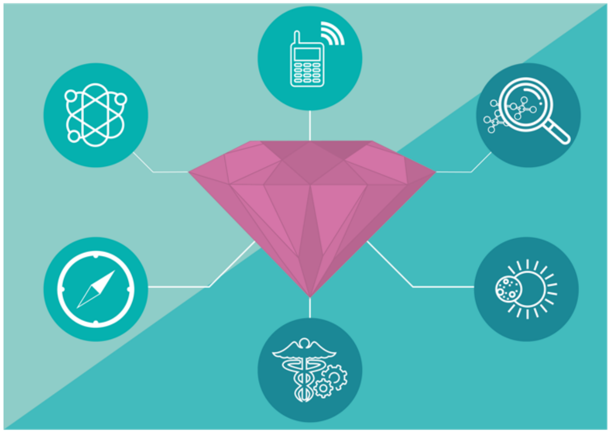

Fig. 1. Electron spin detection of NV centers in diamond has wide application potential in the field of magnetic sensing due to its sensitivity and fast response. The applications can range from navigation, material analysis and biomedical technologies to space weather, communication and quantum computing.

Our device will be used as a magnetic field sensor on board of a stratospheric balloon in the framework of REXUS/BEXUS (Rocket Experiment for University Students / Balloon Experiment for University Students) [8] programe. The device was developed in course of OSCAR-QLITE project, aiming to demonstrate miniaturization possibilities of PDMR NV magnetometry and its use for measurement of magnetic field in stratosphere. Resulting device was tested in laboratory-simulated stratospheric conditions to ensure the environmental compatibility (low pressure, varying temperature, vibrations).

2. Operational Principle

Nitrogen-vacancy (NV) center is a point defect located in the diamond crystalline lattice and it consists out of a nitrogen atom and an adjacent vacancy. There are three different charge states of NV centers (NV^+, NV^0, NV^-). The electronic structure of the negatively charged NV center, NV^-, consists out of four paired and two unpaired electrons. It has thus a triplet ground state (with spin sublevels $m_s = 0$ and ±1) and a well-defined electron spin resonance (ESR) [3,4,5,6]. When illuminated with a green laser (around 532 nm), an electron is promoted from the ground state to the excited state. The relaxation of the excited electron back to the ground state happens through radiative decay, inducing emission of red photons (637 - 750 nm). The photoluminescence of the NV center is stable and resistant to photobleaching [14]. Its intensity is in addition spin-state dependent (i.e. lower for $m_s=\pm1$ than for $m_s= 0$) due to spin-selective transitions for the $m_s=\pm1$ excited state to a metastable state [3,4,5,6].

The NV spin state can be manipulated by applying a resonant microwave field inducing transitions between the 0 and the ±1 spin sublevels. The decrease in detected photons rate under resonant microwave field provides a direct way of determining the NV spin state (see Fig. 2). In an external magnetic field, the spin sublevels +1 and -1 are separated by so called Zeeman splitting effect [3,4], which results in two individual microwave resonant frequencies corresponding to the two sublevels, with the splitting in between resonant frequencies linearly dependent on the projection of the magnetic field on the axis of the NV center. Therefore, by extracting the difference between the two resonant frequencies, it is possible to determine the intensity of the magnetic field [3,4]. NV centers are oriented along the crystalline lattice of diamond, therefore there are four possible orientations. This can be used for vector magnetometry.

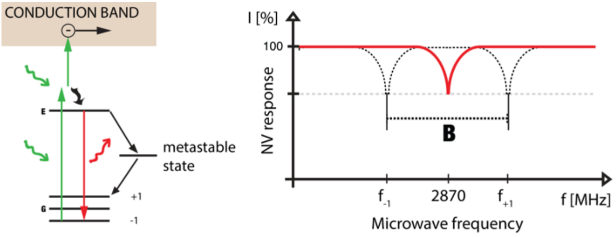

Fig. 2. Energy levels of NV center showing two-photon process of NV ionization (left) and illustration of Zeeman effect that induces splitting in between resonant microwave frequencies in presence of an external magnetic field (right).

