






A GLOBAL SCIENTIFIC ENDEAVOR AND ITS BRAZILIAN CHAPTER: THE FIRST CUT AND POLISHED 2.5-CARAT CVD DIAMOND GROWN IN BRAZIL

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ABSTRACT

The synthesis of diamond films via chemical vapor deposition (CVD) represents one of the most transformative achievements in materials science over the past half-century. This technology transcended diamond from a gemological curiosity and an abrasive grit into a versatile, engineered material capable of meeting the extreme demands of modern technology. Its journey, from foundational thermodynamic paradox to commercial reality, is a story of global scientific collaboration and intense research. This review chronicles the comprehensive history of CVD diamond, describing the fundamental principles that enabled metastable diamond growth, the evolution of deposition techniques, the profound understanding of microstructure property relationships, and the subsequent expansion into a vast application landscape spanning electronics, tribology, optics, and biomedicine. In parallel with the global trajectory, this article integrates the specific history of the development of this technology in Brazil, as evidenced by the extensive national scientific output on the subject. By analyzing the broad collection of Brazilian publications from the 1990s to the 2020s, it is possible to trace the evolution of a research program that advanced in harmony with international progress. From early challenges in adherent diamond growth on metals to sophisticated innovations in nanocomposite films and foundational studies on single-crystal diamond, the Brazilian contribution, led by the National Institute for Space Research (INPE), has been essential to solving practical engineering challenges and expanding the frontiers of carbon-based thin films. This synthesis of the global and the local illustrates how a grand scientific challenge was addressed through a worldwide effort, with Brazil establishing a distinct and respected voice in the international diamond CVD community.

KEYWORDS: CVD diamond, Microwave plasma, Electronics, Optics, Sensors, Quantum technologies.

UM ESFORÇO CIENTÍFICO GLOBAL E SEU CAPÍTULO BRASILEIRO: O PRIMEIRO DIAMANTE CVD LAPIDADO DE 2,5 QUILATAS CRESCIDO NO BRASIL

RESUMO

A síntese de filmes de diamante por deposição química em fase de vapor (CVD) representa uma das conquistas mais transformadoras da ciência dos materiais nas últimas cinco décadas. Essa tecnologia elevou o diamante de uma curiosidade gemológica e de um abrasivo industrial a um material de engenharia versátil, capaz de atender às exigências extremas da tecnologia moderna. Sua trajetória – do paradoxo termodinâmico fundamental à realidade comercial – é uma história de colaboração científica global e

intensa pesquisa. Esta revisão apresenta um relato abrangente da história do diamante CVD, descrevendo os princípios fundamentais que possibilitaram o crescimento metastável do diamante, a evolução das técnicas de deposição, o profundo entendimento das relações entre microestrutura e propriedades, e a subsequente expansão para um vasto campo de aplicações que abrange eletrônica, tribologia, óptica e biomedicina. Em paralelo à trajetória global, este trabalho integra a história específica do desenvolvimento dessa tecnologia no Brasil, evidenciada pela ampla produção científica nacional sobre o tema. Ao analisar o conjunto de publicações brasileiras das décadas de 1990 a 2020, é possível traçar a evolução de um programa de pesquisa que avançou em harmonia com o progresso internacional. Desde os desafios iniciais no crescimento de filmes de diamante aderentes sobre metais até as inovações sofisticadas em filmes nanocompósitos e os estudos fundamentais sobre diamante monocristalino, a contribuição brasileira – liderada pelo Instituto Nacional de Pesquisas Espaciais (INPE) – foi essencial para solucionar desafios de engenharia prática e ampliar as fronteiras dos filmes à base de carbono. Essa síntese entre o global e o local ilustra como um grande desafio científico foi enfrentado por meio de um esforço mundial, com o Brasil estabelecendo uma voz distinta e respeitada na comunidade internacional de pesquisa em diamante CVD.

PALAVRAS-CHAVE: Diamante CVD, Plasma de micro-ondas, Eletrônica, Óptica, Sensores, Tecnologias quânticas.

