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研究課題名（和文）Enhanced quantum sensing with a nitrogen-vacancy centre as gateway to the electron spin of phosphorus

研究課題名（英文）Enhanced quantum sensing with a nitrogen-vacancy centre as gateway to the electron spin of phosphorus

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研究成果の概要（和文）：主な成果は 2 つあります。まず、感度を上げるために近くのリン供与体を使用するのは効率的ではありません。その理由は、リンを多く追加すると、ノイズも増えるからです。高濃度のリンが必要です。したがって、追加されたノイズにより、窒素空孔中心のコヒーレンス時間が大幅に減少します。

次に、不安定な信号を検出するための新しい堅牢な測定方法が設計され、テストされました。感度が非常に低い場合、または測定する信号が非常に弱い場合、信号を検出するには長い測定時間が必要です。この間に、信号は変化する可能性があります (たとえば、位相)。開発された標準偏差量子センシング技術により、これらの信号を正確に測定できます。

研究成果の学術的意義や社会的意義
This research contributes to deciding the roadmap for quantum sensors. The methodology of using donors has been found to be underperforming compared to alternatives. Moreover, the developed standard deviation quantum sensing method’s strength is detecting very weak signals, e.g. dark matter fields.

研究成果の概要（英文）：The main achievements can be divided in two parts. The first is a validation result: using nearby phosphorus donors for increasing the sensitivity is not efficient. The reason is that the more phosphorus is added, the more noise is created as well. To connect a phosphorus donor and a nitrogen-vacancy (NV) centre, a high concentration of phosphorus is required. Hence, the coherence time of the nitrogen-vacancy centres decreases too much due to the added noise. Thus, the sensitivity of a single NV centre by itself would be better.

Secondly, a new robust measurement method was designed and tested for detecting instable signals. When the sensitivity is very low, or when the signal to measure is very weak, long measurement times are required to detect the signal. During this time, the signal might change e.g. its phase. With the developed standard-deviation quantum sensing technique, these signals can still be measured accurately.

研究分野：Quantum physics

キーワード：Nitrogen vacancy centre　Phosphorus doping　Quantum sensing　Standard deviation　Sensitivity　Robust sensing

１．研究開始当初の背景
1. Background at the start of the research

Sensors are at the backbone of society's safety: in hospitals for medical diagnosis, at airports for security, in factories for quality control, and in our smartphones for our comfort. To technologically advance in these areas, continuous improvement of our sensors is essential. The advent of the quantum sensor promised sensing beyond the classical limits. Researchers have been improving the best possible (quantum) sensitivities in various ways. Examples are isotope purification (Balasubramanian et al., 2009), improved measurement techniques (De Lange et al., 2010), and ensembles (Wolf et al., 2015). In my previous research, I set the world record for room-temperature coherence times with a single nitrogen-vacancy (NV) centre by employing phosphorus-doped diamond, a new material from our laboratory. This resulted in the best single-NV centre sensitivity as well. As the coherence time T_2 is getting closer to its limit ($T_2 \leq 2T_1$), new ways need to be explored to push the sensitivity further.

In our phosphorus-doped diamond, most phosphorus donors still have an electron with spin. Thus, this begs the question whether phosphorus's electron spin can be a sensor itself. Compared to the alternative, a substitutional nitrogen atom, phosphorus has advantages: it has a single stable isotope, a higher concentration, and available knowledge as a qubit in silicon.

２．研究の目的
2. Research objectives

The research has two main objectives. The first is to investigate the phosphorus donor in diamond via single NV centres. The second is to use the phosphorus spin to enhance the sensing of diamond sensors.

During the research, two other objectives were encountered. The first being whether it is more suitable to use groups of NV centres instead of combining NV centres with phosphorus donors. The second is how to design a measurement method that is more robust than the conventional measurement techniques.

３．研究の方法
3. Research methods

The strategy to this research was to first grow a sample with good properties. In this case, the desired properties are a high coherence time of the NV centre, and phosphorus donors that are nearby this NV centre. Essentially, it is required to have two electron spins with sensing capabilities close together.

Next, the properties of the second electron spin, in this case of the phosphorus donor, would be measured. Most importantly, these are the coherence times (T_2^* and T_2), as they are relevant for the sensitivity. After finding the coherence times, the sensing measurement sequence can be designed and the effect of a magnetic field on the sensor can be quantified, thus finding the sensitivity.

