# CHAPTER II

# LITERATURE REVIEW

In this section, we describe the brief qubit knowledge with equation and Bloch sphere representation. We give the fundamental knowledge of the NV center consisting of properties of the NV center, energy level of the NV center, Zeeman effects on the NV center, Hamiltonian of the NV center and application of utilizing the NV center as a magnetic field sensor.

## 2.1 Quantum bit

Quantum bit, or qubit, is a fundamental unit in a quantum processor. Unlike the classical bit, which has only existed in one of two binary states (0 or 1), the qubit exists in a superposition of both states simultaneously. As a result, this unique property allows qubits to process calculations more efficiently than classical bits.

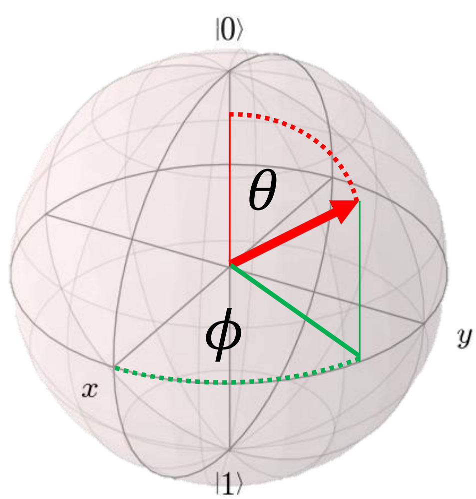


**Figure 2.1** The Bloch sphere is a demonstration of a pure state with $\theta$ and $\phi$ angles. The angles $\theta$ and $\phi$ indicate the direction of the magnetic field relative to the NV center in a diamond.

Qubit can be mathematically represented by Eq. 1, as shown below, and can be visualized using a Bloch sphere.

$$|\Psi\rangle = cos\left(\frac{\theta}{2}\right)|0\rangle + e^{i\phi}\, sin\left(\frac{\theta}{2}\right)|1\rangle \qquad \text{Eq. 1}$$

Where $|\Psi\rangle$ is the state of qubit. $|0\rangle$ and $|1\rangle$ are state 0 and 1, respectively. The Bloch sphere can represent state through defining all parameters in the equation, as visualized in Figure 2.1 $\theta$ and $\phi$ define spherical coordinate on the vertical and horizontal angles of the Bloch sphere and bra-ket defines state 0 and 1 on the Bloch sphere.

## 2.2 Nitrogen Vacancy (NV) center

### 2.2.1 NV center

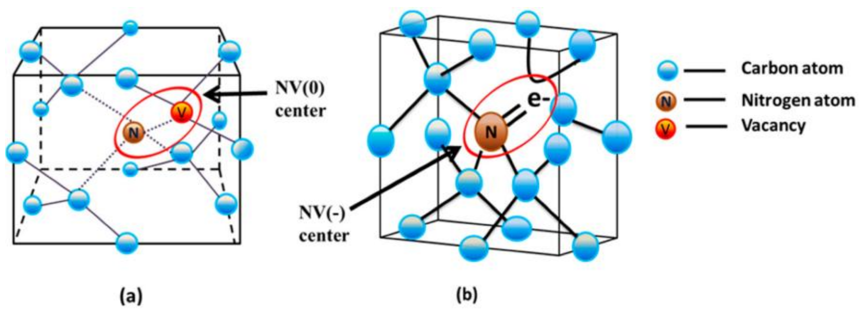


**Figure 2.2** A nitrogen-vacancy (NV) center in diamond is formed by an N substitution and a nearest neighbor vacancy (Haque and Sumaiya, 2017).

The NV center refers to a defect found within a diamond lattice. The defect involves the substitution of a carbon atom with a nitrogen atom next to another vacancy in figure 2.2 The NV centers can be classified into two distinct types: neutral NV centers ($NV^0$) and negatively charged NV centers ($NV^-$) (Haque and Sumaiya, 2017). The $NV^0$ and $NV^-$ exhibit singlet and triplet states, respectively. The triplet state, characterized by a spin quantum number S = 1, comprises three possible spin orientations: $m_s$ = 0, and $m_s$ = ±1, where the states $m_s$ = ±1 are degenerated states. Due to unpaired electrons in $NV^-$, spin-ups and spin-down occur and sense external perturbation. In the field of quantum technology, the utilization of $NV^-$ has garnered considerable attention due to their potential applications in quantum sensing, particularly in magnetic field detection. Normally, NV center comes in two forms: single NV centers and ensemble NV centers. A single NV center is a single nitrogen defect in a diamond lattice. An ensemble NV center is a group of many NV centers in a diamond sample. For this project, we use an ensemble NV center because the larger number of NV centers in an ensemble increases the number of sensors available, thereby enhancing sensitivity to the level of pT/√Hz (Wang Z, et. al., 2022).

