IOP Publishing Mater. Quantum Technol. 4 (2024) 023001 https://doi.org/10.1088/2633-4356/ad4e8d

Materials for Quantum Technology

OPEN ACCESS

RECEIVED
29 September 2023

REVISED
6 April 2024

ACCEPTED FOR PUBLICATION
21 May 2024

PUBLISHED
31 May 2024

PERSPECTIVE

Strained diamond for quantum sensing applications

Limin Yang[1], **Heyi Wang**[2], **Sen Yang**[3] and **Yang Lu**[2,*]

[1] Nano-Manufacturing Laboratory (NML), Shenzhen Research Institute of City University of Hong Kong, Shenzhen 518057, People's Republic of China
[2] Department of Mechanical Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong Special Administrative Region of China, People's Republic of China
[3] Department of Physics and the IAS Center for Quantum Technologies, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong Special Administrative Region of China, People's Republic of China
* Author to whom any correspondence should be addressed.

E-mail: ylu1@hku.hk

Keywords: diamond, quantum sensing, strain engineering, nanomechanics

Abstract

Apart from being an extraordinary optical and electronic material, diamond has also found applications in quantum mechanics especially in quantum sensing with the discovery and research development of various color centers. Elastic strain engineering (ESE), as a powerful modulation method, can tune the quantum properties and improve the performance of diamond quantum sensors. In recent years, deep ESE (DESE, when >5% elastic strain, or $>\sigma_{ideal}/2$ is achieved) has been realized in micro/nano-fabricated diamond and shows a great potential for tuning the quantum mechanical properties of diamond substantially. In this perspective, we briefly review the quantum properties of diamond and some of the corresponding sensing applications carried out with ESE, and look at how DESE could be applied for further tuning the quantum sensing properties of diamond with desired applications and what the critical challenges are.

1. Introduction

Strain engineering is a strategy to tune the physical and chemical properties of a material such as electronic, magnetic, and catalytic properties by applying strain which changes the lattice parameters and shape [1, 2]. Very often, the strain value does not need to be very high, but can change the material properties fundamentally and improve the device performance dramatically. For example, a small strain of ∼1% can enhance the carrier mobility of Si-based field-effect-transistor by more than 50% [3, 4], thus improve the device performance to a greater extent. The implementation of strain engineering relies on the preparation of material with small size and less defects, that is, with the reduction of sample size, the probability of the appearance of internal defects is also reduced, making the material properties more uniform and closer to the theoretical level. Therefore, large strains are more likely to be achieved in nano- and single-crystalline material, which is also known as 'smaller is stronger' [5].

Strain can modulate the quantum mechanical properties of materials by changing energy or breaking symmetry. Firstly, strain changes the interatomic distance and interaction among different atomic orbitals, and modulates the relative position of energy levels and spin states of electrons. For example, strain tunes the energy levels and increase the orbital splitting of the silicon-vacancy (SiV) centers of diamond. By doing so, the spin coherence of SiV center can be improved [6]. Secondly, since the symmetry of a material is closely connected to its energy degeneracy, when strain breaks a specific symmetry of a system, some spin transitions which are not possible without strain can be enabled [7, 8], and more spin manipulation will become possible, such as the spin-spin interaction change of nitrogen-vacancy $(NV)^-$ [9] and the generation of spin relaxation path of the transition-metal dichalcogenides [10] through strain-induced symmetry breaking. In recent years, strain engineering is appearing as an effective method to modulate the quantum mechanical properties of materials, such as modulating the quantum ferroelectric polar and thus the superconducting phase and superconducting transition temperature of materials [11, 12], which has been

accelerating the research of high temperature superconductors [13–15]. Moreover, strain can improve the quantum emission of materials such as hexagonal boron nitride film [16] and transition metal dichalcogenides [17–20] and extend their quantum photonic applications.

Diamond is a promising candidate for quantum mechanics and quantum technology applications such as quantum communication [21, 22], quantum computing [23–25] and quantum electromagnetic sensing [26–30]. With the development of diamond synthesis and nano-fabrication technologies, Elastic strain engineering (ESE) and DESE have been achieved in recently years [31, 32], which makes strain engineering of diamond a hot topic. In this paper, we briefly review the quantum mechanics of diamond and look forward to how ESE and DESE may accelerate the development of diamond quantum mechanics and extend its quantum sensing applications.

2. Color centers and quantum applications of diamond

Pure diamond is composed entirely of carbon and is optically transparent from ultraviolet to the far infrared. However, when diamond is doped by other elements (nitrogen, silicon, boron etc.), point defects form. Optically active point defects are termed color centers [33], of which many have special quantum features. Up to now, hundreds of color centers have been studied experimentally or theoretically [34]. Due to the rigid lattice and chemical stability of diamond, these quantum features can be well protected, even under extreme conditions [34].

Among those color centers, the most widely studied one is NV center, which contains a substitutional nitrogen atom and a vacancy at adjacent site. NV centers can be prepared via nitrogen implantation, irradiation of nitrogen-doped diamond with electron beam to create vacancies and a subsequent high-temperature annealing to combine the vacancies and nitrogen atoms into high-density NV centers, or vacancy creation and NV center formation via ultrahigh temperature annealing [34, 35]. The energy levels of a NV center at room temperature are shown schematically in figure 1(a), with the $m_s = 0$ and $m_s = 1$ states separated by the zero-field splitting parameter (D), which can be affected almost linearly by external strain [36]. NV center can exist in various charged states, i.e. negative (NV^-) or neutral charge (NV^0) states. The zero-phonon line (ZPL) of NV^- and NV^0 center are at 637 nm (1.945 eV) and 575 nm (2.156 eV), respectively and the NV^- center has a broad band from 650–750 nm [37–40]. The spin state of NV^- is sensitive to magnetic and electric field change and mechanical strain, and such change will reflect in its fluorescence signals [41–43]. Moreover, NV^- center has a long spin coherence time (T_2, the time duration that a qubit maintains its quantum state), which can reach a few milliseconds using the Hahn echo in ambient conditions [44, 45], and can be extended to one second or over using dynamical decoupling under cryogenic conditions [46, 47]. Such a long coherence time facilitates NV^- center to be initialized, manipulated and read out, often by using the optically detected magnetic resonance (ODMR). Therefore, diamond with NV center is an excellent material for quantum memory (figure 1(b)) [48–50], magnetic and electric field sensing (figures 1(c) and (d)) [43, 51–56], and computing [23, 25]. For example, as shown in figure 1(b), in a quantum memory protocol, a horizontally polarized photon with a wavelength of 723 nm (green light) is written with a vertically polarized write pulse with a wavelength of 800 nm (red). After a delay of τ, a horizontal read pulse recalls a vertical phonon. Although the spin coherence of NV center can also be affected by environmental sources of noise and disorder such as temperature, some strategies such as the local manipulation of the electron spin bath has been proposed to enhance the coherence and help read out signals [57, 58].

