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Toward real application of quantum sensing and metrology

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"Quantum sensing and metrology" is a relatively new research field. However, this research field is growing rapidly because of some outstanding features that pre-existing technologies do not have. We can thus achieve sensing with extremely high sensitivity across wide dynamic ranges, such as magnetic fields and temperature, or extremely accurate measurements of factors such as gravity, time, and position using quantum sensing and metrology. Multiple sensing of magnetic fields and temperature is also one of the attractive features of quantum sensing. In addition, the information with nanometer ranges extracted in local areas can be observed using nanoparticles with quantum sensors since only one spin defect can act as a sensor. These features for quantum sensing and metrology open new doors to a wide variety of fields and, as a result, ideas for new applications beyond our present imagination.

Although groundbreaking demonstrations have been previously reported (Kucsko et al., 2013; Tetienne et al., 2017; Thiel et al., 2019), it is difficult to say that technology for quantum sensing and metrology is well developed at present. The quality of host materials for spin defects that act as quantum sensors should be improved. For example, diamond is a host material for the negatively charged nitrogen-vacancy (NV) center, which is one of the most famous spin defects that acts as a quantum sensor (Balasubramanian et al., 2008). At present, there is no technology to fabricate diamond wafers of large diameters. Besides, we must develop controlling methods for reducing crystal defects, including unintentionally doped impurities, although the quality of diamond substrates improves day by day. Of course, diamond is not only a host material for spin defects but also other materials, such as silicon carbide (SiC), Gallium nitride (GaN), and hexagonal boron nitride (hBN), are expected to be applied to host materials (Ohshima et al., 2018; Gottscholl et al., 2021; Hoang, 2022), and researchers are making a significant effort to improve the quality of such materials. New host materials for spin defects as well as new spin defects themselves will be found in the future and, as a result, the applications of quantum sensing will be expanded to cover a broad range of fields.

In addition, it is important to establish methodologies for introducing spin defects in host materials. So far, two major methods are applied to the introduction of such spin defects during crystal growth and energetic particle irradiation (Balasubramanian et al., 2009; Yamamoto et al., 2013). Introducing spin defects during crystal growth has an advantage from the point of view of the quality of spin defects as well as host materials since unexpected residual defects that have a harmful impact on spin defects are also introduced by irradiation. For sensing with extremely high sensitivity, spin defects with relatively high concentrations are necessary. In such cases, particle irradiation might be an attractive technique. In addition, by selecting energy of particles and the size of the beam, spin defects can be three dimensionally created in certain locations (Yamazaki et al., 2018). These are advantages to using particle irradiation to create spin defects. However, post-irradiation treatments such as thermal annealing are necessary to recover crystal damage and/or create spin defects (if spin defects are complex defects). So far, the perfect protocol for the post irradiation processes has not yet been developed, and, therefore, this issue remains an open question. For other techniques, the creation of spin defects such as NVs in diamond by femtosecond (fs) pulsed laser irradiation was also demonstrated (Chen et al., 2017). For all methodologies, spin defect creation with a high yield is one of key technologies used to establish quantum sensing technology.

Even if high-quality crystals with high-quality spin defects are realized, it is not enough for highly sensitive sensing. Thus, we must develop spin manipulation protocols to achieve high sensitivity. Dynamical decoupling (DD) sequences such as XY16 are demonstrated to expand spin coherence time t_2 (Gullion et al., 1990). These DD sequences are efficient for AC measurements. On the other hand, for DC measurements, it is necessary to develop protocols to obtain high sensitivity. Of course, not only spin manipulation protocols but also other methodologies can improve sensitivity for quantum sensors. Injection and collection of photons to/from host materials must also be considered. Furthermore, to achieve quantum sensing with high sensitivity, the development of measurement systems is important. Other considerable issues when realizing real applications are the size of systems and their reliability against environmental noise. Thus, compact and highly sensitive measurement systems are necessary for us to use quantum sensing in the real world but not in laboratories. In such a case, the integration of electronics with quantum sensing systems should be considered.

It is expected that quantum sensing systems are integrated with photonics, and the same can be said for quantum metrology. Thus, to apply it to the real world and not laboratories, it is necessary to design compact and reliable systems. Of course, for quantum metrology, if the purpose of the applications is only for standardization, we do not need the systems to be to compact. In this case, we can focus on the improvement of accuracy as much as possible. In any case, robustness against environmental noise must be considered to develop systems, especially for outdoor use.