### 2.2.2 Energy level diagram

The ground state and excited state of energy level NV is a triplet state, as shown in figure 2.3. Ground state electrons undergo excitation to an excited state, while following the selection rule. For example, electrons in the ground state with $m_s = 0$ can transition to an excited state with $m_s = 0$, but they are unable to transition to an excited state with $m_s = \pm 1$.

The investigation of NV interaction is conducted by using fluorescence measurement. Typically, ground state electrons with $m_s = 0$ transition to an excited state with $m_s = 0$, and subsequently return to ground state with $m_s = 0$ and simultaneously emit red fluorescence. We can study NV interaction with fluorescence detection.

The electrons can undergo excitation from the $m_s = 0$ state to the degeneracy state $m_s = \pm 1$ with the energy input corresponding to the energy level transition referred to the zero-field splitting, which is 2.87 GHz. After the excitation process, the electrons with $m_s = \pm 1$ have the probability to follow the spin selection rule or relax through a non-radiative metastable state. As a result, the fluorescence contrast decreases due to vanishing electrons in the non-radiative path.

The NV center can be used to detect external magnetic field, which are indicated by the separation of degeneracy level (Zeeman splitting). The energy difference between $m_s = \pm 1$ states is proportional to $2\gamma B_z$ (Eq. 2.), with $\gamma$ is gyromagnetic ratio of the electron in the NV center having values of 28.024 GHz/T, (Perdriat et al., 2021), and $B_z$ is magnitude of the magnetic field along the z-axis.

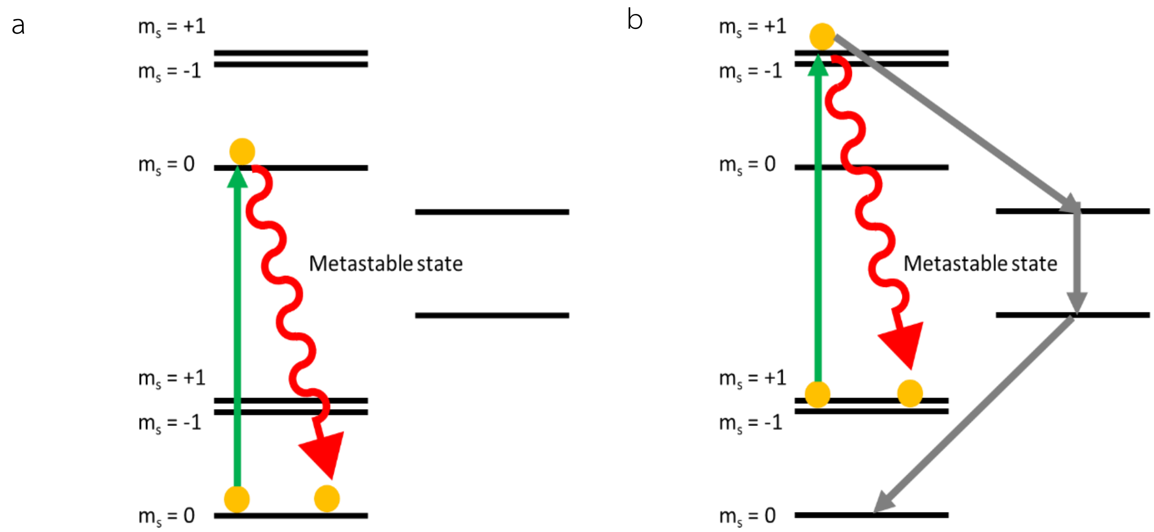


**Figure 2.3** The NV center energy level consists of a ground state at $m_s$ = 0 and degenerated states at $m_s$ = ±1. (a) Electrons move according to the selection rule at $m_s$ = 0. (b) The electrons excited from the ground state at $m_s$ = 0 to the degenerated state at $m_s$ = ±1 can follow the spin selection rule or go to the metastable state and release non-detectable emission before returning to the ground state $m_s$ = 0.

