ODMR effect in spin centers of silicon carbide as sensors of magnetic fields, temperature and mechanical stresses

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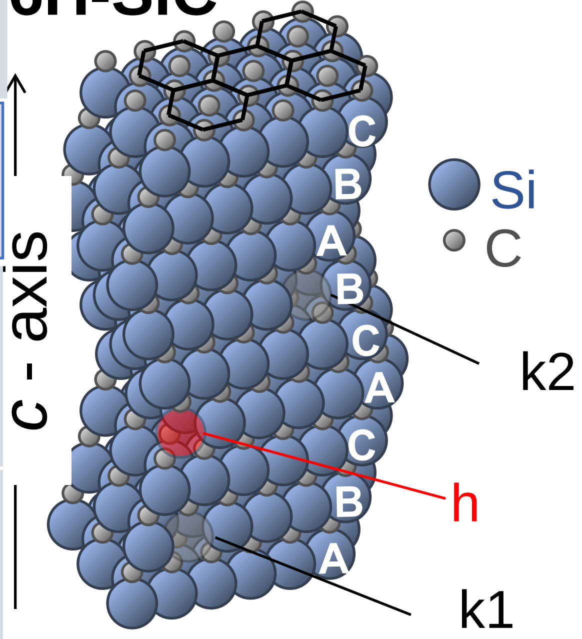
Introduction and Motivation

- The possibility of detecting and manipulating the spin states of localized electron in a solid is of special interest.
- The known solid-state systems where such manipulations at room temperature have become possible is the NV defect in diamond and silicon carbide defects.
- The optical detection of magnetic resonance (ODMR) in a single defect has become possible because of the existence of a unique cycle of optical alignment and, as a result, the creation of an inverse population of sublevels in the defect.
- Atomic-scale color centres in bulk and nanocrystalline SiC are promising systems for quantum photonics compatible with fiber optics, quantum information processing and sensing at ambient conditions. Color centres which acts as stable single photon sources in SiC can be key elements for quantum photonics and communications.

6H-SiC



Silicon Carbide

- Production on industrial scale
- Binary material:
  - different polytypes
  - non-equivalent lattices positions with different physical properties
- Bandgap: 2.36eV … 3.32eV (525 nm … 373nm)
- Silicon vacancy (V_{Si})
  - intrinsic deep-level defects
  - near infrared excitation

➡ 3 non-equivalent lattice sites for Si / V_{Si} (h, k1, k2)

Introduction

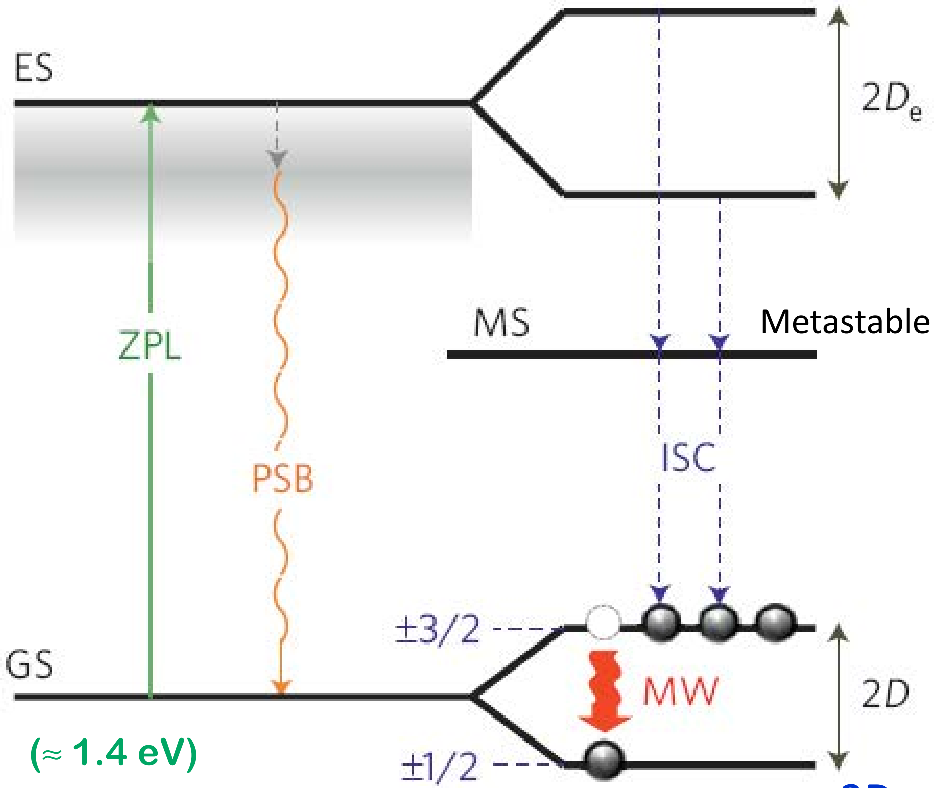
Why Optically Detected Magnetic Resonance – ODMR?