In our recent work we have introduced an alternative photoelectric technique for the readout of NV spin state. The PDMR technique [7] is based on the detection of charge carriers promoted to the conduction band of diamond by a two-photon ionization of NV centers. In PDMR the m_s ±1 spin electrons have a non-zero probability to decay through the non-radiative metastable state and are therefore promoted to the conduction band at a lower rate. As a consequence, one can observe drop in the detected photocurrent for the resonant microwave frequency (similarly to ODMR). In another words, diamond serves itself as a spin-sensitive detector directly without a need of external photon counter. The advantage here is that, due to the direct electric readout, the complex detection path is removed [10,11], which is a crucial step for the miniaturization of the entire device. The PDMR-based miniaturized magnetic field sensor is a first step towards scalable real-life diamond-based detector and it could be employed for various fields of application.

3. Material and methods

Figure 3 presents the key components of the diamond magnetometer system that we have developed to demonstrate the miniaturization concept.

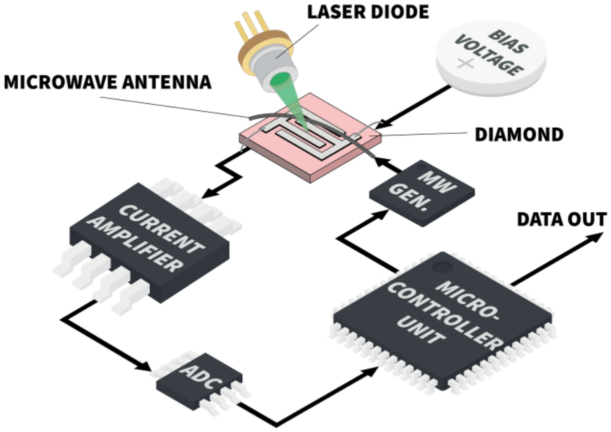

Fig. 3. A diamond plate containing NV centers is equipped with electrodes and plays the role of the sensing element. Laser diode provides excitation of NV centers while a microwave circuitry provides the microwave field used for the manipulation with NV spin states. A bias voltage is applied in between electrodes [10,11]

We constructed devices using a single crystal diamond plate of 2 x 2 x 0,4 mm with lattice orientation [100] containing above 5 ppm of NV centers, homogenously distributed in all the sample volume.

Coplanar electrodes with gap of 5 µm were fabricated on the diamond surface by optical lithography. The metal stack used for metal deposition was 20 nm of titanium and 100 nm of aluminum. The titanium was used as interface layer, whereas aluminum was used for wire-bonding purposes. For wire-bonding, an aluminum wire with a diameter of 25 µm was used.

The light emitted from a green laser diode is focused in between the electrodes on the diamond surface in order to generate the photocurrent. The laser intensity needs to be optimized depending on the concentration of NV centers in the diamond sample and was xxx mW in our case. In order to collect the free photoelectrons generated by the excitation, we applied external electrical field of 2 V/µm (10V over electrodes).

Microwave waveform with frequencies in range of 2820 - 2920 MHz, step resolution 16.6 kHz, and a total power of < +27 dBm was synthetized by microwave synthesizer and applied to the diamond using on-chip antenna. The device allows to program flops between defined microwave frequencies. Important parameter of the device is the locking time, i.e. the time needed for the phase locked loop (PLL) to lock to a certain frequency, or in other words for the frequency control loop to become stable. From this reason, there is an unwanted delay in between application of two consecutive frequencies. Therefore, the loop filter was optimized using Analog Devices PLL simulation software “ADI sim PLL”. In order for the output to be stable, the frequency is fed back into a control circuit that constantly adjusts the output frequency. The Voltage Controlled Oscillator (VCO) is in essence the heart of the radio frequency (RF) synthesizer. The output frequency of a VCO is directly dependent on the applied control voltage. The faster this VCO voltage can be set, the shorter the locking time, therefore the loop filter that outputs this voltage can be optimized.

In the conditions used for the present experiment, the photocurrent generated by the PDMR method is typically in range of 10^{-12} - 10^{-11} A. In order to make the photocurrent signal detectable, it is necessary to amplify the signal with a current amplifier. The signal can be then sampled with analog-digital converter (ADC) and recorded with a microcontroller.