Of course, the most important thing for quantum sensing and metrology is who wants to use this technology. Thus, demonstrations of quantum sensing were reported in a wide variety of fields. However, this necessitates that valuable information by which open questions in these fields can be solved are obtained by quantum sensing and metrology. Using quantum sensing based on NV in diamond, it was reported that temperatures at local area in cells were measured (Kucsko et al., 2013). This is a nice demonstration for quantum sensing because extremely high spatial resolution is one of the excellent features for quantum sensing. It can be expected that we understand “nature of life” when all information on energy transfer between cells and inner cells can be revealed. For not only life/bio science but also material science, the transport and magnetic characteristics of 2D materials (graphene and CrI_3) were measured with high spatial resolution using NV in diamond (Tetienne et al., 2017; Thiel et al., 2019). I believe that features of quantum sensing, such as high spatial resolution, high sensitivity, and multiple sensing, will give us useful information to understand material properties, and, as a result, new effects or/and new materials will be found. For quantum metrology, extremely accurate measurement might change the definition of units and create new applications. An ultra-precise inertial navigation system with cold atoms using quantum de Broglie waves can realize precise global positioning systems without satellites (Feng, 2019). Quantum optical coherence tomography, which is based on two-photon interference between entangled photon pairs, can reach higher resolution beyond the classical optical limit (Okano et al., 2015). In the end, I would emphasize anew that quantum sensing and metrology has enough potential to open doors for wide variety of fields, and I am expecting that doors will be opened to new fields we have yet to imagine.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher’s note

References

Balasubramanian, G., Chan, I. Y., Kolesov, R., Al-Hmoud, M., Tisler, J., Shin, C., et al. (2008). Nanoscale imaging magnetometry with diamond spins under ambient conditions. *Nature* 455, 648–651. doi:10.1038/nature07278

Balasubramanian, G., Neumann, P., Twitchen, D., Markham, M., Kolesov, R., Mizuochi, N., et al. (2009). Ultralong spin coherence time in isotopically engineered diamond. *Nat. Mat.* 8, 383–387. doi:10.1038/nmat2420

Chen, Y.-C., Salter, P. S., Knauer, S., Weng, L., Frangeskou, A. C., Stephen, C. J., et al. (2017). Laser writing of coherent colour centres in diamond. *Nat. Photonics* 11, 77–80. doi:10.1038/NPHOTON.2016.234

Feng, D. (2019). Review of quantum navigation. *IOP Conf. Ser. Earth Environ. Sci.* 237, 032027–032110. doi:10.1088/1755-1315/237/3/032027

Gottscholl, A., Diez, M., Soltamov, V., Kasper, C., Sperlich, A., Kianinia, M., et al. (2021). Room temperature coherent control of spin defects in hexagonal boron nitride. *Sci. Adv.* 7, eabf3630–16. doi:10.1126/sciadv.abf3630

Gullion, T., Baker, D. B., and Conradi, M. S. (1990). New, compensated Carr-Purcell sequences. *J. Magn. Reson.* 89, 479–484. doi:10.1016/0022-2364(90)90331-3

Hoang, K. (2022). Rare-earth defects in GaN: A systematic investigation of the lanthanide series. *Phys. Rev. Mater.* 6, 044601. doi:10.1103/PhysRevMaterials.6.044601

Kucsko, G., Maurer, P. C., Yao, N. Y., Kubo, M., Noh, H. J., Lo, P. K., et al. (2013). Nanometre-scale thermometry in a living cell. *Nature* 500, 54–58. doi:10.1038/nature12373

Ohshima, T., Satoh, T., Kraus, H., Astakhov, G. V., Dyakonov, V., and Baranov, P. G. (2018). Creation of silicon vacancy in silicon carbide by proton beam writing toward quantum sensing applications. *J. Phys. D. Appl. Phys.* 51, 333002–333114. doi:10.1088/1361-6463/aad0ec

Okano, M., Lim, H. H., Okamoto, R., Nishizawa, N., Kurimura, S., and Takeuchi, S. (2015). 0.54 μm resolution two-photon interference with dispersion cancellation for quantum optical coherence tomography. *Sci. Rep.* 5, 18042. doi:10.1038/srep18042

Tetienne, J.-P., Dontschuk, N., Broadway, D. A., Stacey, A., Simpson, D. A., and Hollenberg, L. C. L. (2017). Quantum imaging of current flow in graphene. *Sci. Adv.* 3, e1602429–16. doi:10.1126/sciadv.1602429

Thiel, L., Wang, Z., Tschudin, M. A., Rohner, D., Gutiérrez-Lezama, I., Ubrig, N., et al. (2019). Probing magnetism in 2D materials at the nanoscale with single-spin microscopy. *Science* 364, 973–976. doi:10.1126/science.aav6926

Yamamoto, T., Umeda, T., Watanabe, K., Onoda, S., Markham, M. L., Twitchen, D. J., et al. (2013). Extending spin coherence times of diamond qubits by high-temperature annealing. *Phys. Rev. B* 88, 075206–075218. doi:10.1103/PhysRevB.88.075206

Yamazaki, Y., Chiba, Y., Makino, T., Sato, S. -I., Yamada, N., Satoh, T., et al. (2018). Electrically controllable position-controlled color centers created in SiC pn junction diode by proton beam writing. *J. Mat. Res.* 33, 3355–3361. doi:10.1557/jmr.2018.302