４．研究成果

4. Research results

Finding NV centres coupled to phosphorus donors turned out to be challenging. Although in initial results we found clear indications of such a coupling, this might have been somewhat lucky. When using a sample with a natural abundance of ^{13}C, so about 1.1%, NV centres with a decent coupling to a nearby ^{13}C are fairly easy to find. However, for phosphorus the concentration is about 1 ppm. Hence, the question became whether it is realistic to find one at all in a repeatable manner.

To investigate this in an alternative way, phosphorus-doped diamond samples were implanted with molecules containing multiple nitrogen atoms (as in Haruyama et al., 2019). Since the distance between the nitrogen atoms is determined by straggling, it is in the order of 10 nm. Therefore, the distance between potential NV centres originating from these nitrogen atoms is similar. This is interesting, since in a diamond cube with sides of 10 nm, there are about 1.8×10^5 atoms, so if there would be a single phosphorus donor in this space (so here "modelled" with another NV centre), it is similar to 5 ppm.

Measuring the implanted sample, it was easy to find multiple NV centres in the same optical spot, meaning they are close together. It is possible to verify such spots when the NV centres have different spatial orientations, since they have different Zeeman splittings based on an applied static magnetic field. Figure 1 shows such optically detected magnetic resonance spectra, showing two sets of peaks. They were not very stable, one of the sets would normally disappear during measurement. However, on a few stable ones the coherence time could be measured. One of the better results is plotted in Figure 1 as well. Interestingly enough, the coherence time of the nearby NV centres is rather short. This has two implications. The first, sensing with such a combination would have a much worse sensitivity compared to simply using a single NV centre. Secondly, when the coherence time is short, which is also relevant to detect for example phosphorus donors, it becomes rather challenging to even detect such couplings. The reason is that when trying to measure a coupling, it is similar to measuring a magnetic field. Hence, the better the sensitivity, the easier it is to measure such a field. And for a high sensitivity, a long coherence time is required.

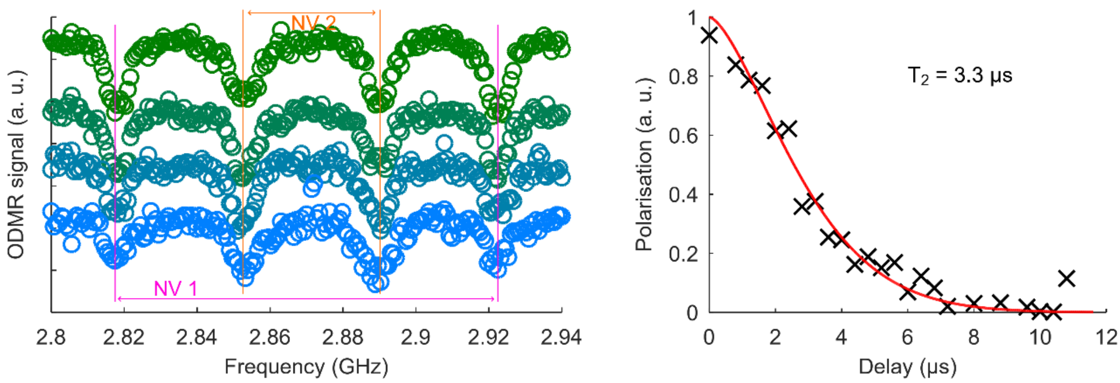

Figure 1: *NV centre pair results. (Left) Optically detected magnetic resonance (ODMR) spectra show that there are two NV centres located within the measured spot. These have a different orientation, therefore the splitting between the energy levels is different. Different colours are measurements at different times, indicating that this pair is stable. (Right) The coherence time, here T_2, of the nearby NV centres is very short, in the order of μs. For comparison, for a single NV centre the longest T_2 is 2.4 ms, while even in high-density ensembles, it can be around 100 μs.*

To overcome this challenge, the idea was to design a measurement method that is much more robust against various kinds of noise, including random changes of the signal to measure itself, since the electron spin of the phosphorus might have a very short coherence time as well.

The designed measurement method I named the "standard-deviation (**std**) method". The idea is depicted in Figure 2. In conventional methods, the magnitude of the signal is measured directly. When there is randomness in the signal, this will result in averaging out the signal, thus measuring zero. However, instead, the standard deviation is measured. The advantage is that this does not depend on e.g. the phase and frequency of the signal, therefore it is robust to changes in the signal.

