QUANTUM COMPUTING USING DIAMOND NV CENTERS

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ABSTRACT

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. With recent advancements in Quantum Computation Technology and algorithms for the same, Diamond Nitrogen Vacancy (N-V) Centres have emerged as upcoming platform for robust, room temperature operation of solid-state qubits. These properties of Diamond N-V Centres have immense applications in Quantum Information Processing (QIP) and Nanoscale Sensing. We will review the basics of Quantum Computing and recent advancements in optical and magnetic manipulation of Diamond N-V centres for operation of solid-state qubits. We discuss how quantum control of individual centers can be harnessed for the protection of NV-center spin coherence, Two spin control (Coupling with C-13 and N-14 Nuclei) and prospective future applications of these. Many of these recently developed diamond based technologies constitute critical components for the future leap toward practical multiqubit devices. Many of these recently developed diamond based technologies constitute critical components for the future leap toward practical multiqubit devices.
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1. Introduction

Quantum mechanics emerged as a branch of physics in the early 1900s to explain nature on the scale of atoms and led to advances such as transistors, lasers, and magnetic resonance imaging. In 1994, interest in quantum computing rose dramatically when mathematician Peter Shor developed a quantum algorithm, which could find the prime factors of large numbers efficiently which was beyond the capability of state-of-the-art classical algorithms.

An individual N-V center can be viewed as a basic unit of a quantum computer, and it has potential applications in novel, more efficient fields of electronics and computational science.

A nitrogen vacancy center (N-V center) is a type of a single paramagnetic point defect in diamond.These have emerged as promising candidates for quantum information processing (QIP) and precision sensing. Electron spins at N-V centers can be changed at room temperature by applying magnetic field, electric field, microwave radiations, photons, or a combination of them, resulting in sharp resonances in the intensity and wavelength of the photoluminescence.

2. Quantum Computing

Quantum and classical computers both solve problems, but the way they manipulate data to get answers is fundamentally different. Quantum computers make use of following two fundamental principles of quantum mechanics which make them unique - superposition and entanglement.

– **Superposition**
  Superposition is the ability of a quantum objects (e.g. an electron) to simultaneously exist in multiple 'states'. For an electron, one of these states may be the lowest energy level in an atom while another may be the first excited level. If an electron is in a superposition of these two states it has some probability of being in the lower state and some probability of being in the upper. Mathematically, it refers to a property of solutions to the Schrödinger equation; since the Schrödinger equation is linear, any linear combination of solutions will also be a solution. A measurement will destroy this superposition, and only then can it be said that it is in the lower or upper state.
– **Entanglement**
  Quantum entanglement is a physical phenomenon that occurs when pairs or groups of particles are generated, interact, or share spatial proximity in ways such that the quantum state of each particle cannot be described independently of the state of the others, even when the particles are separated by a large distance. Measurements of physical properties such as position, momentum, spin, and polarization, performed on entangled particles are found to be perfectly correlated. Individual identities are lost. A measurement on one member of an entangled pair will immediately determine measurements on its partner, making it appear as if information can travel faster than the speed of light.

In reality a quantum computers leverage entanglement between qubits and the probabilities associated with superposition to carry out a series of operations (a quantum algorithm) such that certain probabilities are enhanced (i.e., those of the right answers) and others depressed (i.e., those of the wrong answers). When a measurement is made at the end of a computation, the probability of measuring the correct answer should be maximized.

3. The need for a Quantum Computer

The promise of developing a quantum computer sophisticated enough to execute **Shor's algorithm** for large numbers has been

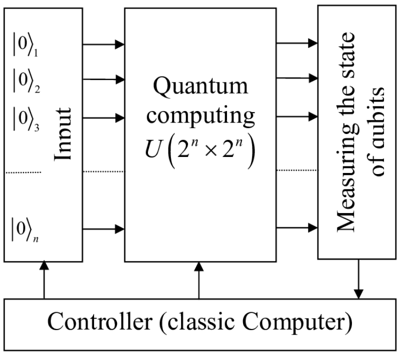

Fig. 1. Typical Function of a Quantum Computer

a primary motivator for advancing the field of quantum computation. But, it is important to understand that they will likely deliver tremendous speed-ups for only specific types of problems.In general, it is believed that quantum computers will help immensely with problems related to optimization.

