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A perspective on doping diamond for quantum computing applications

I. Avradopoulos[1], V. Giosis[1], K. Katsanos[1], A. Chroneos[1,2], R.V. Vovk[3]

[1]*Department of Electrical and Computer Engineering, University of Thessaly, 38333 Volos, Greece*
[2]*Department of Materials, Imperial College London, London SW7 2BP, United Kingdom*
[3]*V.N. Karazin Kharkiv National University, Svobody sq., 61022 Kharkiv, Ukraine*
Corresponding author e-mail: rvvovk2017@gmail.com

Abstract. Diamond is not a mainstream material for nanoelectronic applications, despite its remarkable physical properties. There are many issues in developing efficient semiconductor devices based on diamond. In this perspective, we focus on the introduction of dopants using various doping techniques (thermal doping diffusion, delta doping, chemical vapour deposition (CVD), *etc*). Forming *n*-type doped diamond using conventional dopants such as phosphorus (P) is challenging. Nitrogen (N) can be implemented with boron (B) using co-doping. Forming *p*-type doped regions in diamond is less problematic compared to *n*-type doped regions. This is because B is an appropriate acceptor dopant, and additionally there is the possibility of forming H-diamond, which is also an acceptor. Presently, the dream of a diamond transistor has given way to its application in the field of quantum computing. In the current context, we consider *n*-type and *p*-type doping in diamond, focusing on the difficulties of *n*-type doped diamond. We consider the integration of diamond in quantum computing with account of the nitrogen-vacancy pairs.

Keywords: diamond, doping, point defects, dislocations, defect clusters, magnetic field, microwave radiation.

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1. Introduction

Understanding of physical and chemical properties is key to improving materials for semiconductor, superconductor, battery, and quantum computing applications [1–3]. Theoretical modeling and thermodynamic approaches can offer additional perspectives, thus aiding experimental studies and technological progress [4].

Even though diamond has a unique set of physical, chemical, and mechanical properties, its application in mainstream semiconductor devices has not been realized. Silicon (Si) was the mainstream semiconductor material for microelectronic devices for nearly six decades owing to its advantageous native oxide (*i.e.,* silicon dioxide (SiO_2)) [5, 6]. This trend was overturned with the introduction of CVD and molecular beam epitaxy (MBE), which led to the subsequent replacement of SiO_2 with high-*k* dielectric materials [7]. This, in turn, led to the consideration of alternative materials for microelectronics, and the spotlight was on semiconductor materials with better properties (*i.e*., electron and hole mobilities) such as germanium (Ge) and silicon germanium ($Si_{1-x}Ge_x$) [7]. Another trend around the same time was carbon-based materials such as carbon nanotubes, fullerenes, graphene, and diamond [8]. Compared to Si, diamond has a higher thermal conductivity, which allows better heat dissipation, and a wider band gap, which allows operation at higher voltages and temperatures. Furthermore, the high electron mobility in diamond facilitates faster electronic signal processing. With the dream of a conventional diamond transistor fading away, the community is focused on utilizing diamond in quantum computing [9].

It is anticipated that quantum technologies will have a very significant impact on productivity, scientific research, health, energy, communications, and sensing. The cornerstone of the technology is the quantum bit (qubit), which is the building element of quantum computing. Qubits can be formed *via* different paths such as photons, trapped ions, and spin and charge states in quantum dots. Formation of qubits for quantum circuits led to the investigation of numerous material systems including gallium arsenide, Ge, Si, and diamond [10–14].

This paper is organized as follows: Section 2 considers the *n*-type and *p*-type doping in diamond. The focus is on the difficulties in *n*-type doped diamond. Section 3 considers the integration of diamond in quantum computing. Finally, in Section 4 we present our perspectives and conclusions.

