NV-Centers in Diamond as a Qubit Platform

An Overview

Alex Heilman

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What's a Qubit?

I think we've seen this plenty of times.

Criteria for Qubit Platforms

Initializable
Readable
Robust
Scalable
See: DiVicenzio's Criteria

Universality of Gates

If we have a Hamiltonian parametrizing the Pauli's and a non-local two-qubit gate (like CNOT), we have a universal set of gates.

Why Defects?

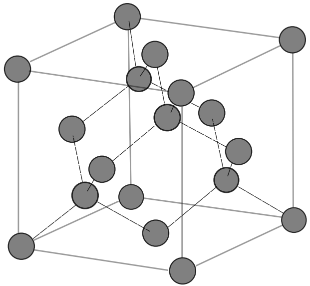
Defects can give us localized electronic and spin states trapped in a solid state system.

Also, gives us more prospective systems, since for every solid state system we'll have (atleast) a few possible defects

Really, the concepts discussed below should apply to most similar systems, it's just that this system is well-studied and has convenient energy levels

Why Diamond?

Diamond is an ideal candidate due to low density of phonon modes (relatively high Debye temperature)



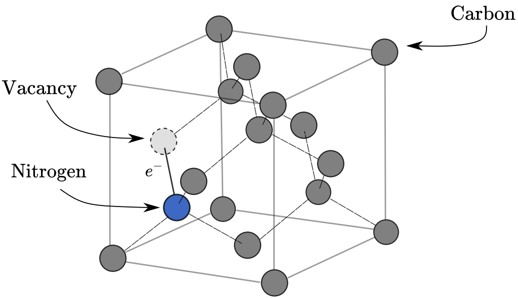
This leaves spins of defects and electrons less influenced by phonon modes, increasing their coherence times

What's an NV-Center

NV-Center refers to a type of defect in diamond lattices with several charge states (-, +, neutral). The most commonly discussed charge state is the (-) NV-Center. If unspecified, this is most likely the defect under consideration.

What's an (-) NV-Center

An (-) NV-Center is a neighboring nitrogen-vacancy defect in diamond with an extra electron (completes the neighboring carbon's valence shell)



(-) NV-Center

This results in a 'center' between the two with localized energy/spin states.

These energy states may be used as a Qubit platform.

Spin Hamiltonian Effects

We're really interested in the spin state of the electron. Primarily dependent on spin-spin and spin-magnetic field interactions (we'll ignore electric fields here). The relevant effects then are:

(Electron State) Zero-Field Splitting (ZFS): SDS

(Nuclear Spin) Quadrapole Interaction: IQI

(Spin-Spin) Hyper-fine Interactions: SAI

(Spin-B Field) Zeeman Effects: $g_s SB, g_i I_i B$

NV-Center Hamiltonian

The electron will be taken to be localized to the defect. We'll take this localized two electron state to be the unperturbed solution and apply some interaction effects, with the corresponding interaction Hamiltonian below (again, assuming no external electric field/Stark effects):

$$H = \underbrace{\vec{\hat{S}}\mathbf{D}\vec{\hat{S}}}_{\text{ZFS}} + \underbrace{\vec{\hat{I}}_N\mathbf{Q}\vec{\hat{I}}_N}_{\text{Quadrapole}} + \underbrace{\vec{\hat{S}}(\mathbf{A}_N\vec{\hat{I}}_N + \sum_i \mathbf{A}_{C_i}\vec{\hat{I}}_{C_i})}_{\text{Hyperfine}}$$

$$+ \underbrace{(\vec{\hat{S}}\mathbf{g}_s + \vec{\hat{I}}_N\mathbf{g}_N + \sum_i \vec{\hat{I}}_{C_i}\mathbf{g}_{C_i})\vec{B}}_{\text{Zeeman}} \quad [2]$$

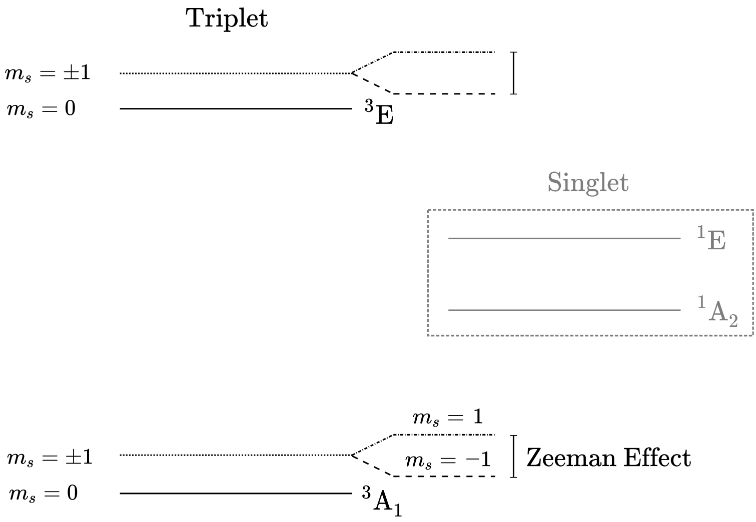
Simplifications

Assuming we apply a magnetic field only along the symmetry axis, which we define to be the z direction, and neglecting the surrounding carbon's effects (both Zeeman and hyperfine, though these allow us to use the nv-center as register for these surrounding sites):

$$H_{NV} \approx DS_z^2 + \omega_e S_z + QI_z^2 + \omega_n I_z + AS_z I_z \quad [1]$$