Multiple additional applications for qubit systems that are not related to computing or simulation also exist and are active areas of research:

- **Quantum sensing and meteorology**, which uses the extreme sensitivity of qubits to the environment to realize sensing beyond the classical noise limit
- **Quantum networks and communications**, which may lead to revolutionary ways to share information.

4. A Qubit

A qubit is a quantum bit, the counterpart in quantum computing to the binary digit or bit of classical computing. Just as a bit is the basic unit of information in a classical computer, a qubit is the basic unit of information in a quantum computer. A number of elemental particles such as electrons or photons can be used, with either their charge or polarization acting as a representation of 0 and/or 1. Each of these particles is known as a qubit; the nature and behavior of these particles form the basis of quantum computing.

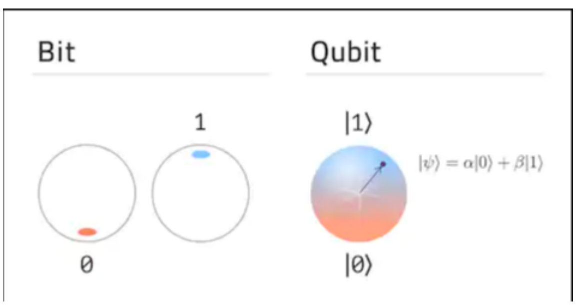

Fig. 2. Representation of a Qubit

A quantum logical qubit state is a quantum superposition of the 'basis states'. $|0\rangle$ and $|1\rangle$. Here $|0\rangle$ is the Dirac notation for the quantum state that will always give the result 0 when converted to classical logic by a measurement. Likewise $|1\rangle$ is the state that will always convert to 1.

Ion traps, optical traps, quantum dots, semiconductor impurities, etc can act as qubits.

As summarized by David DiVincenzo, properties of a good Qubit are as follows:

- Having a method of initialization
- Having a universal set of **q**uantum gates:
  A quantum logic gate is a basic quantum circuit operating on a small number of qubits. Unlike many classical logic gates, quantum logic gates are reversible. The number of qubits in the input and output of the gate must be equal; a gate which acts on **n** qubits is represented by a $2^n x 2^n$ unitary matrix. (As shown in Fig.1)
- Long coherence time relative to the gate operation time: Qubits store the information in the form of superposition states. But this superposition can be jeopardised due to environmental interactions in the form of Radiation, light, sound, vibrations, heat, magnetic fields or even the act of measuring a qubit Time it takes for superposition to disappear is known as decoherence time
- Qubit specific state readout:
  Trying to do measurement collapses the wave function into any one of the 2^N states available of N qubits. Using proper quantum computing algorithms (like Shor's Algorithm, Grover's Algorithm) and quantum logic gates, one can increase the probability of obtaining correct state after wave function collapse almost up to certainty and readout the desired information.

5. The Diamond N-V Center

A diamond cubic lattice can be thought of as two interpenetrating face-centered cubic lattices with one displaced by 1/4 of the diagonal along a cubic cell. Negatively charged N-V centers are paramagnetic point defects in the diamond lattice.

The structure, shown in **Fig. 3**, consists of a carbon (C) vacancy in a neighboring lattice site to a substitutional N impurity. Because the energies of the bound electronic states, including the $\approx$ 2 eV orbital transition, are within the 5.5 eV bandgap of diamond, the N-V center's states are isolated from the bulk bands of the diamond host.

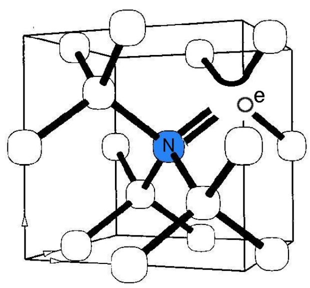

Fig. 3. Simplified atomic structure of the N-V center

In this way, NV centers may be regarded as "trapped atoms", where the role of the diamond is to confine the electronic state and provide primary protection against the decohering influence of the solid-state environment.