INTRODUCTION

Diamond has captivated humanity for millennia, but its allure for scientists and engineers is rooted not in its brilliance but in its unparalleled portfolio of physical properties. It is the hardest known natural material, possesses the highest thermal conductivity at room temperature (exceeding 2200 W/m·K), is transparent from the deep ultraviolet to the far infrared, is chemically inert, and exhibits a wide bandgap (5.45 eV), a high breakdown electric field (> 10 MV/cm), and high charge carrier mobility. This unique combination makes it the ultimate “extreme environment” material, promising revolutionary advances in high-power electronics, thermal management, radiation detection, wear-resistant coatings, and biomedical devices.¹

For centuries, the technological application of diamond was constrained by nature’s limitations: scarcity, small crystal size, and high cost. The advent of high-pressure high-temperature (HPHT) synthesis in the 1950s offered a synthetic route, primarily producing grit for abrasives. The true paradigm shift occurred with the development of chemical vapor deposition (CVD) in the 1980s. CVD demonstrated that diamonds could be grown metastably at low pressures from a vapor phase, enabling the production of continuous films, coatings on complex shapes, and free-standing wafers. This breakthrough, as noted by Spitsyn et al.², transformed diamond from a static material into a dynamic engineering platform.

The foundational principle of diamond CVD involves activating a carbon-containing gas mixture, typically methane highly diluted in hydrogen, using a hot filament, microwave plasma, or combustion flame. The key insight, which ignited a global “diamond fever,” was the indispensable role of atomic hydrogen. As elucidated,^{3,4} atomic hydrogen selectively etches the thermodynamically stable graphite phase while stabilizing the sp³ bonds of diamond on the growing surface. The C-H-O phase diagram developed by Bachmann provided a universal roadmap for successful deposition across various techniques.

This review will chart the global scientific journey of CVD diamond, from nucleation to advanced applications. Furthermore, it will weave into this narrative the specific contributions from Brazil to illustrate how a national research ecosystem developed, confronted fundamental challenges, and contributed meaningfully to the international body of knowledge.

THE SCIENTIFIC FOUNDATIONS AND GLOBAL TECHNOLOGICAL EVOLUTION

The CVD of diamond is a triumph of kinetics over thermodynamics. At typical deposition pressures of 10 to 200 Torr and temperatures between 700 and 1,000 °C, graphite is the stable phase of carbon. The success of diamond growth relies on creating a “super-equilibrium” of atomic hydrogen that preferentially gasifies sp²-bonded carbon.

The methyl radical (CH_3) is widely accepted as the primary growth precursor. The pioneering work of Eversole in the 1950s and later Soviet scientists like Deryagin, Spitsyn, and Fedoseev laid the groundwork, but it was the reproducible, high-quality growth demonstrated by Japanese (NIRIM) and American groups in the 1980s that truly launched the field.⁵ The two most prevalent CVD techniques became hot-filament CVD (HFCVD) and microwave plasma CVD (MPCVD).

HFCVD, one of the first successful techniques, relies on a resistively heated metal filament, typically composed of tungsten or tantalum, positioned in proximity to the substrate. Operating at temperatures exceeding 2,000 °C, the filament catalytically breaks molecular hydrogen, generating the essential atomic hydrogen and reactive hydrocarbon species that diffuse to the substrate surface. The primary merit of HFCVD lies in its conceptual and operational simplicity, making it a widely adopted tool for fundamental research and cost-sensitive applications.⁶ It has been extensively used to study the influence of core parameters like methane concentration and substrate temperature on growth morphology, as quantified by Menon et al.,⁷ and for fabricating devices such as alpha-particle detectors.

Microwave plasma-assisted CVD (MPCVD) operates at microwave frequencies of 2.45 GHz or 915 MHz to generate a high-energy plasma ball that dissociates gas molecules, producing a dense concentration of reactive species. This technique has become the workhorse for the growth of high-purity, electronic-grade diamond and for high-rate deposition.⁸ Owing to its high degree of ionization and the precise control it offers over the plasma environment, MPCVD remains the preferred method for synthesizing electronic-grade diamond, homoepitaxial layers, and thick, free-standing substrates. Advances in reactor power and plasma uniformity have further enhanced growth performance. For instance,⁹ demonstrated improved homoepitaxial growth in high-power systems, while Kasu and Kobayashi¹⁰ achieved exceptional crystalline quality, evidenced by a Raman peak full width at half maximum of only 2.35 cm^{-1} . The ability of MPCVD to produce large single-crystal diamonds was also demonstrated by Israel and Vohra,¹¹ who reported growth rates comparable to those obtained by HPHT methods for fabricating high-pressure anvils.