2. Doping diamond

2.1. Synthesis

The aim of doping in semiconductors is to alter the conductivity of the material by adding charge carriers. Introducing donor atoms (for example pentavalent atoms such as phosphorus (P), arsenic (As) or antimony (Sb), into the crystal structure (in a tetravalent host lattice, *i.e.* Si or Ge or diamond) will lead to additional electrons in the conduction band, whereas acceptor atoms (for example boron, aluminium, gallium, or indium) will create a deficit of electrons (holes) in the valence band. The most suitable candidates for diamond doping are N and P for *n*-type doping and B for *p*-type doping. All three dopants are generally deep and not activated at room temperature.

A way to dope diamond is the synthesis of diamond membranes using the CVD technique. The presence of atomic hydrogen and carbon radicals is necessary for the deposition of diamonds, which is achieved by various methods. For example, the hot filament CVD (HFCVD) method employs heated filaments to break down precursor gases into radicals that are then deposited on a substrate to form diamond. The dopant atoms are incorporated through the precursor gases into the diamond structure during synthesis. Advantages of the HFCVD technique include uniformity over a large surface area, ease of operation, the possibility to form complex product geometries, reproducibility of results, and low cost. Nevertheless, these advantages come at a price, namely, in the HFCVD process, materials are introduced into the membrane during deposition, which leads to a slow growth rate [15]. The problem of contamination that is introduced on the diamond membranes by HFCVD can be eliminated by the microwave plasma CVD (MPCVD) method [15]. MPCVD allows the production of polycrystalline and monocrystalline diamond membranes on various substrates, using a microwave generator and waveguide components [15]. In the MPCVD system, the precursor gases are activated to form a plasma sphere, with the diamond growth rate reaching 10 μm/h under optimal conditions [15]. MPCVD is reliable for the development of electronic-grade epitaxial diamonds, although this method is limited due to the low growth rate and the inability to form large membranes. Another problem with the MPCVD membranes is the high internal stress [15].

2.2. *n*-type doping

n-type doping of diamond is challenging. Dopants are not shallow enough and do not have corresponding properties to form *n*-type diamond. Phosphorus substitutional atoms are shallow donors. Koizumi *et al.* [16] determined that P-doped diamond is electrically active in CVD. The resistivity of a P-doped diamond film with a concentration of $1.2 \cdot 10^{20}$ cm^{-3} was 42 Ω·cm at room temperature [16].

During the CVD process, phosphine (PH_3) gas is introduced along with methane and hydrogen [17]. The high-energy plasma breaks down these gases into their constituent atoms and radicals. Phosphorus atoms from the phosphine gas become incorporated into the growing diamond lattice, substituting for carbon atoms [17]. The effectiveness of phosphorus doping heavily depends on the concentration of PH_3 in the gas mixture and the overall growth conditions, such as temperature and pressure [17].

Heavy phosphorus doping, crucial for reducing electrical resistivity and forming Ohmic contacts, can be easily achieved by MPCVD. This should be stressed because MPCVD has issues (unstable plasma discharge) under heavy doping. On the other hand, HFCVD offers advantages such as a larger growth area and simpler setup, though it introduces metal contaminants from the filament, which could affect the epitaxial growth for electronic components. Despite this, HFCVD can achieve heavily B-doped *p*-type diamond films without MPCVD's technical issues, suggesting metal impurities have limited impact on electrical properties [15].

In experiments, P-doped diamond films were grown using HFCVD on synthetic diamond substrates, with phosphorus doping achieved through trimethylphosphine gas. The grown films demonstrated a phosphorus concentration controllable up to 10^{20} cm^{-3}, comparable to MPCVD, though with varying incorporation efficiencies. The electrical properties were evaluated through resistivity and Hall-effect measurements, indicating *n*-type conductivity and a mix of band and hopping conduction mechanisms. Hall effect describes the production of a measurable voltage across a conductor or semiconductor when it carries an electric current in the presence of a perpendicular magnetic field. This effect is crucial for sensing magnetic fields, characterizing materials, and developing electronic devices.