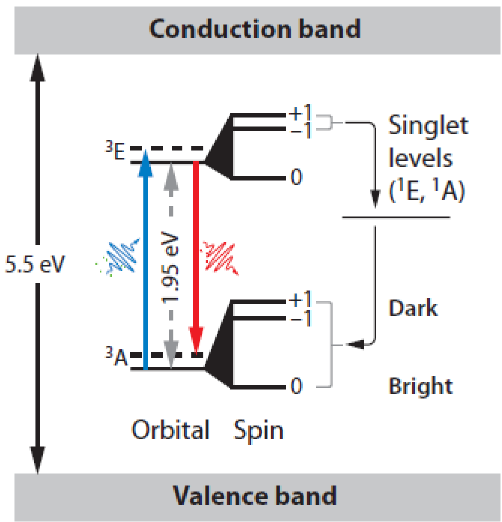

Fig. 4. Energy diagram of the orbital and spin-level structures of N-V centers. The defect is a spin triplet in both the ground and excited states.

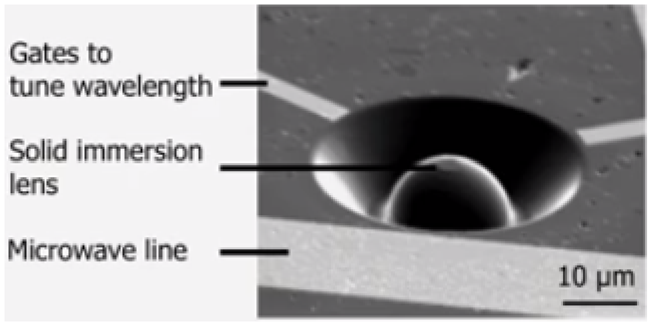

Fig. 5. Scanning electron microscope image of a solid immersion lens fabricated around a single NV center in diamond, with an integrated microwave strip line (front) and two electrodes (back) for controlling the defect quantum states.

The N-V center can have a very long spin coherence time even at room temperatures. They have ability to combine different qubits (for eg. coupling of spin of localised electron and nuclear spin of neighbouring C-13 atoms). We can also create a quantum network of entangled qubits using optical interface created by photons. Since, the N-V center satisfies almost all of the criteria given by David Di Vincenzo, it is regarded as a very good qubit and community is looking forward to extract potential of quantum realm using them.

6. Magnetic Resonance of single N-V Spins

Magnetic control of the electronic spin of a single NV center most often employs a resonant driving technique developed in the field of magnetic resonance. It is a widely used technique to control spin of electrons. It is implemented by applying an AC magnetic field (Rabi driving field) with a carrier frequency close to the frequency of a relevant spin transition. We apply a linearly polarized Rabi driving field of magnitude $2B_1$, oscillating at the carrier frequency ω with the phase ϕ, along x-axis. Resulting motion of the spin is very complex and is hard to analyse. However, the situation greatly simplifies if we consider special rotating frame of reference, rotating with the frequency ω around the z-axis. In this rotating frame oscillating driving field $2B_1$ decomposes into a sum of static component (which is co-rotating with the rotating reference frame) of the magnitude B_1 and a component oscillating at the frequency 2ω (counter-rotating against the rotating reference frame) of the same magnitude B_1.The contribution of this component can be neglected (Rotating Wave Approximation) as it is moving too fast in order to have some observable changes in one cycle. As a result, we are just left with a static field B_1 co-rotating with precessing spin, lieing in the x-y plane. Continuous driving and pulsed fields in magnetic resonance are applied to spin ensembles positioned within a radio- or microwave-frequency cavity (As shown in Fig). Spectral measurements are performed using one or more fixed-frequency driving fields while the static external field is varied.