In addition to NV center, other color centers such as SiV, germanium-vacancy (GeV) and tin-vacancy (SnV) have also been investigated and found potential applications in quantum sensing. In the SiV structure, the Si occupies the center of two adjacent vacancies. SiV is a well-studied color center only second to NV center. Compared with the NV center, SiV center has a higher proportion (∼70%) of its emission in ZPL (at 738 nm) and therefore allows a sharp ZPL to be detected, making SiV center advantageous in labeling [34, 59, 60], quantum communication [61] and quantum repeater [62]. Unfortunately, the coherence time of SiV center is too short (under no strain condition) and coherence spin control can also be realized by cooling down to low temperature [62]. GeV and SnV centers have geometric structures similar with SiV (that is, both Ge or Sn takes the place between two adjacent vacancies), as well as similar optical properties [63], but SnV has a longer spin coherence time than SiV and GeV at higher temperatures [64, 65]. Nevertheless, due to the large atomic size of Si, Ge and Sn, their correspondent color centers will bring more lattice distortion than the NV center does.

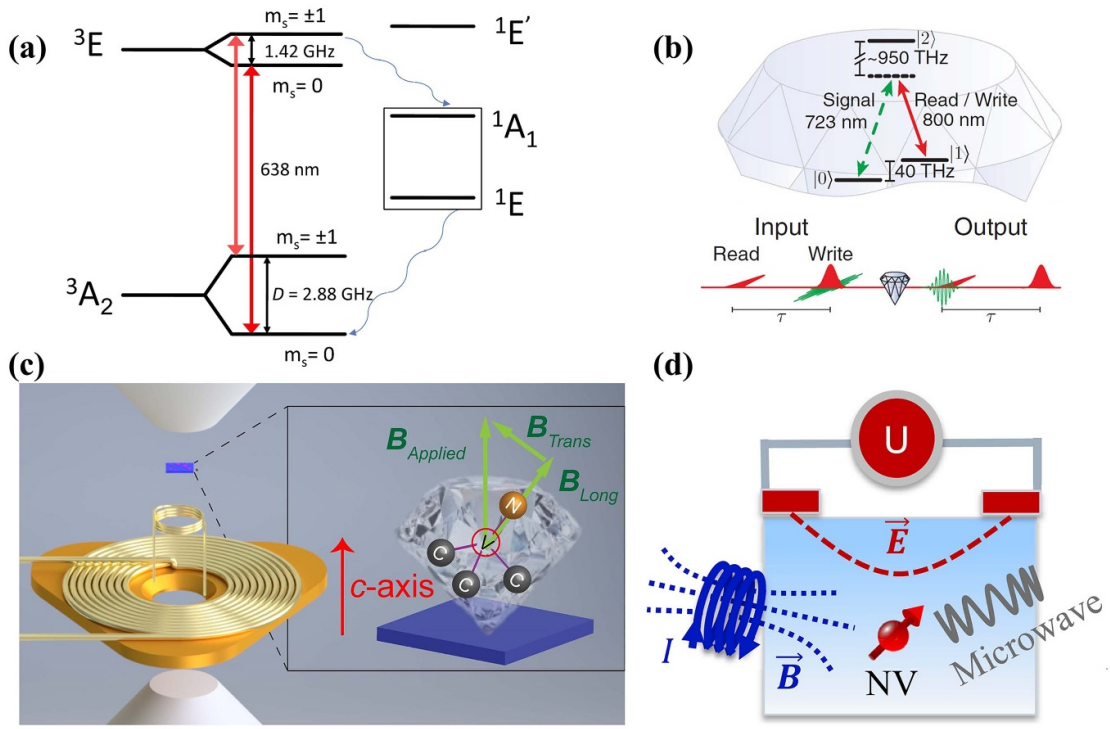

Figure 1. (a) Schematic of energy levels of NV center at room temperature; Reprinted figure with permission from [36], Copyright (2014) by the American Physical Society. (b) Energy levels of diamond quantum memory and protocol of a diamond quantum memory, where a horizontal green photon is written with a vertically polarized red pulse. After a delay of τ, the horizontal pulse recalls a vertical photon. Reprinted figure with permission from [50], Copyright (2015) by the American Physical Society; (c) NV center for measuring of magnetic field in a high-pressure condition From [43]. Reprinted with permission from AAAS; (d) NV center for electrical field sensing. Reprinted figure with permission from [56], Copyright (2020) by the American Physical Society.

3. Strain engineered quantum properties of diamond

Naturally, the orientations of NV centers (i.e. the direction NV axis is parallel with) are random, which would greatly compromise the device performance in quantum computing and sensing [69]. The alignment of NV centers can be achieved by carefully adjusting the parameters of the diamond growth during chemical vapor deposition (CVD) process, and of nitrogen implantation and high-temperature annealing [69–71]. ESE is a potentially alternative approach to modulate the atomic structure and align the orientations of the color centers. First principles calculations predicted that applying strains along some selected directions would make these orientations of the NV centers more energetically favorable over others, e.g. a compressive biaxial strain of 2% perpendicular to [111] direction or a small scale of tensile strain along [111] in high-temperature environment could make ∼90% of NV centers align along the [111] directions (figure 2(a)) [66]. Such strategy could be employed to modulate the qubit coupling of NV centers already formed in diamond in order to make them ideal for quantum sensing and computing [72]. Moreover, diamond with well-aligned NV centers is also an excellent candidate for stress imaging [73] and high-accuracy magnetometry [74, 75]. Therefore, straining engineering can be employed as part of the post-processing treatments for the geometry optimization of the NV color center.