4. Results and discussion

The main aim of this work was to develop a miniature magnetic field sensor based on the PDMR working principle. The sensor dimensions 45 x 25 x 25 mm and a weight of 27 g have been achieved. The sensor and its dimensions are shown in Figure 4. The power consumption of the sensor is 3.5 W and operation voltage is +5 V. The measurement frequency of the device is 6 Hz.

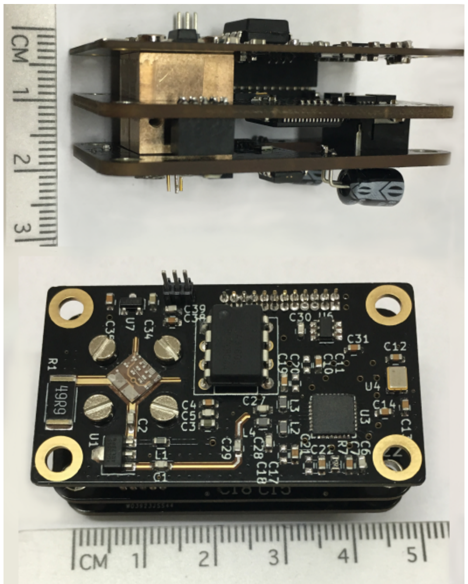

Fig. 4. Diamond PDMR-based magnetic field sensor dimensions

The laser used for diamond excitation is a 50 mW green 520 nm laser diode (L520P50, Thorlabs), with an integrated photodiode. The driving circuit is equipped with a feedback sensor for the laser output power stabilization. As the laser diode requires 8V in order to operate, we developed a laser diode unit booster circuit, transforming 5V of system power to 8V. The iC-WJB laser driver is used to drive the laser diode, together with an external potentiometer, allowing setting of the output laser power. Since the excitation laser intensity is sample specific, an adjustable laser output power is needed for the optimization of the sensor performance.

For laser integration to the board we developed a laser focusing unit (see Fig. 5). This part has two important functions. First, it serves as housing for the laser diode and the focusing optics (i.e. collimation lens and focusing lens, with NA 0.31 and working distance of 1mm). Secondly, it acts as a heatsink for the laser diode. The entire block is 12 x 12 x 12 mm and is made out of copper.

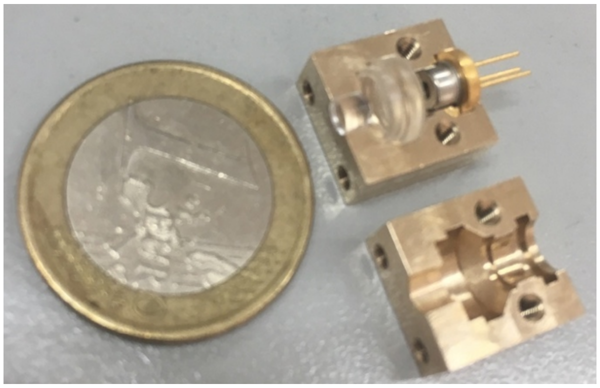

Fig. 5. Laser focusing unit

For the synthesis of the microwave field, we used the ADF4351 (company) microwave synthesizer with integrated VCO unit. In order to improve the measurement speed, we developed an optimized loop filter for the sweeping range 2.5 – 3.5 GHz with a locking time of 28 µs. This allows us to obtain a measurement repetition frequency of 6 Hz. The RF ADF4351 pins provide a differential output, but they can be used individually to provide single-ended RF output. By this we gained higher output power. As RF power provided from ADF4351 is generally low, we used the ADL5545 (company) microwave amplifier with a fixed gain of +20 dB. With this designed system we can reach a microwave power up to 600 mW. The power needed for realization of PDMR is also sample-specific and needs to be optimized analogically to laser power.