- In ODMR a microwave-induced repopulation of Zeeman sublevels is detected optically, i.e., there is a giant gain in sensitivity since an energy of optical quantum is by several orders of magnitude higher compared with microwave one, it becomes possible to detect a very small number of spins **down to single spin !**

- ODMR is a “trigger detection” in that the absorption of a resonance microwave photon triggers a change in emission (absorption) of an optical photon due to the selective feeding of the magnetic sublevels. At the root of the selective feeding are spin selection rules for the optical transitions and for the non-radiative decay.

Spin selective inter system crossing

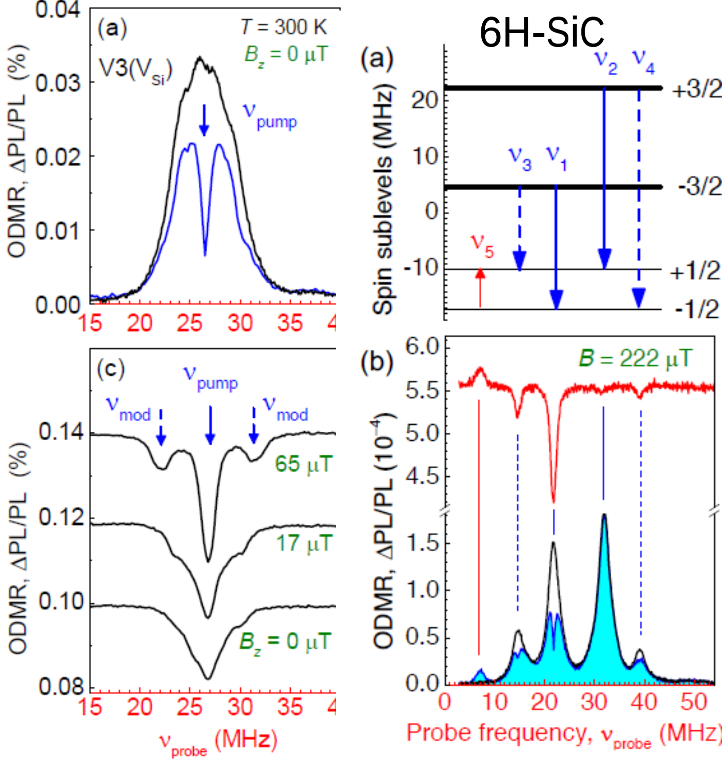
2De-parameter
- Depend on the temperature
- Depends on the magnetic field (Zeeman effect)
- Depends on mechanical deformation – open question