Strain often inevitably exists from intrinsic defects and can be caused by external stress as well. In some cases, strains are unwanted since they bring extra broadening of optical and spin spectra of NV centers [76]. But strain can be a powerful tool if used properly. For example, strain can modulate the orbital states and spin levels of NV center by shifting the spin states or inducing state mixing, such as the global shift of excited state, as shown in figure 2(b) [67, 77], or the coupling between the $|m_s = \pm 1$, which is an important effect of strain engineering tuning the quantum properties of diamond. For the NV^- center, the ZPL is highly dependent on strain field, which can split the ^3E fine structure into two branches [40]. Based on these effects, strain susceptibilities can be obtained in a strain sensor for plotting the strain profile, which may find applications in hybrid quantum sensing devices such as nanomechanical resonators [78–81]. Since strain can shift the optical transition frequency of each electron spin, a strain field can be introduced for individually tuning the transition frequencies of NV centers embedded in a diamond cantilever, which enables manipulation of individual qubits and help to achieve high-fidelity quantum operations [82]. In addition,

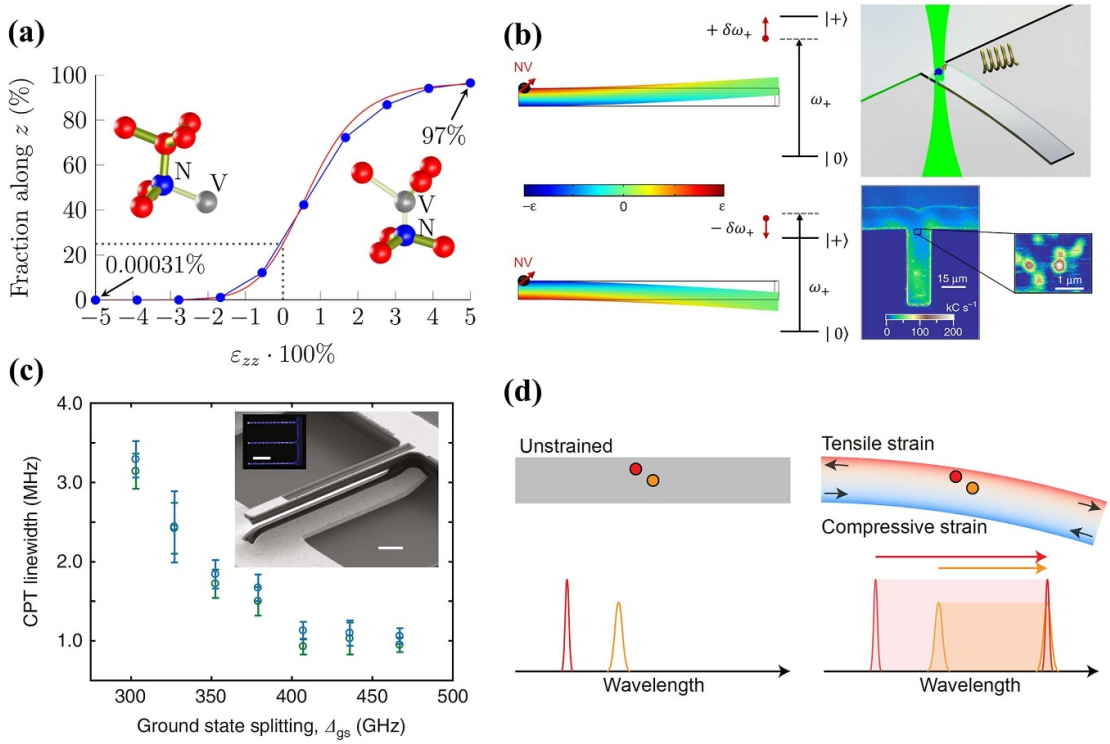

Figure 2. (a) Alignment of NV centers along z direction with tensile strain along z axis applied. Reprinted from [66], with the permission of AIP Publishing; (b) Strain modulates energy level and spin population difference of NV center embedded in a cantilever and a green laser is used for initialization and readout. Reproduced from [67], with permission from Springer Nature; (c) Reduced linewidth of coherent population trapping (CPT) spectra with increasing ground state splitting indicates the improved spin coherence of a SiV^- NEMS with increasing strain. Reproduced from [6]. CC BY 4.0; (d) Alignment of emission spectra of two GeV emitters by introducing small values of strain gradient in a cantilever. Reprinted figure with permission from [68], Copyright (2018) by the American Physical Society.

strain effect can also be used for tuning the nuclear spins in diamond lattice such as nitrogen or C^{13} atoms, which are useful for qubit registers and sensors [83, 84]. Since strain influences the distance and distribution of NV centers, which is strongly related to ODMR spectra, applying straining can be a way to facilitate the readout of nuclear spin. Moreover, by coupling the surface acoustic wave to the NV spin states through a dark state, it is possible to tune the NV spin states while without populating the excited state, therefore avoiding the unwanted decoherence [85]. Since strain fields can enhance the spin coherence of NV center, strain engineering could be employed together with electrical field tuning, which may bring noise and decoherence [86]. In addition, the coupling between strain and the NV spin could be used to facilitate the coherent spin-phonon interactions, which are important for quantum control and long-range spin-spin interactions [87, 88]. Apart from applying mechanical vibrations, using diamond anvil cell (DAC) is another way to introduce strain into diamond. In this way, compressive strain decreases the distance between atomic orbitals and makes the localized electrostatic potential of NV centers deeper. As a result, the electron density becomes more concentrated in the inner neighbor shells of the NV centers, which favors the spin-spin interaction [89].