7. Resonant Optical Control

N-V centers emit bright red light which can be conveniently excited by visible light sources. An important property of the luminescence from individual N-V centers is its high temporal stability. Whereas many single-molecular emitters bleach after emission of $10^6 - 10^8$ photons, no bleaching is observed for the N-V centers at room temperature.
In this section, we summarize excited-state-level structures and associated optical transitions of the NV center as they appear at low temperature and then discuss how the optical transitions can be used to obtain single-spin control and, in the future, to interface the N-V center with a photonic network. More than a decade ago, it was recognized that fluorescence from a single NV center could be used to observe transitions of its electronic spin, even at room temperature. It is now possible to prepare the electronic and nuclear spins of a NV center with high fidelity and detect their quantum states in a single measurement. The NV center has spin degrees-of-freedom associated with both its bound electrons and nearby nuclear spins, and, much like atomic states, these spins can be addressed using optical transitions.

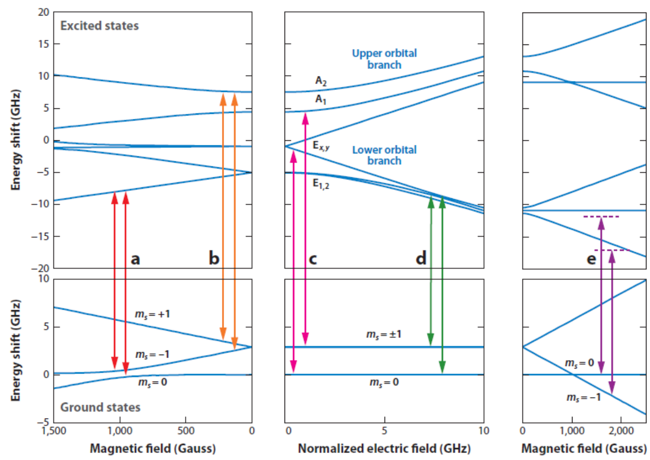

Fig. 6. Energy levels on application of external Magnetic field, Electric field and a particular combination of both respectively

8. Coupling with Nuclear Spin

The nuclei of the ^{13}C isotope carrying spin 1/2 are naturally present in diamond with an abundance of 1.07%; some can also occur very close to the NV center (within the first two to three coordination spheres) and be strongly coupled to the N-V electronic spin. Owing to strong hyperfine coupling, the resonance frequency of the N-V electron spin becomes dependent on the state of the proximal ^{13}C nuclear spins and the resonance lines of the proximal ^{13}C spins become dependent on the state of the N-V spin.

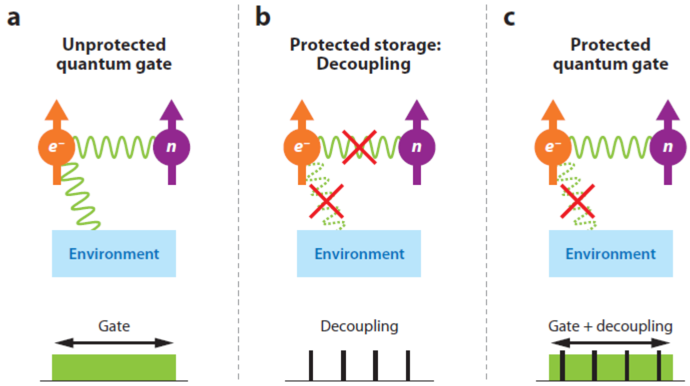

Fig. 7. (a) Without decoherence protection, the fidelity of two-qubit gates is limited by interactions with the environment. (b) Dynamical decoupling (DD) efficiently preserves the qubit coherence by turning off the interaction between the qubit and its environment. However, this generally also decouples the qubit from other qubits and prevents two-qubit gate operations. (c) DD during the gate operation, thus ensuring that the gates are protected against decoherence.

Hence, we can control the interaction of the N-V Qubit with the external factors by using the ^{13}C nucleus.

However, the probabilistic appearance of C-13 isotopes near N-V Center largely decreases as we use isotopically purified samples (to increase coherence time). Hence, a better approach is to use the always present nuclear spin of neighboring N atom as qubit. In contrast to C, spin of N nucleus is always present. Its properties are fixed by the N-V geometry and can be measured with high precession.

References

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