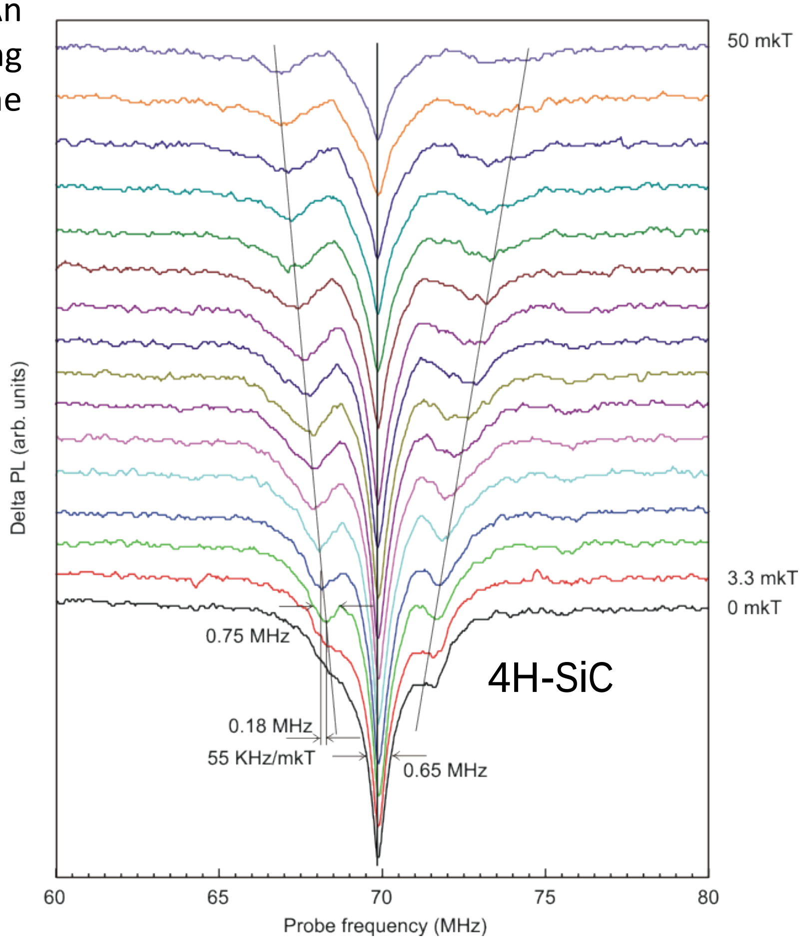
2D-parameter
- Does not depend on temperature
- Depends on the magnetic field (Zeeman effect)
- Depends on mechanical deformation

Sensors of magnetic fields

A scanning optical quantum magnetometer with submicron spatial resolution is proposed that is based on the phenomenon of hole burning in the signal of optically detected magnetic resonance (ODMR) on atomic-sized color centers in silicon carbide crystals under conditions of spin level saturation by means of additional high-frequency resonance pumping. An increase in the sensitivity is achieved due to narrowing of the ODMR line and increasing slope of the dependence of signal frequency on the magnetic field.



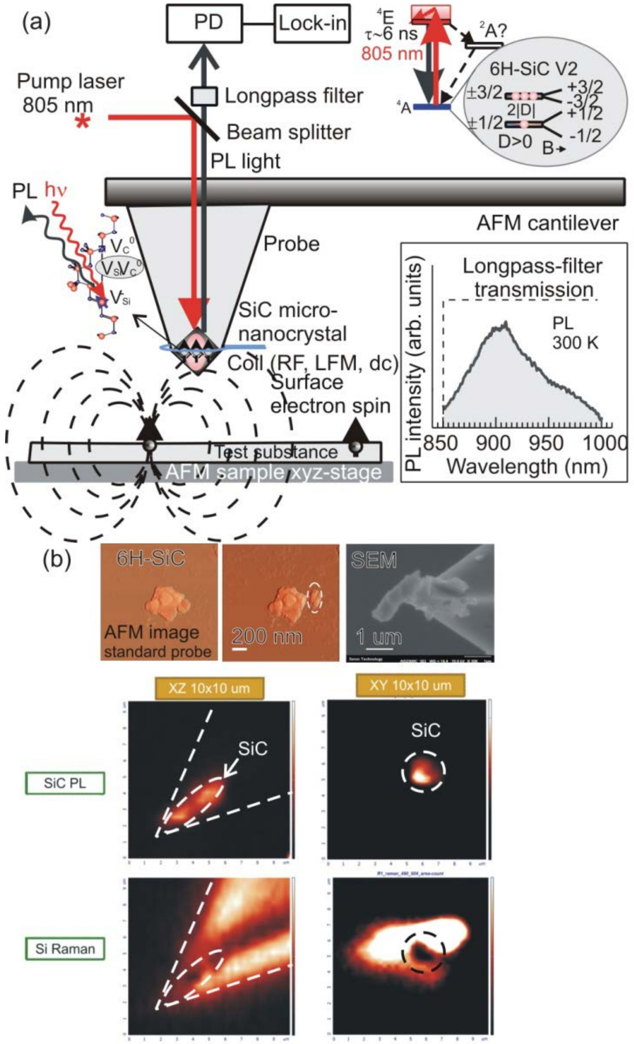
A.N. Anisimov., et al Nature Comm. 10, #1678 (2019)