In addition to the modulation of the quantum properties of NV center, strain engineering can also tune the properties and improve the performance of other color centers. For example, the electronic level structure of SiV^- center in a nano-electro-mechanical system (NEMS) can be modulated by applying static strain, which can be used for tuning the optical and spin transition frequencies [90]. Moreover, the thermal-induced quantum decoherence of SiV^- center in a NEMS can be effectively suppressed by applying a slight static strain (as shown in figure 2(c)), which provides a feasible way to control the phonon-induced decoherence of color centers in quantum emitters without lowering the operating temperature [6]. Similarly, static tensile strain, even of a small scale (0.05%–0.1%), can suppress the electron-phonon interaction of SnV in diamond at elevated temperatures effectively and improve the coherence time considerably [91]. For multiple GeV centers in a diamond cantilever, applying a strain gradient can tune the emission spectra of these GeV centers and achieve spectral alignment (as shown in figure 2(d)), which can promote the development of spectrally identical quantum emitters.

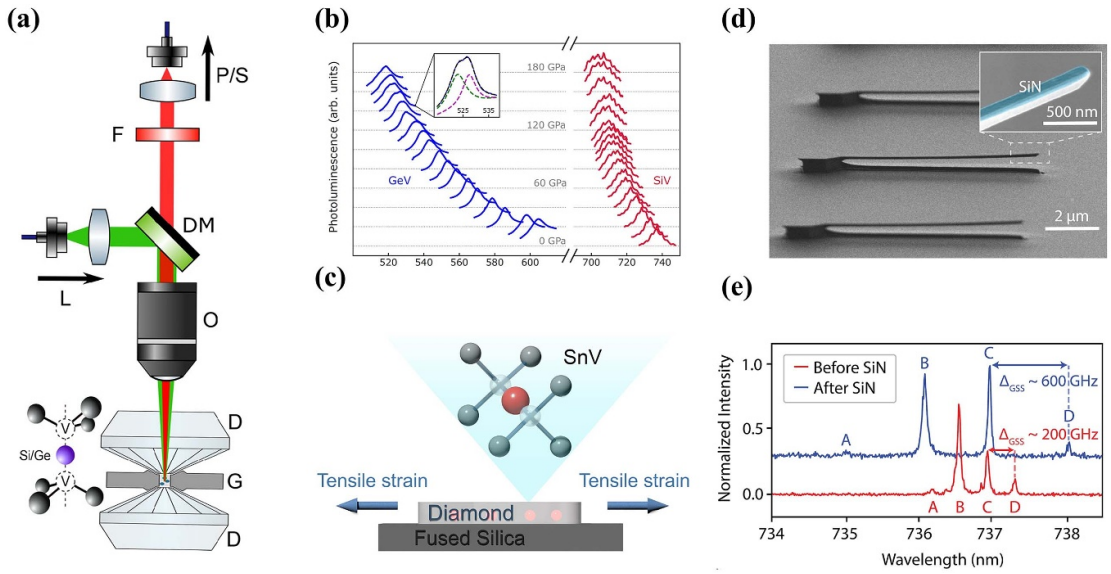

Figure 3. (a) Schematic diagram of SiV and GeV in DAC high pressure environment and (b) the corresponding photoluminescence (PL) spectra. Reprinted figure with permission from [95], Copyright (2022) by the American Physical Society.; (c) Schematic of strained diamond membrane with SnV on fused silica. Reproduced from [91]. CC BY 4.0; (d) Strained diamond embedded with SiV centers and deposited on SiN, and the PL spectra before and after SiN deposition, which shows an increased ground state splitting by strain. Reprinted from [96], with the permission of AIP Publishing.

4. Deep strain engineering

Although strain engineering has been considered as a potential approach to modulate the quantum mechanical properties of material, in most cases, the strains applied are of small values (<1%) [1, 5]. Due to the unavoidable existence of defects (vacancies, interstitials, dislocations, cracks etc.), the mechanical performance of a material is often compromised such that it can hardly reach the ideal level. With the reduction of the material size to micro and even nano scale, the probability of the appearance of these defects can be reduced to lower level and the mechanical performance will be improved substantially. For example, it has been demonstrated that high-quality silicon nanowires can be stretched elastically above 10%, which is more than half of its theoretical limit (17%–20%) [92]. Accordingly, first principles calculations predicted an indirect to direct bandgap transition and a metallization transformation with ultra large strain of Si [93, 94], indicating the great potential of DESE, and one may think about what DESE can do for further tuning the optical, electronic and even quantum mechanical properties of more materials.

For diamond, due to its high brittleness, it is extremely difficult to achieve high elastic strain experimentally [97]. One of the most straightforward methods is to use DAC to generate ultrahigh static pressure. For example, with applying hydrostatic pressure of up to 180 GPa, large deformation of diamond can be obtained and blueshifts of ZPL of SiV and GeV can be observed and the shift becomes slower at high pressures, as shown in figures 3(a) and (b) [95]. Such a blue-shifting trend can also be observed in NV center under DAC [98]. Such work should be meaningful for carrying out quantum sensing at ultrahigh pressures. However, strain values cannot be measured with such a configuration and it is hard to guarantee a well uniform strain or to realize a controllable strain gradient. Therefore, the application of DAC tuning the quantum sensing properties is limited.