The photocurrent readout circuit was designed to amplify and digitize the measured photocurrent. This is done in two steps: current to voltage amplification and analog to digital conversion. For the first step we used the CA3160 (company) amplifier with amplification of 100 pA/V. Since the readout current is in order of pico-amperes, the input tracks were designed to be as short as possible in order to minimize their capacitance. The input lines are protected by a guard voltage maintained by the ADA4851-4 (company) to reduce the noise floor, similarly to the low-current measurement techniques, where the guard voltage is kept on the same potential as the conducting track to reduce leakage current. Second step, the analog to digital conversion, is done by the ADCS746 (company), which has a sampling rate of 1 Ms/s with a resolution of 12 bits. The preliminary tests proved detection of the resonances in the photocurrent and their variations in presence of an external magnetic field.

To ensure the operability in near-space environment, the individual sensor subsystems were tested in a vacuum chamber (up to 25 mBar) and their thermal responses were examined. The vacuum chamber was sealed and the pressure was gradually pumped down to the target pressure of 25 mbar. Before, during and after the pumping the temperatures were monitored with sensors attached to the subsystems under test. After reaching the target pressure, it was kept at 25 mbar until the temperatures of tested subsystems stabilized. The tested subsystems were microwave circuitry and the laser unit, due to their relatively high power. Respectively to the entire system, the biggest heat contributors were the laser diode and the laser driver. While operating on the highest power used in our experiments (22 mW), the temperature of laser driver and laser diode in vacuum did not exceed 84 °C (see Fig. 6). For the microwave circuitry, the biggest heat contribution was from the synthesizer, but its temperature was well below expectations and did not exceed 42°C (see Fig. 7).

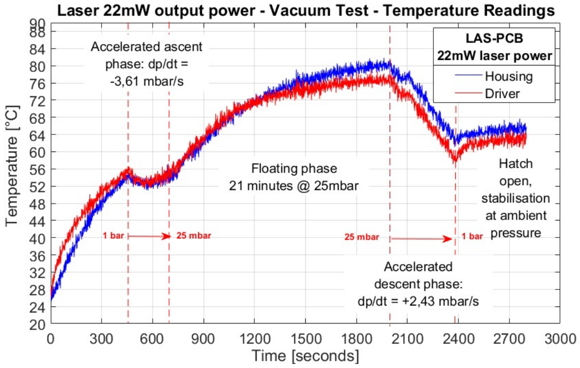

Fig. 6. Temperature test results of the laser unit in vacuum. The laser unit was supplied with 2W of power. Measured points were laser housing (blue) and laser driver (red).

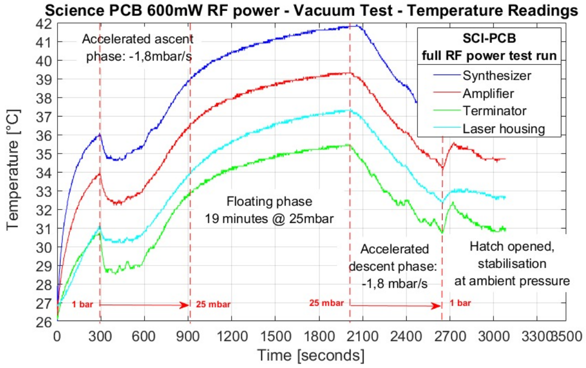

Fig. 7. Temperature test results of the microwave unit in vacuum. The microwave unit was supplied with input power of 0.65 W. The measuring points were microwave synthesizer (dark blue), microwave amplifier (red), 50 Ohm terminator (green) and laser casing (light blue). Note that the laser was off during measurements.

5. Conclusions

In this work we have performed a miniaturization of the PDMR NV readout that is standardly conducted on an optical confocal setup mounted on an optical table [7,11]. The advantages of miniaturization are obvious, such as portability, less complexity and cost reduction. However, this also implies certain drawbacks such as less control over diamond sample positioning with respect to the laser beam.

In course of the OSCAR-QLITE project we successfully demonstrated the possibilities of the miniaturization concept enabled by the PDMR readout method. The developed sensor is the first prototype diamond magnetometer with electric readout. This proves the down-scalability of the PDMR method and unlocks further application potential of diamond as a portable quantum sensor. Further possibility to incorporate pulsed PDMR measurement schemes can both improve the sensitivity of the magnetometer and enable precise measurements of alternating magnetic fields.

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