A.N. Anisimov., et al *Tech. Phys. Lett.* **45**, iss. 5, 494–498 (2019)

«Magnetic field measurement method» RF patent No. 2695593

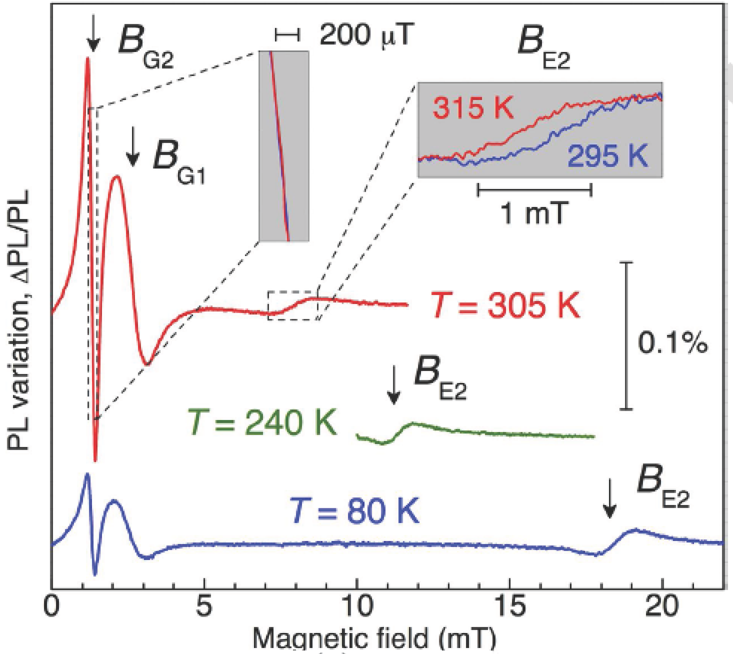
A scanning device where ensembles of spin centers placed on the tip of the AFM cantilever serve as sensitive sensors of magnetic and temperature fields has been proposed. It has been shown that a SiC sensor has a unique capability of switching between regimes of detection of magnetic and temperature fields. For this reason, it is a universal detection system for applications in biology.



A.N. Anisimov., et al *JETP Letters* **108**, iss. 9, pp. 610–615 (2018)