With the development of diamond synthesis and nanofabrication technology, high-quality single crystal diamond nano needles and bridge structures can be prepared by CVD followed by reactive/focused ion beam etching [31, 32, 99]. It was also found that diamond structure of such small size can sustain much higher elasticity compared to their bulk counterparts. For diamond nanoneedles, the highest elastic tensile strain reported was 13.4% and the compressive strain was even higher [99]. Moreover, diamond nano bridge structures exhibited a uniform elastic tensile strain of up to 9% and such structure may be applied for electronic, photonic and quantum devices [31]. Bandgap reduction and indirect to direct bandgap transformation were predicted by first principles calculations. Compared with indirect bandgap material, the direct bandgap materials can emit photons with higher efficiency, therefore, the strain-induced evolution of bandgap from indirect to direct makes DESE a potential approach to apply diamond to optoelectronic devices, such as laser diodes. Moreover, considering the deep-strain-induced bandgap reduction and indirect

to direct bandgap transition, for the NV center, we may imagine ZPL peak shift under the deep straining, opening new potential for highly efficient photonic device with reversible, modulated emission wavelength. Deep strain engineering is also a potential approach to turn the band structure and spin states of nitrogen-doped diamond. In addition to the predicted bandgap reduction, we also predicted symmetry breaking, band degeneracy and a reduction of total spin with applying deep compressive strain [100]. Since symmetry, energy degeneracy and spin transition are closely correlated, we would expect DESE to change the quantum properties of nitrogen doped diamond (and even NV center) substantially.

While diamond has been studied mostly as a bulk material, it can also be used in the form of membrane and bonded with various substrates for quantum applications [101]. Such deformation mode is similar with that of the two-dimensional material. Due to the thin thickness nature, large strain is more likely to be achieved and such a structure is suitable for flexible optoelectronic devices. This deformation process relies on the stable bonding between diamond and another different material as substrate [102, 103], and strains can be introduced via bending, stretching and pre-strain of the substrate material, such as the straining of diamond membrane with SnV center on fused silica [91], or diamond with SiV center on SiN [96], as shown in figures 3(c)–(e). In these two examples, strain plays an important role in increasing the ground state splitting (Δ_{GSS}), which is useful for improving the coherence time, especially for the high-temperature operation. Although only small strains (<1%) are introduced in the two examples, such protype is expected to generate high static strain and enhance the spin coherence and improve the detection accuracy for more color centers of diamond.

5. Summary and outlook

With the development of diamond synthesis techniques and research on diamond nanomechanics and color centers, more and more quantum mechanical properties of diamond are being revealed and find applications in quantum sensing. Strain engineering is an emerging approach for tuning the quantum mechanical properties of diamond, but for most of the current studies, only small values of strain have been considered. Until now, deep strain has been achieved in diamond nano structures, laying solid foundation for deep strain induced physical properties modulation. Theoretical studies have predicted the great potential of deep strain engineering of diamond such as the bandgap reduction, indirect to direction bandgap transition, and symmetry-breaking induced spin degeneracy. We are expecting to see DESE induced wider ZPL shift and increase of spin coherence of more color centers of diamond, which should improve the detection accuracy, make more color centers useable and bring diamond to wider quantum sensing applications. Moreover, one may also expect the combination of strain and electrical fields, to tune the diamond quantum sensing performance together. Nevertheless, for the modification of quantum sensing properties of diamond by deep strain engineering, it is still a relatively new topic. In terms of the quantum application of deep strained diamond, there are still many challenges to be addressed such as how to generate and fix the high strains. We hope that more experimental and theoretical work will be conducted to shed more light on this topic in the near future.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

The authors acknowledge the financial support from Research Grants Council of the Hong Kong Special Administrative Region, China (RFS2021-1S05, GRF/16305422), RGC Theme-based Research Scheme (T45-406/23-R), NSFC/RGC Joint Research Scheme project (N_HKU159/22) and Department of Science and Technology of Hunan Province (2022RC4017).

ORCID iDs

Limin Yang https://orcid.org/0009-0006-3158-4805
Yang Lu https://orcid.org/0000-0002-9280-2718

References

[1] Li J, Shan Z and Ma E 2014 Elastic strain engineering for unprecedented materials properties *MRS Bull.* **39** 108–14
[2] Li J 2021 EML webinar overview: elastic strain engineering for unprecedented properties *Extrem. Mech. Lett.* **54** 101430
[3] Thompson S E *et al* 2004 A logic nanotechnology featuring strained-silicon *IEEE Electron Device Lett.* **25** 191–3