### 2.2.3 Zeeman splitting effect on NV center

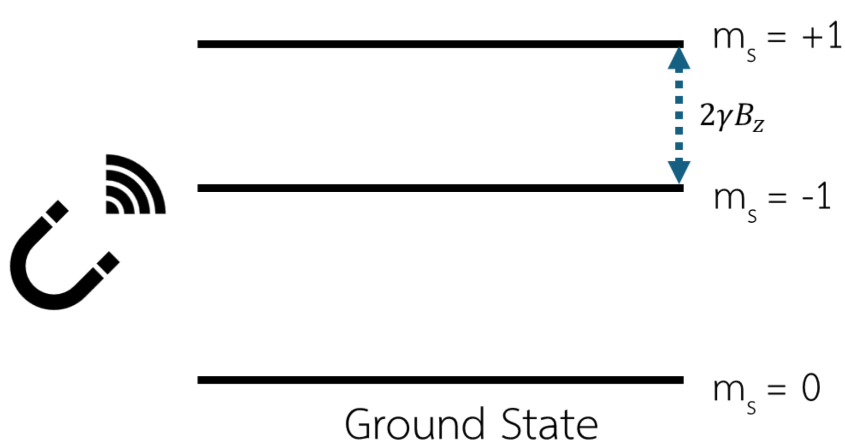


**Figure 2.4** When a magnetic field is applied, degenerate energy levels of $m_s$ = ±1 split with distance with Eq. 2.

We can input an external magnetic field for $m_s$ = ±1 Zeeman splitting like in figure 2.4. When magnets are added into the system, the NV center has the capability to be a magnetometer in the z axis. As a result, it separates into two dips from a dip from zero-field splitting, representing the $m_s$ = ±1 transition. They have a distance of

$$\Delta w = 2\gamma B_z \qquad \text{Eq. 2}$$

Where $\Delta w$ is difference of ODMR splitting, $\gamma$ is gyromagnetic ratio of NV center and $B_z$ is magnitude of the magnetic field along the z-axis.

### 2.2.4 Hamiltonian of Nitrogen Vacancy center

$$\frac{\hat{H}}{h} = D\hat{S}_Z{}^2 + \gamma_{NV}\vec{B}\cdot\vec{S} \qquad \text{Eq. 3}$$

Hamiltonian equation, previously outlined by (Childress et al., 2006, Perdriat et al., 2021), describe the NV center both in the absence and presence of external magnetic field. This equation is defined in a coordinate system where the z-axis aligns with the NV center's [111] crystal axis. The first term is Zero-field splitting where $D$ represents the transition between $m_s$ = 0 and $m_s$ = −1 or +1 due to $C_{3V}$. The $C_{3V}$ symmetry defines spin states, leading to the NV center having spin S = 1 at ground state. In the absence of any external magnetic field, the microwave frequency at 2.87 GHz matching $D$ can excite electrons at $m_s$ = 0 to $m_s$ = 1 or −1. The second term is the magnetic field interaction term where $\gamma_{NV}$ is the electron gyromagnetic ratio, which represents magnetic field effect that perturbs the NV center. When an external magnetic field is applied, the energy level of NV $m_s$ = ±1 states split from each other, called the Zeeman effect. The parameter $\gamma_{NV}$ represents the ratio of the frequency shift between energy level $m_s$ = −1 and +1 energy levels to the magnetic field, resulting from the Zeeman splitting. $\vec{B}$ represents magnetic field in each axis, where the Z axis is along the NV axis and X, Y are perpendicular magnetic field with NV axis.

### 2.2.5 Application of utilizing NV center

Due to the strongest material and diamond bond, the diamond does not interact with other matters. From the reason, it is non-toxic to the human body. So, NV being hosted in diamond is unique to apply to applications such as biosensor and magnetometry. A biosensor is a device merging biological material and a transducer for detecting cells and diseases. In 2011, (McGuinness et al., 2011) brought the NV center to observe HeLa cells being tissue culture cell line of human. Using position, spin-level and spin coherence specific to locations of HeLa cells. In 2018, (Guarina et al., 2018) studied the effect of fluorescent nanodiamonds (FNDs) in organisms using mouse nervous system or hippocampal neurons since cell culture. As a result, FNDs show action potential in their cells to measure difference while does not affecting nerve cells. In 2020, (Miller et al., 2020) used the NV center as an ultrasensitive label to detect the HIV virus. The virus is annealed between base by primer and FNDs are flowed into the virus. They can detect signals from magnetic resonance with NV center fluorescence. We can bring NV center to measure the magnetic field in matter. In 2014, (Müller et al., 2014) used NMR technique to demonstrate coupling between NV center and silicon with field gradient and achieve high signal-to-noise ratio. In 2015, (DeVience et al., 2015) used NV center to characterize NMR, where fluorinated sample with hydrogen and fluorine compound can be detected via the NV NMR spectra measurement.

These works use NV center to sense changing magnetic field in microscale samples. For our work, the NV center is utilized to do vector magnetometry and mapping unknown magnetic fields with ensemble NV center in macroscale sample, being a magnet.