Sensors of temperature

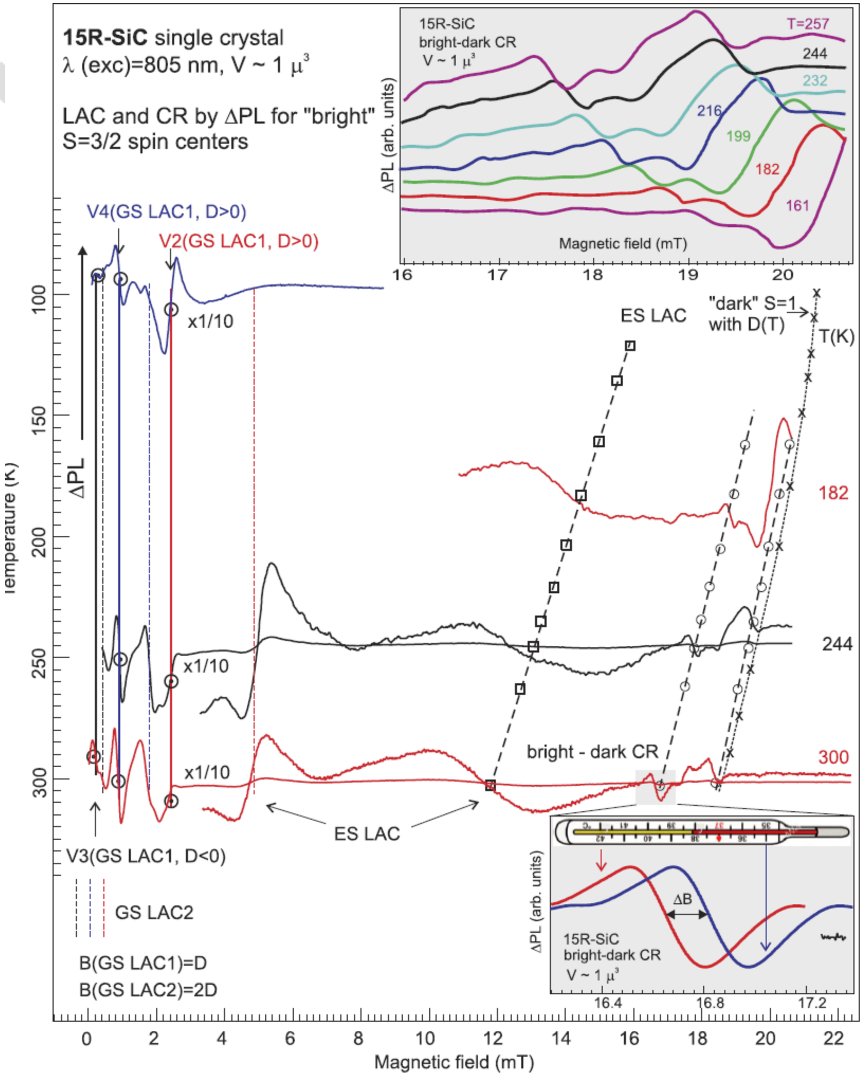
All-optical thermometry technique based on the energy level cross-relaxation in atomic-scale spin centers in SiC is demonstrated. This technique exploits a giant thermal shift of the zero-field splitting for centers in the triplet ground state, S=1, undetected by photoluminescence (so called “dark” centers) coupling to neighbouring spin-3/2 centers which can be optically polarized and read out (“bright” centers), and does not require radiofrequency fields. EPR was used to identify defects. The width of the cross-relaxation line is almost an order of magnitude smaller than the width of the excited state level-anticrossing line, which was used in all-optical thermometry and which can not be significantly reduced since determined by the lifetime of the excited state. With approximately the same temperature shift and the same signal intensities as for excited state level-anticrossing, cross-relaxation signal makes it possible to increase the sensitivity of the temperature measurement by more than an order of magnitude. Temperature sensitivity is estimated to be approximately 10 mK/Hz^1/2 within a volume about 1 µm^3, allocated by focused laser excitation in a scanning confocal microscope. Using cross-relaxation in the ground states of “bright” spin-3/2 centers and “dark” S=1 centers for temperature sensing and ground state level anti-crossing of “bright” spin-3/2 centers an integrated magnetic field and temperature sensor with submicron space resolution can be implemented using the same spin system.



$$2D_E(T) = 2D_E^{(0)} + \beta T$$

$$\beta = -2.1 \pm 0.1\,\mathrm{MHz/K}$$

$\delta T \approx$ 100 mK/Hz$^{1/2}$ within a detection volume of approximately 10^{-6} mm^3