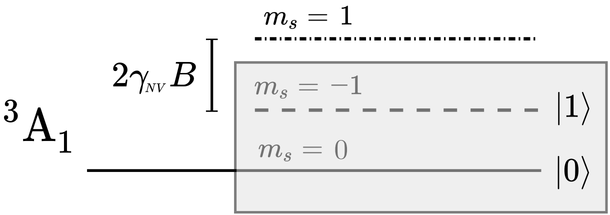
where $\omega_i = \gamma_i B$, the Larmor frequency.
$D = 2\pi \times (2.87GHz)$, the dipole coupling constant
$Q = 2\pi \times (-4.95GHz)$, the nuclear quadrapole coupling constant
$A = 2\pi \times (-2.16GHz)$, the hyperfine coupling constant

Energy Levels



Qubit States

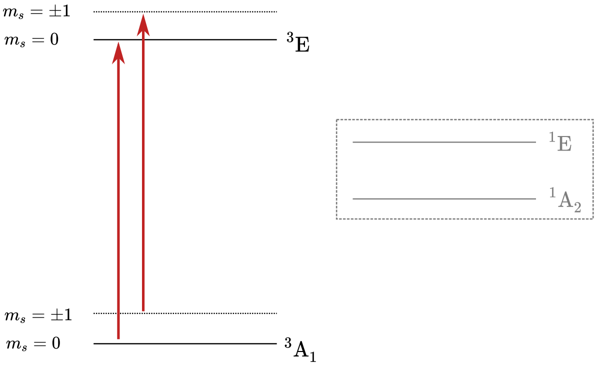
The localized spin states of the defect may be used as a two-level system.
We make the identifications:



The transitions between these states are in the microwave regime.

Initialization

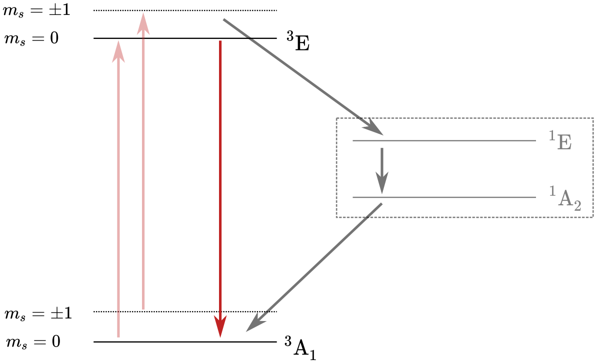
Initialization to the zero state can be achieved by an asymmetric relaxation from the first excited triplet state (^3E) to the triplet ground state (^3A).



Applying a resonant pulse (532 nm) excites all triplet ground states to their corresponding excited states ($\Delta m_s = 0$).

Initialization cont.

Excited $m_s = 0$ states have been shown to decay back into $m_s = 0$ ground states, but $m_s = \pm 1$ excited states favor a non-radiative (vibrational) decay mode via the singlet states, back into the $m_s = 0$ ground state.



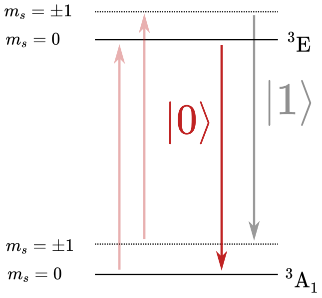
This may be exploited to intialize the spin state into our $|0\rangle$ state.

Local Control

Perpendicular (polarization relative symmetry axis) microwave pulses can induce Rabi flopping of state between $|0\rangle$ and $|1\rangle$.

Optically Detected Magnetic Resonance

Much like the initialization technique, optically detected magnetic resonance (ODMR) takes advantage of the asymmetric relaxation modes of the excited state.



Hence, if the defect flouresces when hit with a resonant pulse, it was measured to be in the $|0\rangle$ state, but if it's 'dark' after a resonant pulse, it can be considered to have been in the $|1\rangle$ state.

Measurement Cont.

Note also that these allows our read-out to essentially be part of the next computation's initialization.

One problem, however, is the possibility of internal reflection of the emitted photon. This can be solved with an immersion lens built into the diamond.

Conclusion & Outlook

Promising candidate due to practical methods of initialization, measurement, and qubit manipulation.

Long coherence times, room temperature stability

Haven't discussed scalability, two (or more) qubit operations, quantum networking, etc.

Recent works have used neighboring spins (of carbon and nitrogen) as additional qubits or used spin-photon coupling to get distant centers to interact

Some have also considered defect levels as qutrits

References I

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