[4] Thompson S E et al 2004 A 90-nm logic technology featuring strained-silicon IEEE Trans. Electron Devices 51 1790–7
[5] Zhu T and Li J 2010 Ultra-strength materials Prog. Mater. Sci. 55 710–57
[6] Sohn Y-I et al 2018 Controlling the coherence of a diamond spin qubit through its strain environment Nat. Commun. 9 2012
[7] Tsymbalov E, Shi Z, Dao M, Suresh S, Li J and Shapeev A 2021 Machine learning for deep elastic strain engineering of semiconductor electronic band structure and effective mass npj Comput. Mater. 7 76
[8] Guan S, Yu Z-M, Liu Y, Liu G-B, Dong L, Lu Y, Yao Y and Yang S A 2017 Artificial gravity field, astrophysical analogues, and topological phase transitions in strained topological semimetals npj Quantum Mater. 2 23
[9] Batalov A, Jacques V, Kaiser F, Siyushev P, Neumann P, Rogers L J, McMurtrie R L, Manson N B, Jelezko F and Wrachtrup J 2009 Low temperature studies of the excited-state structure of negatively charged nitrogen-vacancy color centers in diamond Phys. Rev. Lett. 102 195506
[10] Liu T, Xiang D, Ng H K, Han Z, Hippalgaonkar K, Suwardi A, Martin J, Garaj S and Wu J 2022 Modulation of spin dynamics in 2D transition-metal dichalcogenide via strain-driven symmetry breaking Adv. Sci. 9 2200816
[11] Herrera C, Cerbin J, Jayakody A, Dunnett K, Balatsky A V and Sochnikov I 2019 Strain-engineered interaction of quantum polar and superconducting phases Phys. Rev. Mater. 3 124801
[12] Ivashko O et al 2019 Strain-engineering Mott-insulating La_2CuO_4 Nat. Commun. 10 786
[13] Ruf J P et al 2021 Strain-stabilized superconductivity Nat. Commun. 12 59
[14] Llordés A et al 2012 Nanoscale strain-induced pair suppression as a vortex-pinning mechanism in high-temperature superconductors Nat. Mater. 11 329–36
[15] Locquet J P, Perret J, Fompeyrine J, Mächler E, Seo J W and Van Tendeloo G 1998 Doubling the critical temperature of $La_{1.9}Sr_{0.1}CuO_4$ using epitaxial strain Nature 394 453–6
[16] Mendelson N, Doherty M, Toth M, Aharonovich I and Tran T T 2020 Strain-induced modification of the optical characteristics of quantum emitters in hexagonal boron nitride Adv. Mater. 32 1908316
[17] Cong C, Shang J, Wang Y and Yu T 2018 Optical properties of 2D semiconductor WS_2 Adv. Opt. Mater. 6 1700767
[18] Kumar S, Kaczmarczyk A and Gerardot B D 2015 Strain-induced spatial and spectral isolation of quantum emitters in mono- and bilayer WSe_2 Nano Lett. 15 7567–73
[19] Branny A, Kumar S, Proux R and Gerardot B D 2017 Deterministic strain-induced arrays of quantum emitters in a two-dimensional semiconductor Nat. Commun. 8 15053
[20] Yu L, Deng M, Zhang J L, Borghardt S, Kardynal B, Vučković J and Heinz T F 2021 Site-controlled quantum emitters in monolayer $MoSe_2$ Nano Lett. 21 2376–81
[21] Gisin N and Thew R 2007 Quantum communication Nat. Photon. 1 165–71
[22] Bhaskar M K et al 2020 Experimental demonstration of memory-enhanced quantum communication Nature 580 60–64
[23] Prawer S and Greentree A D 2008 Diamond for quantum computing Science 320 1601–2
[24] Pezzagna S and Meijer J 2021 Quantum computer based on color centers in diamond Appl. Phys. Rev. 8 011308
[25] Childress L and Hanson R 2013 Diamond NV centers for quantum computing and quantum networks MRS Bull. 38 134–8
[26] Zhang T et al 2021 Toward quantitative bio-sensing with nitrogen–vacancy center in diamond ACS Sens. 6 2077–107
[27] Ho K O, Shen Y, Pang Y Y, Leung W K, Zhao N and Yang S 2021 Diamond quantum sensors: from physics to applications on condensed matter research Funct. Diam. 1 160–73
[28] Schirhagl R, Chang K, Loretz M and Degen C L 2014 Nitrogen-vacancy centers in diamond: nanoscale sensors for physics and biology Annu. Rev. Phys. Chem. 65 83–105
[29] Wu D, Liang H, Jiao M, Cai Y-F, Duan C-K, Wang Y, Rong X and Du J 2023 Improved limits on an exotic spin- and velocity-dependent interaction at the micrometer scale with an ensemble-NV-diamond magnetometer Phys. Rev. Lett. 131 071801
[30] Liao M, Sang L, Teraji T, Koizumi S and Koide Y 2019 Ultrahigh performance on-chip single crystal diamond NEMS/MEMS with electrically tailored self-sensing enhancing actuation Adv. Mater. Technol. 4 1800325
[31] Dang C et al 2021 Achieving large uniform tensile elasticity in microfabricated diamond Science 371 76–78
[32] Banerjee A et al 2018 Ultralarge elastic deformation of nanoscale diamond Science 360 300–2
[33] Breeding C M and Shigley J E 2009 The "type" classification system of diamonds and its importance in gemology Gems Gemol 45 96–111
[34] Mzyk A, Ong Y, Ortiz Moreno A R, Padamati S K, Zhang Y, Reyes-San-Martin C A and Schirhagl R 2022 Diamond color centers in diamonds for chemical and biochemical analysis and visualization Anal. Chem. 94 225–49
[35] Wong K C et al 2022 Microscopic study of optically stable coherent color centers in diamond generated by high-temperature annealing Phys. Rev. Appl. 18 024044
[36] Ivády V, Simon T, Maze J R, Abrikosov I A and Gali A 2014 Pressure and temperature dependence of the zero-field splitting in the ground state of NV centers in diamond: a first-principles study Phys. Rev. B 90 235205
[37] Khalid A, Chung K, Rajasekharan R, Lau D W M, Karle T J, Gibson B C and Tomljenovic-Hanic S 2015 Lifetime reduction and enhanced emission of single photon color centers in nanodiamond via surrounding refractive index modification Sci. Rep. 5 11179
[38] Gali A, Janzén E, Deák P, Kresse G and Kaxiras E 2009 Theory of spin-conserving excitation of the $N\text{-}V^-$ center in diamond Phys. Rev. Lett. 103 186404
[39] Gali A, Fyta M and Kaxiras E 2008 Ab initio supercell calculations on nitrogen-vacancy center in diamond: electronic structure and hyperfine tensors Phys. Rev. B 77 155206
[40] Doherty M W, Manson N B, Delaney P, Jelezko F, Wrachtrup J and Hollenberg L C L 2013 The nitrogen-vacancy colour centre in diamond Phys. Rep. 528 1–45
[41] Mamin H J, Sherwood M H and Rugar D 2012 Detecting external electron spins using nitrogen-vacancy centers Phys. Rev. B 86 195422
[42] Hauf M V et al 2011 Chemical control of the charge state of nitrogen-vacancy centers in diamond Phys. Rev. B 83 081304
[43] Yip K Y et al 2019 Measuring magnetic field texture in correlated electron systems under extreme conditions Science 366 1355–9
[44] Jahnke K D, Naydenov B, Teraji T, Koizumi S, Umeda T, Isoya J and Jelezko F 2012 Long coherence time of spin qubits in ^{12}C enriched polycrystalline chemical vapor deposition diamond Appl. Phys. Lett. 101 012405
[45] Balasubramanian G et al 2009 Ultralong spin coherence time in isotopically engineered diamond Nat. Mater. 8 383–7
[46] Abobeih M H, Cramer J, Bakker M A, Kalb N, Markham M, Twitchen D J and Taminiau T H 2018 One-second coherence for a single electron spin coupled to a multi-qubit nuclear-spin environment Nat. Commun. 9 2552
[47] Bar-Gill N, Pham L M, Jarmola A, Budker D and Walsworth R L 2013 Solid-state electronic spin coherence time approaching one second Nat. Commun. 4 1743

