Decoherence Phenomena in Nitrogen-Vacancy Diamond

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Abstract:

Nitrogen vacancy (NV) centers in diamonds are atom-sized spin defects whose unique properties enable their use as robust quantum sensors. Recent research efforts have focused on NV magnetometry, where both single and ensemble NVs are used for highly sensitive magnetic field detection with nanoscale spatial resolution. While NV sensors have been successfully applied to many fields, ensemble NV diamonds are still below the sensitivity threshold needed for many more potential applications. This project aims to investigate the relationship between crystallographic strain and the spin coherence time T^*_2 in NV-diamonds grown by chemical vapor deposition (CVD). A better understanding of this relationship can provide valuable input for improving diamond growth methods and eventually extending T^*_2.

Summary of Research:

While CVD allows for relatively high control over the depths and concentrations of nitrogen impurities, samples produced this way can contain unwanted and sometimes large strain features. This crystallographic strain can couple to NV spins, resulting in faster dephasing and lower DC magnetic field sensitivity.

Although it is understood that this stress decreases NV coherence, the exact details of the interaction are relatively unknown. For example, there still exists uncertainty in widely used spin-strain coupling coefficients in addition to the effects that large (sample-sized) strain patterns have in high-stressed crystals [2].

Dephasing Mechanisms. T^*_2 is a decay constant that characterizes the coherence time of our NV spins. When static or gradually changing inhomogeneities are present within a sample, T^*_2 will be shortened, resulting in decreased magnetic field sensitivity. Common contributors to dephasing are shown in the equation displayed in Figure 1.

Samples. Both high and low strain samples were used, allowing observation of strain effects in different diamond environments. The nitrogen limited T^*_2 value was 1.6 μs for the lower strain sample (Figure 4) and 2.5 μs for the higher strain sample (Figure 2). This means that our measured T^*_2 can only take values between the limited maximum and zero.

$$\frac{1}{T_2^*} \approx \frac{1}{T_2^*\{\text{electronic spin bath}\}} + \frac{1}{T_2^*\{\text{nuclear spin bath}\}} + \frac{1}{T_2^*\{\text{strain gradients}\}} + \frac{1}{T_2^*\{\text{electric field noise}\}} + \frac{1}{T_2^*\{\text{magnetic field gradients}\}} + \frac{1}{T_2^*\{\text{temperature variation}\}} + \frac{1}{T_2^*\{\text{unknown}\}} + \frac{1}{2T_1}, \quad (18)$$

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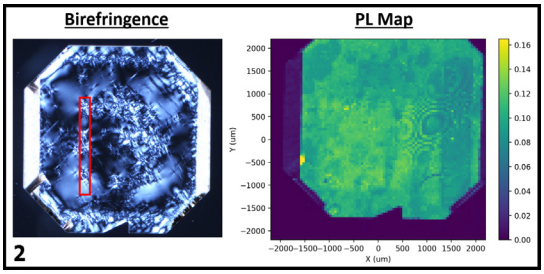

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Figure 1, top: Equation for T^*_2 in terms of common contributors to spin dephasing [1]. Figure 2, bottom: Birefringence image and photoluminescence colormap of the higher strain sample. The red outline shows the location of the line test in Figure 3.