Increasing phosphorus concentration decreases electrical resistivity significantly, achieving a minimum resistivity of 42 Ω·cm at high phosphorus doping levels. HFCVD is a technologically important method to produce *n*-type diamond-based electronic devices and provides a viable alternative to MPCVD [17].

Nitrogen presents unique challenges as an *n*-type dopant for diamond. Unlike other dopants, nitrogen can be used for *n*-type doping, but it is limited as it is a deep donor, having an energy level close to 1.7 eV below the conduction band [18]. A possible arrangement for substitutional N in diamond is with N receding from one of its C nearest-neighbor atoms, in a different way compared to P.

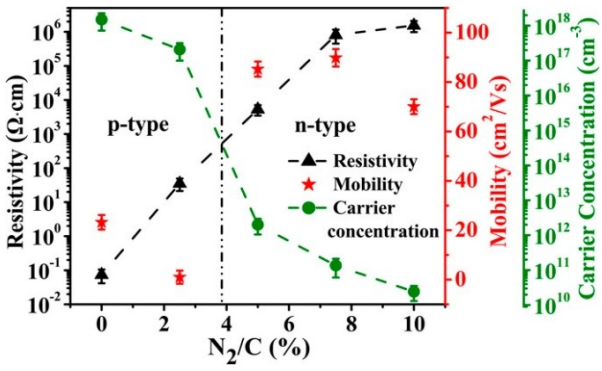

Fig. 1. Importance of co-doping in *n*-type diamond. Experimental results of resistivity, mobility, and carrier concentration at 773 K for B-doped and B–N co-doped diamond films [19]. B-doped films correspond to 0 in the x-axis.

This distortion is not due to the Jahn–Teller effect [19]. N is not a shallow donor in diamond, and so co-doping is a convenient method to utilize nitrogen. Co-doping involves introducing another element alongside nitrogen to improve its doping efficiency [19].

Liu *et al.* [19] co-doped N with B and determined better crystalline quality, faster growth, and higher N solubility. They propose that this co-doping strategy can lead to *n*-type diamond [19]. The experimental results of resistivity, mobility, and carrier concentration at 773 K for B-doped and B–N co-doped diamond films are given in Fig. 1.

2.3. *p*-type doping

For *p*-type doped regions (*i.e.* positively charged regions) acceptor atoms are typically required to form holes in the valence band. For carbon lattices, as C is tetravalent, acceptor atoms are typically trivalent (*i.e.*, B, Al, Ga, In). Another way to form *p*-type regions in diamond is the use of the effect of hydrogen termination. The movement of these charge carriers (*i.e.* holes) results to *p*-type conductivity. Initially, Al was considered to be the best *p*-type dopant in diamond. It was later recognized that B is the most effective dopant to produce high-conductivity *p*-type diamond. B is not fully activated at room temperature, having an acceptor level at 0.37 eV below the valence band maximum [20], while hole mobility is significantly reduced at high B concentrations. If the B doping level is high enough, a small zone will form and begin to overlap with the valence zone, thereby reducing the activation energy and allowing tunneling contacts. B is the only atom that has been shown to be effective for doping diamonds with high reproducibility and high concentration, making it particularly useful for electronic applications. For diamond, various techniques have been developed to create electronic devices with different requirements, but also to solve different problems. The most well-known and applicable ways are through CVD, as well as delta-doping layers in diamond and *p*-type doping by thermal diffusion [9, 21].

The *p*-type doping with thermal diffusion in the narrow rhomboid lattice can be done through rapid thermal diffusion of B at high temperature (around 1400 °C), where cubic boron nitride is the source of diffusion. This leads to the formation of thin *p*-type conductive layers with relatively low conductivity. To optimize rapid thermal diffusion as a source, an evaporated boron film covered by a layer of molybdenum can be used, and this results in better conductivity and mobility of holes [21].