[48] Laube C, Temme R, Prager A, Griebel J, Knolle W and Abel B 2023 Fluorescence lifetime control of nitrogen vacancy centers in nanodiamonds for long-term information storage *ACS Nano* **17** 15401–10
[49] Zhu X *et al* 2011 Coherent coupling of a superconducting flux qubit to an electron spin ensemble in diamond *Nature* **478** 221–4
[50] England D G, Fisher K A G, MacLean J-P W, Bustard P J, Lausten R, Resch K J and Sussman B J 2015 Storage and retrieval of THz-bandwidth single photons using a room-temperature diamond quantum memory *Phys. Rev. Lett.* **114** 053602
[51] Janitz E, Herb K, Völker L A, Huxter W S, Degen C L and Abendroth J M 2022 Diamond surface engineering for molecular sensing with nitrogen—vacancy centers *J. Mater. Chem.* C **10** 13533–69
[52] Cui Y, Leong W-H, Liu C-F, Xia K, Feng X, Gergely C, Liu R-B and Li Q 2022 Revealing capillarity in AFM indentation of cells by nanodiamond-based nonlocal deformation sensing *Nano Lett.* **22** 3889–96
[53] Liu C-F, Leong W-H, Xia K, Feng X, Finkler A, Denisenko A, Wrachtrup J, Li Q and Liu R B 2020 Ultra-sensitive hybrid diamond nanothermometer *Natl Sci. Rev.* **8** nwaa194
[54] Xia K, Liu C-F, Leong W-H, Kwok M-H, Yang Z-Y, Feng X, Liu R-B and Li Q 2019 Nanometer-precision non-local deformation reconstruction using nanodiamond sensing *Nat. Commun.* **10** 3259
[55] Dolde F *et al* 2011 Electric-field sensing using single diamond spins *Nat. Phys.* **7** 459–63
[56] Li R *et al* 2020 Nanoscale electrometry based on a magnetic-field-resistant spin sensor *Phys. Rev. Lett.* **124** 247701
[57] Zheng W, Bian K, Chen X, Shen Y, Zhang S, Stöhr R, Denisenko A, Wrachtrup J, Yang S and Jiang Y 2022 Coherence enhancement of solid-state qubits by local manipulation of the electron spin bath *Nat. Phys.* **18** 1317–23
[58] Shen Y, Wang P, Cheung C T, Wrachtrup J, Liu R-B and Yang S 2023 Detection of quantum signals free of classical noise via quantum correlation *Phys. Rev. Lett.* **130** 070802
[59] Tamura S *et al* 2014 Array of bright silicon-vacancy centers in diamond fabricated by low-energy focused ion beam implantation *Appl. Phys. Express* **7** 115201
[60] Hepp C *et al* 2014 Electronic structure of the silicon vacancy color center in diamond *Phys. Rev. Lett.* **112** 036405
[61] Sipahigil A *et al* 2016 An integrated diamond nanophotonics platform for quantum-optical networks *Science* **354** 847–50
[62] Sukachev D D, Sipahigil A, Nguyen C T, Bhaskar M, Evans R, Jelezko F and Lukin M 2017 Silicon-vacancy spin qubit in diamond: a quantum memory exceeding 10 ms with single-shot state readout *Phys. Rev. Lett.* **119** 223602
[63] Bradac C, Gao W, Forneris J, Trusheim M E and Aharonovich I 2019 Quantum nanophotonics with group IV defects in diamond *Nat. Commun.* **10** 5625
[64] Iwasaki T 2020 Color centers based on heavy group-IV elements *Semiconductors and Semimetals* ed C E Nebel, I Aharonovich, N Mizuochi and M Hatano (Elsevier) pp 237–56
[65] Trusheim M E *et al* 2020 Transform-limited photons from a coherent tin-vacancy spin in diamond *Phys. Rev. Lett.* **124** 023602
[66] Karin T, Dunham S and Fu K-M 2014 Alignment of the diamond nitrogen vacancy center by strain engineering *Appl. Phys. Lett.* **105** 053106
[67] Ovartchaiyapong P, Lee K W, Myers B A and Jayich A C B 2014 Dynamic strain-mediated coupling of a single diamond spin to a mechanical resonator *Nat. Commun.* **5** 4429
[68] Maity S, Shao L, Sohn Y-I, Meesala S, Machielse B, Bielejec E, Markham M and Lončar M 2018 Spectral alignment of single-photon emitters in diamond using strain gradient *Phys. Rev. Appl.* **10** 024050
[69] Fukui T *et al* 2014 Perfect selective alignment of nitrogen-vacancy centers in diamond *Appl. Phys. Express* **7** 055201
[70] Ozawa H, Tahara K, Ishiwata H, Hatano M and Iwasaki T 2017 Formation of perfectly aligned nitrogen-vacancy-center ensembles in chemical-vapor-deposition-grown diamond (111) *Appl. Phys. Express* **10** 045501
[71] Michl J *et al* 2014 Perfect alignment and preferential orientation of nitrogen-vacancy centers during chemical vapor deposition diamond growth on (111) surfaces *Appl. Phys. Lett.* **104** 102407
[72] Duan L M, Lukin M D, Cirac J I and Zoller P 2001 Long-distance quantum communication with atomic ensembles and linear optics *Nature* **414** 413–8
[73] Trusheim M E and Englund D 2016 Wide-field strain imaging with preferentially aligned nitrogen-vacancy centers in polycrystalline diamond *New J. Phys.* **18** 123023
[74] Tsukamoto M, Ogawa K, Ozawa H, Iwasaki T, Hatano M, Sasaki K and Kobayashi K 2021 Vector magnetometry using perfectly aligned nitrogen-vacancy center ensemble in diamond *Appl. Phys. Lett.* **118** 264002
[75] Zhao N, Hu J-L, Ho S-W, Wan J T K and Liu R B 2011 Atomic-scale magnetometry of distant nuclear spin clusters via nitrogen-vacancy spin in diamond *Nat. Nanotechnol.* **6** 242–6
[76] Liu G-Q, Liu R-B and Li Q 2023 Nanothermometry with enhanced sensitivity and enlarged working range using diamond sensors *Acc. Chem. Res.* **56** 95–105
[77] Chen H Y, MacQuarrie E R and Fuchs G D 2018 Orbital state manipulation of a diamond nitrogen-vacancy center using a mechanical resonator *Phys. Rev. Lett.* **120** 167401
[78] Lee K W, Lee D, Ovartchaiyapong P, Minguzzi J, Maze J R and Bleszynski Jayich A C 2016 Strain coupling of a mechanical resonator to a single quantum emitter in diamond *Phys. Rev. Appl.* **6** 034005
[79] Tao Y, Boss J M, Moores B A and Degen C L 2014 Single-crystal diamond nanomechanical resonators with quality factors exceeding one million *Nat. Commun.* **5** 3638
[80] Meesala S, Sohn Y I, Atikian H A, Burek M J, Kim S, Choy J and Loncar M 2015 Strain coupling of diamond nitrogen vacancy centers to nanomechanical resonators *2015 Conf. on Lasers and Electro-Optics (CLEO)* pp 1–2
[81] Burek M J, Ramos D, Patel P, Frank I W and Lončar M 2013 Nanomechanical resonant structures in single-crystal diamond *Appl. Phys. Lett.* **103** 131904
[82] Xu Z, Yin Z-Q, Han Q and Li T 2019 Quantum information processing with closely-spaced diamond color centers in strain and magnetic fields *Opt. Mater. Express* **9** 4654–68
[83] Wang G, Barr A R, Tang H, Chen M, Li C, Xu H, Stasiuk A, Li J and Cappellaro P 2023 Characterizing temperature and strain variations with qubit ensembles for their robust coherence protection *Phys. Rev. Lett.* **131** 043602
[84] Shang Y-X, Hong F, Dai J-H, Lu Y N, Yu H, Yu Y H, Yu X H, Pan X Y and Liu G Q 2022 High-pressure NMR enabled by diamond nitrogen-vacancy centers (arXiv:2203.10511)
[85] Golter D A, Oo T, Amezcua M, Lekavicius I, Stewart K A and Wang H 2016 Coupling a surface acoustic wave to an electron spin in diamond via a dark state *Phys. Rev.* X **6** 041060
[86] Kim M, Mamin H J, Sherwood M H, Ohno K, Awschalom D and Rugar D 2015 Decoherence of near-surface nitrogen-vacancy centers due to electric field noise *Phys. Rev. Lett.* **115** 087602
[87] Teissier J, Barfuss A, Appel P, Neu E and Maletinsky P 2014 Strain coupling of a nitrogen-vacancy center spin to a diamond mechanical oscillator *Phys. Rev. Lett.* **113** 020503