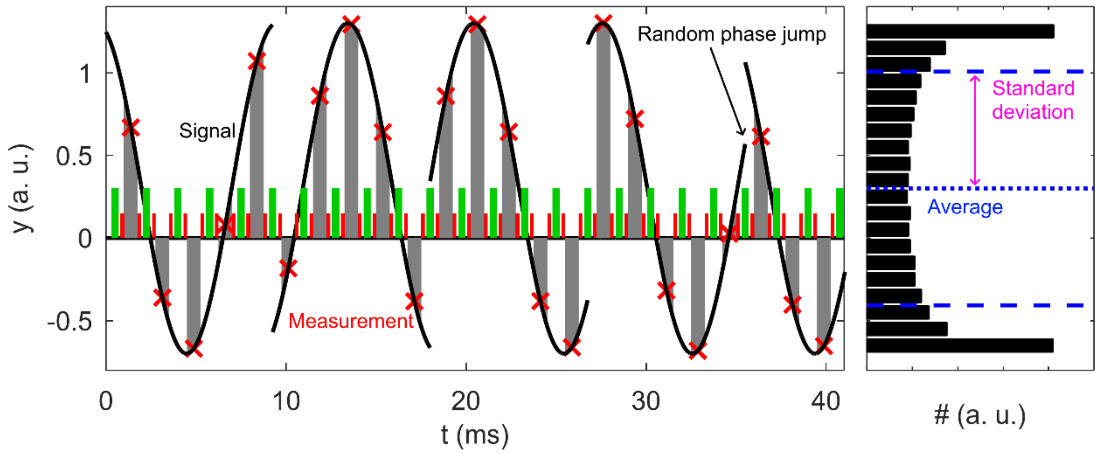

Figure 2: *Standard-deviation quantum sensing method. (Left) When the signal has random phase jumps, conventional methods that accumulate data over multiple periods will find an average of zero. (Right) However, by measuring the standard deviation instead, the amplitude of the signal can be found. For example, for a sinusoidal signal, the relation between the amplitude* A *and the standard deviation of the signal* σ *is* $A = \sqrt{2}\sigma$*.*

I investigated the details of the std method analytically, in numerical simulations, and with measurements. This is the main result of this research, and the results are under review for publication. Here, I will shortly show some properties of the method (analytical/numerical result), and some measurement results.

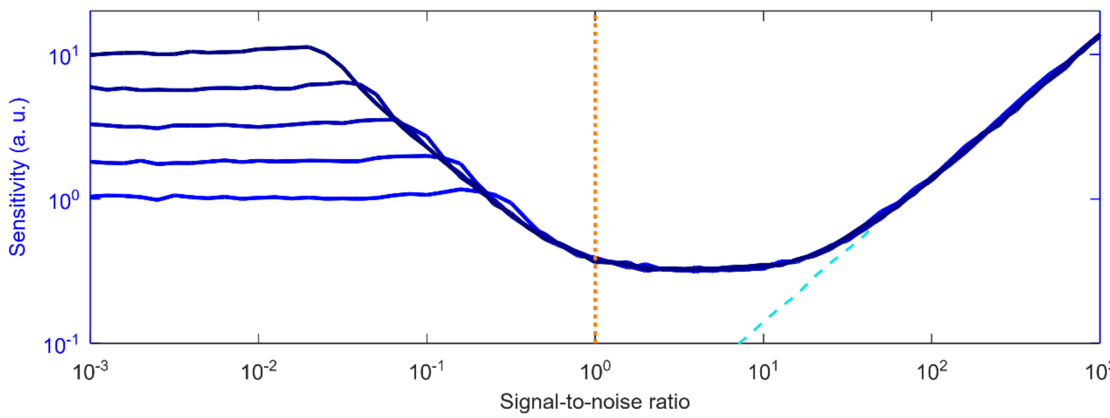

Figure 3: *Sensitivity. At the centre, when the SNR is about 1, the sensitivity is the same as for conventional methods. For higher SNR, the randomness of the signal dictates the sensitivity, while for lower SNR, the randomness of the noise is the limiting factor. Please note that the measured signal is as in Figure 2, hence conventional methods cannot sense the signal at all.*

In Figure 3, the sensitivity of the method is plotted. What should be noted is that the sensitivity depends on the signal-to-noise ratio (**SNR**). For the middle part, so when the SNR is around 1, the sensitivity is exactly the same as for conventional methods (with non-random signals). For lower and higher SNRs, the sensitivity becomes worse. However, please note that conventional methods cannot be used here when the signal is not regular (regular would be without any randomness).

The method is applied to a single NV centre, and the results are plotted in Figure 4. A comparison is made between measuring a regular signal and a signal with randomness, here random phase jumps. In both cases, the standard deviation quantum sensing method accurately detects the magnetic field.