The development of CVD *p*-type diamond films has been achieved by adding boron-containing molecules to the gas mixture in either a microwave reactor or a hot filament reactor. Different boron-containing compounds can be used, including diborane (B_2H_6), which is a gas at room temperature but very toxic and dangerous. Safer alternatives are trimethylboron (TMB) and triethylboron (TEB), which have been successfully used in hot-filament CVD processes achieving high concentrations of boron. Additionally, boron powder, boron wires, and molten B_2O_3 powder can be used by heating a hexagonal BN substrate retainer, leading to the diffusion of boron. Finally, boron trichloride gas is another available source of boron, leading to form boron-doped diamond [21].

Depositing B-doped polycrystalline diamond films using Microwave Plasma Enhanced Chemical Vapor Deposition on Si or SiO_2 substrates involves control over gas composition and deposition pressure to achieve the desired crystal sizes and electrical properties. The deposition pressure will significantly impact boron-doping efficiency, grain size, and film conductivity. Raman spectroscopy shows that increasing boron content decreases the intensity and shifts the diamond vibrational mode peak at 1332 cm^{-1}, while new peaks at 500 cm^{-1} and 1200…1220 cm^{-1} emerge, which indicates structural defects and B clustering within the diamond lattice. Using an $Ar/H_2/CH_4$ plasma produces higher conductivity films with smaller grain sizes. The detailed control of deposition parameters, including pressure and boron concentration, is essential for manufacturing the structural integrity and electrical properties of efficient B-doped diamond films, enabling their use in advanced electronic applications [22].

The delta-doping method was developed to address the restriction of B, which requires a high concentration (above 10^{20} cm^{-3} and up to $5{\cdot}10^{20}$ cm^{-3}) for its full activation in combination with the maximum sheet charge density in the field-effect transistor (FET) channel, which can be up to $4{\cdot}10^{13}$ cm^{-3}, as electrical damage is subsequently created to the diamond due to the lack of shallow doping. The delta-doping method is fast and avoids the problem of delay time in the supply of a gas source, due to filling and emptying the chamber with doping gas, during which the development must be strictly stopped. However, there is the issue of background contamination with B during growth [21].

An alternative to B doping for forming a *p*-type doped region is surface transfer doping. The creation of H-diamond requires breaking the oxygen bonds formed on the diamond surface and replacing them with hydrogen. This can be realized by using 2.6 kW hydrogen microwave plasma in ultra-high vacuum (UHV) at 650 °C [9]. When the surface of H-diamond is coated with a material that has a higher electron binding energy, electrons leave the diamond, thus creating a conductive layer of holes. These holes accumulate near the surface of the diamond with hydrogen termination and can be modeled as a 2-dimensional hole gas (2DHG). However, surface transport doping of H-diamond when exposed to ambient air is highly sensitive to environmental conditions such as temperature, humidity, and molecular composition, severely limiting the manufacture of diamond transistors [9].

The development of functional and efficient diamond transistors marks a significant advancement in semiconductor technology despite remaining challenges (refer to Section 2.4 below). Additionally, B-doped conductive diamond shows promise in electrochemistry by creating durable, inert electrodes that can withstand harsh chemical environments. Delta-doping allows for precise control in manufacture of FETs and *p-n* junctions,

enabling the creation of transistors that operate reliably in highly corrosive conditions. Hydrogen-terminated diamond is particularly valuable in high-power Metal Oxide Semiconductor FETs (MOSFETs) due to its high resistance to voltage breakdown and ability to function at elevated temperatures, making it ideal for power electronics and RF communication systems [9, 21, 23].