[88] Udvarhelyi P, Shkolnikov V O, Gali A, Burkard G and Pályi A 2018 Spin-strain interaction in nitrogen-vacancy centers in diamond *Phys. Rev.* B **98** 075201
[89] Ho K O, Wong K C, Leung M Y, Pang Y Y, Leung W K, Yip K Y, Zhang W, Xie J, Goh S K and Yang S 2021 Recent developments of quantum sensing under pressurized environment using the nitrogen vacancy (NV) center in diamond *J. Appl. Phys.* **129** 241101
[90] Meesala S *et al* 2018 Strain engineering of the silicon-vacancy center in diamond *Phys. Rev.* B **97** 205444
[91] Guo X *et al* 2023 Microwave-based quantum control and coherence protection of tin-vacancy spin qubits in a strain-tuned diamond-membrane heterostructure *Phys. Rev.* X **13** 041037
[92] Zhang H *et al* 2016 Approaching the ideal elastic strain limit in silicon nanowires *Sci. Adv.* **2** e1501382
[93] Li S, Zhang H, Chou J-P, Wei J, Lu Y and Hu A 2018 Deep ultra-strength"-induced band structure evolution in silicon nanowires *J. Phys. Chem.* C **122** 15780–5
[94] Li S, Chou J-P, Zhang H, Lu Y and Hu A 2018 A study of strain-induced indirect-direct bandgap transition for silicon nanowire applications *J. Appl. Phys.* **125** 082520
[95] Vindolet B *et al* 2022 Optical properties of SiV and GeV color centers in nanodiamonds under hydrostatic pressures up to 180 GPa *Phys. Rev.* B **106** 214109
[96] Assumpcao D R *et al* 2023 Deterministic creation of strained color centers in nanostructures via high-stress thin films *Appl. Phys. Lett.* **123** 244001
[97] Field J E 1992 *The Properties of Natural and Synthetic Diamond* (Academic)
[98] Dai J-H, Shang Y-X, Yu Y-H, Xu Y, Yu H, Hong F, Yu X H, Pan X Y and Liu G Q 2022 Quantum sensing with diamond NV centers under megabar pressures (arXiv:2204.05064)
[99] Nie A *et al* 2019 Approaching diamond's theoretical elasticity and strength limits *Nat. Commun.* **10** 5533
[100] Yang L, Fan R, Hu A, Ma J, Liu Y and Lu Y 2023 Tuning donor level of nitrogen-doped diamond by deep strain engineering—an *ab initio* study *Appl. Phys. Lett.* **123** 062105
[101] Guo X *et al* 2023 Direct-bonded Diamond Membranes for Heterogeneous Quantum and Electronic Technologies (arXiv:2306.04408)
[102] Liang J, Kobayashi A, Shimizu Y, Ohno Y, Kim S-W, Koyama K, Kasu M, Nagai Y and Shigekawa N 2021 Fabrication of GaN/diamond heterointerface and interfacial chemical bonding state for highly efficient device design *Adv. Mater.* **33** 2104564
[103] Liang J, Masuya S, Kasu M and Shigekawa N 2017 Realization of direct bonding of single crystal diamond and Si substrates *Appl. Phys. Lett.* **110** 111603