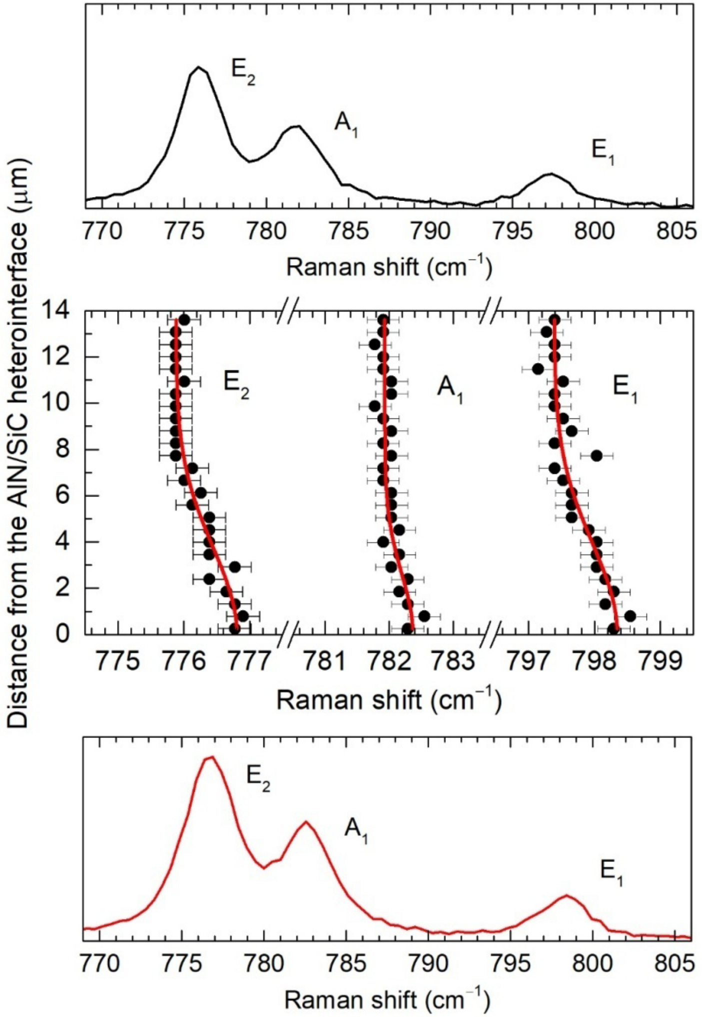


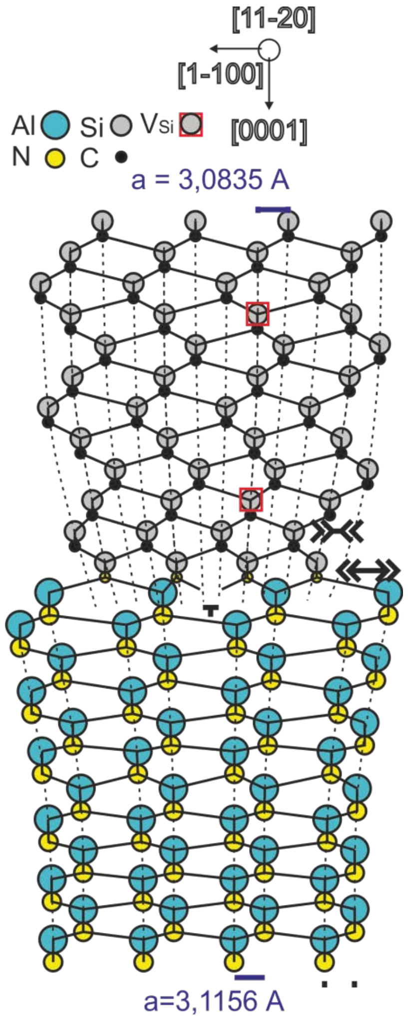
A.N. Anisimov et al. *Nature Scientific Reports* **6**, 33301 (2016)