2.4. Perspectives of doping

In mainstream microelectronic devices, both *n*-type and *p*-type doped regions are required. For diamond, the *p*-type region can be formed using B as an acceptor dopant, as the acceptor level is about 0.37 eV below the valence band maximum [20]. On the other hand, diamond is compromised by the absence of an appropriate shallow donor to form an efficient *n*-type doped region, as both P and N are problematic [16]. N does not contribute to the conduction band but instead forms a lone electron pair on N and a dangling bond on one of its nearest-neighbour C atoms. This unpaired electron is localized more on one of the C nearest-neighbour atoms than on the N donor atom [24]. The deep donor level of the N atom, with an activation energy of 1.7 eV, will result in almost zero excitation of electrons into the conduction band at room temperature, and this in turn means that the device cannot perform efficiently [16]. To facilitate comparison, P has a shallower donor level of 0.6 eV and is essentially a more appropriate donor (refer to Fig. 2) [25, 26]. In Fig. 2, on the left, the electron density map of the (110) plane of diamond illustrates the difference between a neutral NC_{63} supercell and a positively charged NC_{63}^{+} supercell, and on the right side – a neutral PC_{63} supercell and a positively charged PC_{63}^{+} supercell. The darker blue shade shows where charge is lost. The N atom accumulates charge, whereas P does not, and this reflects their electronegativity differences [26].

The localization of the unpaired electron near the N dopant atom in diamond can be explained by the Pauling electronegativity. C (electronegativity 2.55) is far less electronegative than N (electronegativity 3.04), and therefore charge should be transferred from C to N. For *p*-type doping in diamond, acceptor dopants such as B have smaller electronegativities than C, and therefore charge will be transferred from B to C.

Considering the doping of diamond with P (electronegativity 2.19), which is less electronegative than C, it leads to shallower donor levels [27]. In effect, from this fundamental viewpoint, the donated electron is localized in the vicinity of the C atom. At any rate, the donor level of P is still quite deep, and therefore there is only a small number of conduction electrons.

A common way to overcome doping issues in semiconductors is to use defect engineering and co-doping [28–32]. A popular co-doping strategy in diamond is the formation of defect clusters containing both donor and acceptor atoms [33, 34]. Through clustering, the Coulomb coupling between the donor and acceptor atoms can increase the solubility, whereas at the same time the defect level concentration can be reduced *via* the donor and acceptor level repulsion [35].

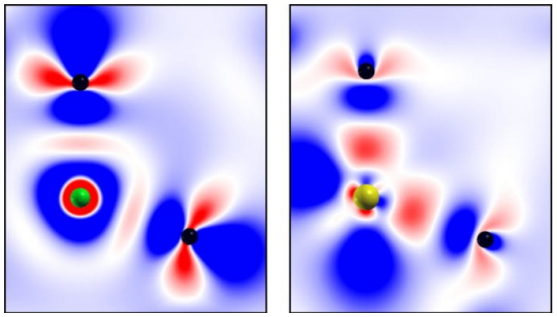

Fig. 2. Nitrogen (left side) and phosphorus (right side) substitutional impurities in diamond. Small black spheres are the C atoms, and larger (green/yellow) spheres are the N/P dopant atoms.

Katayama-Yoshida *et al.* [35] proposed the N–B–N defect cluster, which reduces the donor level of a single N to 1.17 eV. This reduction, which is still not enough for activation at room temperature, is mainly because of the delocalization of the donor electron wavefunction into the N–B–N cluster that avoids bond breaking and limits atomic distortion from the N substitutional [35]. The co-dopant should have a higher electronegativity than the donor atoms; thus, N is very limiting due to its very high electronegativity. In these terms, a better choice for a donor atom would be P, as there are numerous elements with higher electronegativities compared to P. This is consistent with the density functional theory calculations by Schwingenschlögl *et al.* [26], who proposed that co-doping strategies better focus on P, where there are more co-dopants that are appropriate (*i.e.,* exhibit higher electronegativities than P).

The prevalence of P as an *n*-type dopant in diamond has also been determined in the *n*-channel MOSFET diamond transistor by Liao *et al.* [36].

3. Integrating diamond in quantum computing

3.1. Introduction to quantum computing

Quantum computing uses the principles of quantum mechanics to process information differently from classical computing. Compared to classical computers, quantum computers have a different fundamental unit, the qubit, which has significant differences from the conventional bit, with some of the most important being superposition and entanglement.