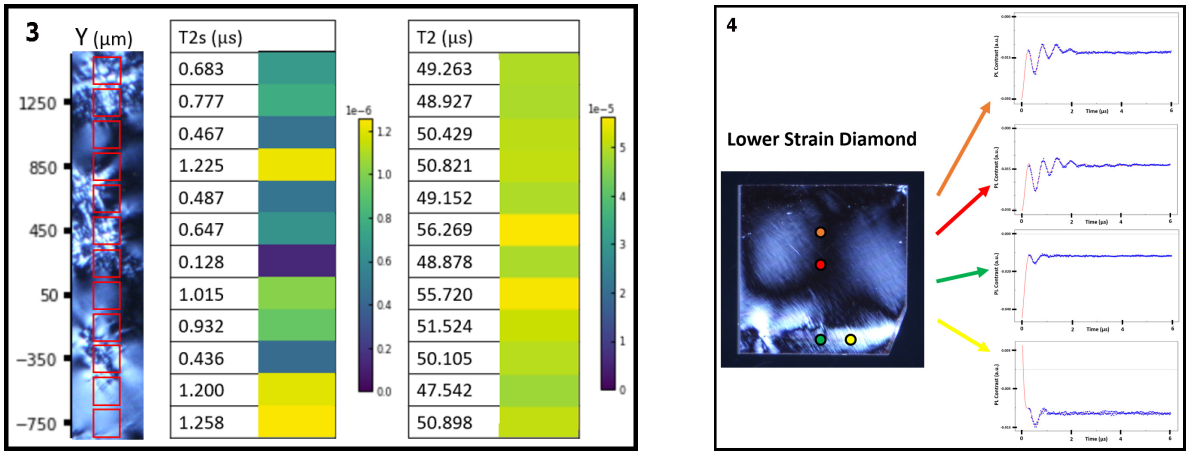

*Figure 3, left: T*2 and T*2 values for a single line test in the high strain sample. Figure 4, right: Comparison of free induction decay (FID) curves at different strain locations. T*2 shown to decrease in areas of high strain.*

Measurement Technique. To study the correspondence between strain and T^*_2 both birefringence microscopy and optically detected magnetic resonance (ODMR) techniques were used. The Deep Focal Depth Confocal (DFDC) microscope, an instrument designed and built by Dr. Masuyama, was used to measure T^*_2. The primary components consist of a 532 nm green laser for optical initialization and readout, a coplanar waveguide to supply uniform microwave control pulses, and a permanent magnet to lift spin-state degeneracies. A movable stage was used to control the position of samples with respect to the beam. Traditional birefringence imaging was used to determine the strain features present within each sample. This was then overlayed with a photoluminescence (PL) map taken by continuously scanning the laser over the sample's surface. Both images for the higher strain sample are shown in Figure 2. After several calibrating pulse measurements, a Ramsey sequence was performed to determine T^*_2 at each location tested. The sequence consists of a microwave π/2 pulse, followed by a variable interval of free precession, and ended by a second π/2 pulse. The result of repeating this sequence over increasing intervals of free precession is a free induction decay curve, whose exponential decay constant gives the value for T^*_2.

Results. Initial tests on the lower strain diamond confirmed the assumption that strain results in lower T^*_2 values (Figure 3). Further tests on the high strain diamond also show a correspondence between dislocation bundles and the lowest T^*_2 measurements (Figure 4). T^*_2 values were also measured at these locations to rule out the possibility of nitrogen concentration discrepancies causing the dephasing differences. Whether or not this trend is a direct result of crystal strain remains to be fully understood. There are many points where the relative strain seen in the birefringence image and the measured T^*_2 value do not follow the expected relationship of higher observed strain leading to lower coherence times. Such as at the 450 and 250 μm positions. It should be noted that the current experimental setup is only sensitive to crystallographic strain along the NV axis the laser is aligned with. Therefore, there are components of the stress tensor we are insensitive to and thus features in the birefringence image that we do not sense the effects of.

Conclusion and Next Steps:

These results are the first attempt at mapping and characterizing the strain-T^*_2 relationship in these diamond samples on a newly designed instrument. Future efforts will be to refine the experimental and data analysis techniques used to obtain T^*_2 values in addition to testing more samples. An important observation is that the maximum T^*_2 values observed in even the most uniform areas displayed values that were each around half of their nitrogen-limited maximum. This suggests that there is an unaccounted-for dephasing mechanism or non-optimized instrumentation parameters preventing these maximum values. Inhomogeneous magnetic fields, electric fields, or temperature gradients could all play a part, and limiting or accounting for their effects must be done to fully characterize the effect that crystallographic strain may have on our samples.

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References:

[1] J. F. Barry, J. M. Schloss, E. Bauch, M. J. Turner, C. A. Hart, L. M. Pham, and R. L. Walsworth, Rev. Mod. Phys. 92, 015004 (2020).

[2] P. Kehayias, M. J. Turner, R. Trubko, J. M. Schloss, C. A. Hart, M. Wesson, D. R. Glenn, and R. L. Walsworth, Physical Review B 100, 174103 (2019).