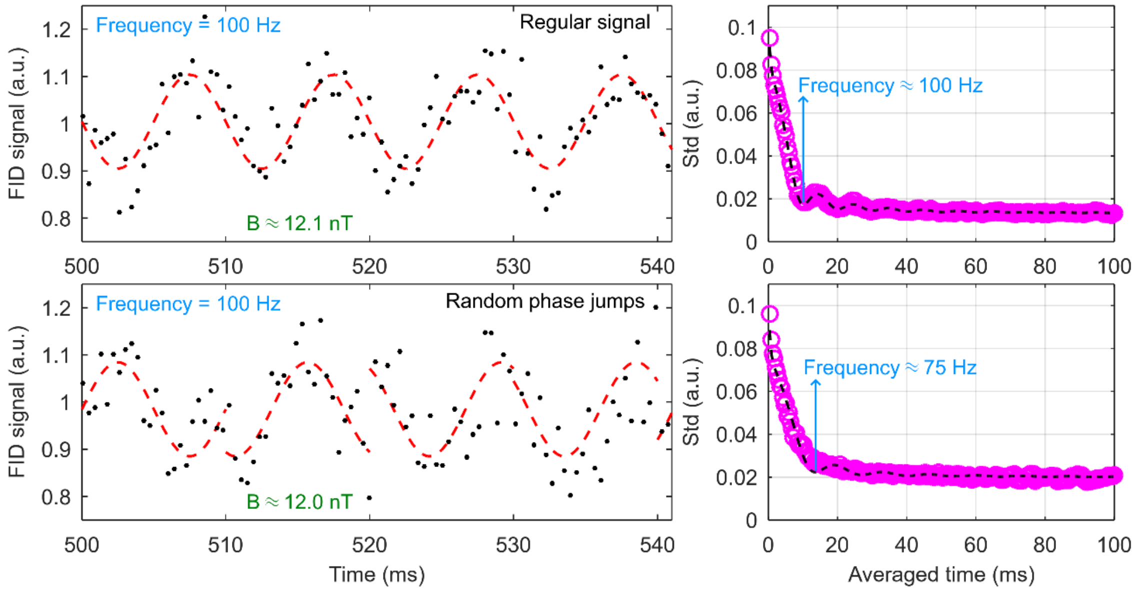

***Figure 4**: Measurements. (Top left) A regular sinusoidal magnetic field is measured (data with black dots, red dashed line guide-to-the-eye). (Top right) By calculating the standard deviation for different time averages, information about the frequency of the signal is found. (Bottom left) A signal with a random phase jump once per period is measured (data with black dots, red dashed line guide-to-the-eye). (Bottom right) Since the random phase jumps reduce the temporal information, the frequency is not found with high accuracy. Please note that the amplitude is still found with a high accuracy, which is the purpose of the standard deviation sensing method.*

Finally, to conclude, I think that the result for the originally proposed research question is likely that to have a phosphorus concentration that is high enough to have a reliable connection to a NV centre (so with a high probability of a strong coupling), the properties of the electron spins, both of the NV centre and the phosphorus donor, have deteriorated so much that any advantage gained from the quantum sensor pair is lost. Moreover, as it is fairly random to have these pairs to start with, using multiple NV centres is probably a better direction for research. The main positive result of this research, the standard deviation quantum sensing method, is very useful for fields of science that need to detect very weak signals over long periods of time, which usually adds randomness to the signal. A great example, that already proposes to use this method, is in the search for dark matter [e.g. arXiv:2302.12756].

５．主な発表論文等

〔雑誌論文〕　計0件

〔学会発表〕　計3件（うち招待講演　0件／うち国際学会　1件）

１．発表者名 Ernst David Herbschleb, So Chigusa, Riku Kawase, Hiroyuki Kawashima, Masashi Hazumi, Kazunori Nakayama, Norikazu Mizuochi
２．発表標題 Robust quantum sensing via statistics
３．学会等名 APS March Meeting (USA)（国際学会）
４．発表年 2024年

１．発表者名 Ernst David Herbschleb, So Chigusa, Riku Kawase, Hiroyuki Kawashima, Masashi Hazumi, Kazunori Nakayama, Norikazu Mizuochi
２．発表標題 Robust standard-deviation quantum sensing
３．学会等名 JPS Spring Meeting (Japan)
４．発表年 2024年

１．発表者名 Ernst David Herbschleb, So Chigusa, Riku Kawase, Hiroyuki Kawashima, Masashi Hazumi, Kazunori Nakayama, Norikazu Mizuochi
２．発表標題 Using the standard deviation for robust quantum sensing
３．学会等名 JSAP Autumn Meeting (Japan)
４．発表年 2024年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

The submitted manuscript was not accepted yet, so I can't add it here. However, the results for the standard-deviation quantum sensing method will be published.

6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関