• Superposition is the ability of a qubit to simultaneously be in the state of 0 or 1, which is considerably different from a conventional bit that can only be in one state at a time.

• Entanglement is another attribute of qubits, which means that the state of one qubit can depend on the state of another qubit, independently of the distance separating the two qubits. This property is utilized by quantum algorithms to enable calculations with more than one qubit.

Another important difference between classical and quantum computing is wave interference. It is used by quantum computers, up to a certain error margin, for making fault-tolerant systems [37]. Another fundamental difference is the function of gates in quantum computers.

Quantum gates work by manipulating qubits to achieve both conventional operations and other operations that are specific to quantum computers. One important detail about the function of quantum gates is how they handle the atoms that have to be manipulated in a certain way in order to be able to perform quantum computing.

An approach is to trap ions. These ions must be trapped because, in that state, their energy levels tend to be the most reliable for their use as qubits. This can be done for one ion using electric fields, but for multiple ion qubits, there can be entanglement through a laser-induced coupling of their spins. These types of gates, called trapped-ion Coulomb gates, are one case where there can be entanglement for a small number of ions, but it is difficult to scale up to many ions as laser cooling and noisy electric fields can become a problem.

There is also the possibility of using neutral atoms instead of trapped ions that produce similar qubits. This is achieved by using a pattern of laser beams that confines the atoms in free space and forms an optical lattice, which can be controlled using the geometry, polarization, and intensity of the lasers used. This method has the disadvantage that it is more difficult to initialize, interact with, and measure the qubits, but there are advancements in this matter.

As we can conclude from the two methods above, one major challenge is trapping and cooling the atoms that are used for quantum computing. For large arrays of qubits, it is easier to achieve this by 'integrating' the atoms into a solid-state host. This is where the concept of Quantum dots comes into discussion to solve this problem. Quantum dots have a wide variety, with one being the electrostatically defined dot, which uses lithographically defined gates, and the self-assembled quantum dots, which use defects in the semiconductor material for qubits [38].

3.2. Nitrogen-vacancy defects in diamond

The nitrogen-vacancy (NV) centers in diamond have a unique combination of properties that eliminate many of the challenges faced in quantum computing [39]. The NV defect exists in two charge states in diamond: a) the neutral charge state (NV^0) and b) the single negatively charged state (NV^-). For quantum computing, NV^- centers are more useful due to their electronic and spin properties.

Diamond NV centers in the ground state are composed of an orbital singlet, spin-triplet state ($S = 1$), and there are also spin sublevels ($m_s = 0$ and $m_s = \pm 1$). The zero-phonon line (ZPL) of the NV^- centers is 637 nm [40]. These properties, combined with the weak spin-orbit coupling in the NV centers, enable them to have long electron spin coherence times and a low likelihood of the quantum states decohering, which means that the qubits can be in a stable state for much longer compared to other quantum dots, allowing for many more quantum operations within the coherence period. Also, the NV centers can be initialized with readily available lasers and be manipulated with a simple green LED [41].

Another significant advantage of NV centers is that they can operate at room temperature, which both simplifies quantum computing and widens the operating conditions and, in turn, the potential applications of a quantum computer. A quantum computer with diamond can also be scalable if the hurdle of fabricating a big enough single-crystal diamond is overcome.

There are two characteristics of the NV^- in diamond that differentiate it from other solid-state qubit systems [42]: (a) NV^- in diamond has highly localized bound states that are isolated from sources of decoherence and (b) the structure of the excited states of the defect allows it to be optically initialized under ambient conditions. In a seminal study, Weber *et al.* [42] set out several criteria that centers in materials should possess to exhibit NV^- in diamond characteristics (refer also to Fig. 3):

(1) The bound state must be appropriate for use as a qubit, *i.e.*, paramagnetic and long-lived. Additionally, there should be energy splitting within at least two of the state's spin sublevels. To manipulate the qubit state through electron spin resonance, the size of the energy splitting must be within the radio frequency spectrum [42].