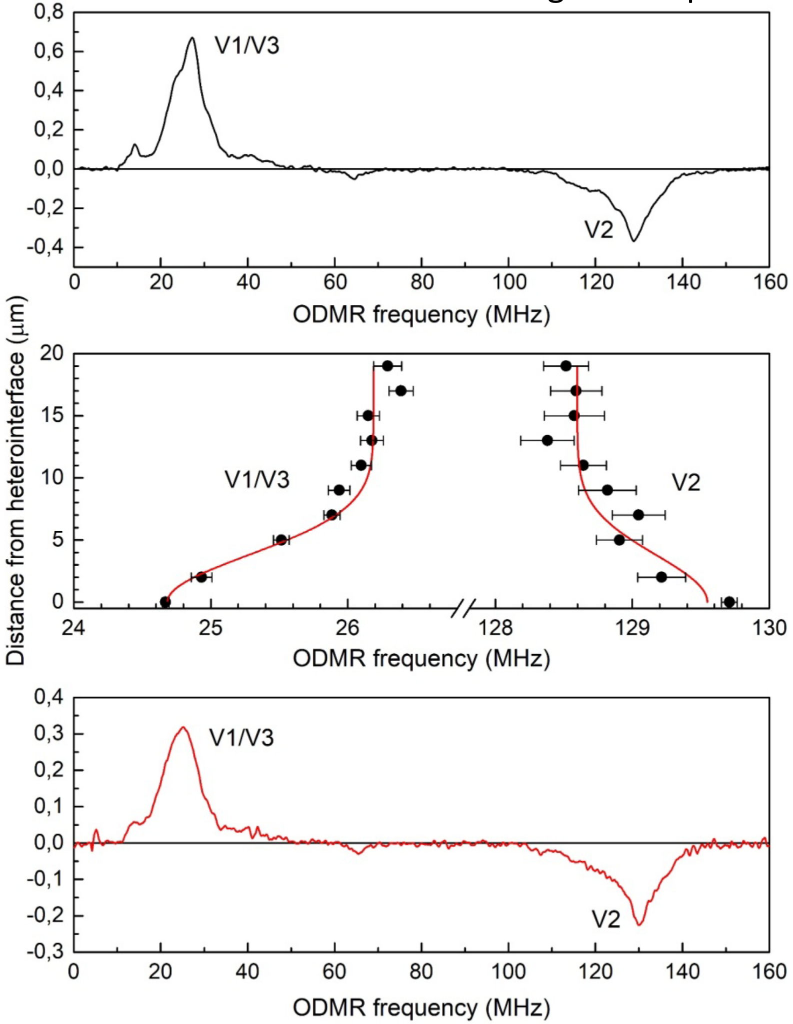
Anisimov *et al. AIP Advances* ***8, 085304 (2018)***

Sensors of mechanical stresses

A detailed analysis of the effect of static mechanical deformation on the spin system, which is a silicon vacancy insilicon carbide, is carried out. For this, a SiC/AlN structure deformed by growth conditions was chosen, in which it wasfound by the methods of optically detected magnetic resonance that the splitting of the zero field into spin centers witha spin of 3/2 in 6H-SiC changes when approaching the interface. Using Raman spectroscopy with spatial resolution ona micron scale, it was possible to estimate the stress and determine the constant of spin-deformation interaction. Animportant application of this research could be the synchronization of quantum modes. For our studies, we chose theV1 / V3 and V2 centers in 6H-SiC, since they contain a unique ensemble of centers with opposite signs of the splittingparameters, which is also confirmed by the dependence we observed. The results can also be used to fine-tune theenergies of spin transitions by deformation.







Sensors of mechanical stresses

Firstly, the measured parameters of deformation in these structures may be of interest to technologists for optimizing the method of growth of aluminum nitride crystals. These deformations seriously interfere with the production of thick layers of aluminum nitride without cracks and chips.

Second, the information obtained on the effect of mechanical stresses on the position of D suggests another model to explain the broadening of lines on ensembles of centres in silicon carbide and the presence of a set of different spin packets in an inhomogeneously broadened line.

Thirdly, the obtained dependence indicates what order of deformation must be created in silicon carbide using the piezoelectric effect to control and adjust the quantum state of spin centers during synchronization of their quantum modes.

Conclusion

-Registration of weak magnetic fields, temperature and stress components with nanometer resolution is a fundamental problem of physics and biophysics.

-It has been shown that a SiC sensor has a unique capability of switching between regimes of detection of magnetic and temperature fields. For this reason, it is a universal detection system for applications in biology.

-Use of effects: LAC, hole burning (spin packet) in ODMR and classic ODMR allow sensors with different characteristics and application in different applications. For example, for the study of living cells and currents of integrated circuits.

-The coupling of individually addressable “bright” spin-3/2 centers connected by a chain of “dark” S=1 spins, could be considered in quantum information processing and multicenter entanglement under ambient conditions

-Our results hence open new possibilities for quantum sensors.

-Silicon vacancies in silicon carbide have great potential in the creation of quantum Qudite.

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