(2) There must be an optical pumping cycle polarizing the qubit state. Typically, it requires an optical transition from the ground state to an excited state that is followed by a spin-selective decay path with one or more non-radiative transitions between states of differing spin multiplicity [42].

(3) Luminescence to/from the qubit state that varies by qubit sublevel (*i.e.*, by intensity, wavelength, *etc.*).

(4) A wide band gap host material to accommodate deep centers so that the optical transitions do not introduce interference from the electronic states of the host. The optical transitions to prepare and measure the qubit state must be lower in energy than the energy required to transfer an electron to the electronic states of the host [42].

(5) The bound states should be separated by energies that are substantial to avoid thermal excitation between them [42].

(6) The crystalline material hosting the defect should have properties that reduce decoherence in the defect [42]. These include: (a) small spin-orbit coupling (to avoid unwanted spin flips), (b) high-quality single crystals to avoid imperfections or paramagnetic impurities, and (c) constituent elements with naturally occurring isotopes of zero nuclear spin to eliminate spin bath effects from the material using isotopic engineering.

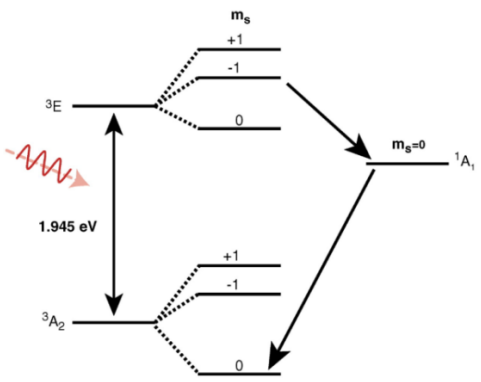

Fig. 3. A schematic representation of the multiplet structure of the NV^- defect in diamond. There is a 1.945-eV spin-conserving optical transition between $^3A_2$ (the ground state) and ^3E (excited state triplets) [42].

Finally, considering in more detail Fig. 3 the transitions from the $m_s = \pm 1$ sublevels of ^3E to an intermediate spin singlet are considerably stronger than transitions from the $m_s = 0$ sublevel. It is the spin-selective nature of this decay path that can be employed with the 1.945 eV transition to optically polarize and measure the spin state of NV^-.

3.3. Technological perspectives

One of the major challenges of diamond as a material in quantum computers is the challenge of fabricating the material and as such nanofabrication needs to be developed further. Another challenge that must be solved is the defects and erosion of the wafer masks that are used in the lithography process. This would eliminate the roughness that is currently observed in diamond nano-structures, enabling much better optical and acoustic quality, which are important for improving the trans-mission of information between two systems, something that is required for quantum communication applications.

Current applications of diamond NV centers in quantum computing are not strictly limited to quantum processors but can also include the "quantum internet". This is a network of quantum repeater nodes that transmit information over large distances. Another application that has emerged is microwave amplification by stimu-lated emission of radiation (Maser), which would be helpful in radio astronomy and deep-space communica-tion, as quantum-based masers are much more compact than their conventional counterparts. NV in diamond can be used to measure magnetic fields in the nanometric scale and thus has applications in materials detection as well as GPS that relies on the Earth's magnetic field (as opposed to satellites). It can also be used to increase the resolution of Magnetic Resonance Imaging (MRI) scans from anatomical to molecular imaging [41].

Diamond has a wide range of applications in the space of quantum computing, ranging from conceptual designs to applications that are closer to technologically feasible applications. One concept with great potential is the integration of FinFET-based quantum dots with CMOS-based control electronics [43]. There is also the possibility of detecting RF fields, which could help with measuring across the radio frequency spectrum with high resolution. This could be helpful in isolating 5G cell towers and reducing interference between them. Additionally, NV centers in diamond could be used to reduce quantum error and implement error correction and fault-tolerant systems. Finally, there are Hybrid quantum systems that could include diamonds with other photonic materials such as AlN and GaP for on-chip photon routing, and also, they could be used in piezoelectric materials as an interface between superconducting qubits and diamond-based quantum memories, which produces less heat, thus making the system easier to cool, more efficient, and helping preserve coherence [40].

Finally, it should be stressed that as alternative systems and materials will continue to be considered by the community, diamond will always be the archetypal system for quantum computing applications [44–48].

4. Conclusions

In the present review, we considered *n*-type and *p*-type doping in diamond, and particularly the difficulty of *n*-type doped diamond. In essence, B is an efficient acceptor dopant for the formation of *p*-type regions; however, P and N are inappropriate. It has been concluded that *via* defect engineering strategies involving co-doping, there could be a path leading to *n*-type doped diamond. Co-doping should involve P as the donor atom, as N is limited by its very high Pauling electronegativity.

Thereafter, the integration of diamond in quantum computing was discussed. Through this review, we presented various aspects that are important to diamond development and the future that beholds in semi-conductor devices. We considered NV centers and their importance for quantum computing. Diamond can offer new improvements and minimize the problems that exist in quantum computers. Interestingly, N in diamond that is inappropriate for nanoelectronic devices is of unique importance in the form of the NV center and a paradigm for the emerging field of quantum computing.

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Conflicts of Interest: The authors declare no conflict of interest.

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Authors and CV

Alexander Chroneos, Professor at the University of Thessaly, Greece (Visiting Reader at Imperial College London). He defended his PhD thesis in Materials in 2008 at the Imperial College London. Prof. Chroneos has authored over 400 refereed papers and 3 book chapters. The area of his scientific interests includes physics and technology of semiconductor materials, diffusion properties of energy materials, superconducting properties, nuclear materials, and computational modeling. https://orcid.org/0000-0002-2558-495X

Vovk R.V. Academician of the National Academy of Sciences of Ukraine, Doctor of Sciences, Professor at the V.N. Karazin Kharkov University, Ukraine. Authored and co-authored more than 500 scientific publications, 3 monographs, and 30 patents. The area of his scientific interests is physics of condense matter.
https://orcid.org/0000-0002-9008-6252

Перспектива легування алмазу для квантових обчислювальних застосувань

I. Avradopoulos, V. Giosis, K. Katsanos, A. Chroneos, R.V. Vovk

Анотація. Алмаз не є основним матеріалом для наноелектронних застосувань, незважаючи на його чудові фізичні властивості. Існує багато проблем у розробці ефективних напівпровідникових приладів на основі алмазу. У цій перспективі ми зосереджуємося на введенні легуючих домішок за допомогою різних методів легування (термічне легування, дифузія, дельта-легування, хімічне осадження з парової фази (CVD) тощо). Формування легованого *n*-типу алмазу з використанням звичайних легуючих домішок, таких як фосфор (P), є складним завданням. Азот (N) можна вводити разом з бором (B) за допомогою спільного легування. Формування легованих *p*-типу областей в алмазі є менш проблематичним порівняно з легованими *n*-типу областями. Це пояснюється тим, що B є відповідною акцепторною легуючою домішкою, і крім того, існує можливість формування H-алмазу, який також є акцептором. Наразі мрія про алмазний транзистор поступилася місцем його застосуванню в галузі квантових обчислень. У поточному контексті ми розглядаємо легування *n*- та *p*-типу в алмазі, зосереджуючись на труднощах, пов'язаних з легованим *n*-типу алмазом. Ми розглядаємо інтеграцію алмазу в квантові обчислення з урахуванням пар азот-вакансія.
Ключові слова: алмаз, легування, точкові дефекти, дислокації, кластери дефектів, магнітне поле, мікрохвильове випромінювання.