Beyond these two dominant techniques, other methods have been explored. Combustion synthesis offers a relatively low-cost approach, as investigated by Wongprasert and Titiroongruang¹² for selective-area deposition. Laser-assisted CVD has also been demonstrated, with Molian et al.¹³ reporting the synthesis of fluorinated diamond films using laser-induced precursor gas interactions. The choice of technique ultimately involves a trade-off between cost, scalability, growth rate, and the specific quality requirements of the intended application.

A paramount initial challenge was achieving high nucleation density on non-diamond substrates. Early methods relied on mechanical abrasion with diamond powder, which damaged the substrate. The development of bias-enhanced nucleation (BEN) was a major advancement, using a substrate bias to attract ions and achieve nucleation densities $> 10^{10} \text{ cm}^{-2}$, a prerequisite for heteroepitaxial growth.¹⁴ An alternative, highly effective method was the seeding of substrates with nanodiamond suspensions, particularly from detonation synthesis, which enabled conformal coatings on complex geometries.^{15,16} The microstructure of CVD diamond films is profoundly influenced by deposition parameters. Through competitive growth, pronounced crystallographic textures (e.g., $\langle 100 \rangle$ or $\langle 110 \rangle$) develop. Microcrystalline diamond (MCD) films, with large, faceted grains, are optimal for thermal and optical applications but have rough surfaces. The addition of argon or nitrogen to the process gas promotes renucleation, leading to nanocrystalline diamond (NCD) and ultrananocrystalline diamond (UNCD) films, which exhibit extremely smooth surfaces ideal for tribology and microelectromechanical systems (MEMS).^{17,18}

PRINCIPAL APPLICATION DOMAINS OF CVD DIAMOND

The exceptional combination of physical, chemical, and electronic properties of CVD diamond has enabled its adoption across an increasingly diverse spectrum of advanced technologies. Its unmatched hardness, chemical stability, wide bandgap, and record-breaking thermal conductivity have translated into both industrial and scientific applications that continue to expand as synthesis techniques mature. Today, CVD diamond is deployed not only as a coating material for wear-resistant cutting tools and heat spreaders in high-power electronics but also as a

platform for optical, electronic, and quantum devices. In the gem and jewelry sector, CVD diamond represents a profound technological evolution that has redefined the global diamond market by achieving gem-grade purity and color control through refined growth and post-treatment processes. In optics, its broadband transparency and exceptional mechanical resilience make it ideal for windows and domes used in high-power lasers, infrared systems, and aerospace applications. In electronics, CVD diamond serves both as an active semiconductor and a superior thermal management material, with applications ranging from radiation detectors to high-frequency transistors. Beyond classical electronic and optical roles, CVD diamond now underpins the rapid development of quantum technologies, where nitrogen-vacancy (NV) centers enable quantum sensing, computing, and communication. These advances were made possible by the emergence of “quantum-grade” CVD materials with controlled impurity and isotopic composition. Finally, a new wave of emerging applications demonstrates the continuing diversification of CVD diamond technologies. Together, these developments illustrate how the evolution of CVD diamond, from thin industrial coatings to precisely engineered single crystals, has positioned it as one of the most versatile materials, bridging traditional industry, advanced electronics, and the quantum frontier.

Gems and jewelry

The history and evolution of CVD diamonds in jewelry represent a transformative narrative of scientific innovation leading to commercial viability. The foundational research phase (1950s-1980s) established critical low-pressure deposition concepts through microwave and hot-filament approaches that produced micron-sized diamond particles and thin films, creating the essential chemical framework for future gem production.^{19,20} The 1990s witnessed the commercialization of polycrystalline CVD diamond films for industrial applications, which provided crucial technological foundations through improved reactor engineering and reduced deposition costs. The pivotal breakthrough to gem-grade crystals occurred in the late 1990s-2003 period, when companies developed patented low-pressure CVD methods capable of producing facetable single-crystal Type IIa material, with Apollo Diamond emerging as a pioneer by supplying early brown-to-near-colorless gem samples and announcing limited faceted diamond sales in 2003, thereby capturing immediate attention from gemological laboratories worldwide.²¹

Substantial quality and size improvements characterized the 2004-2012 period, driven by significant advances in high-growth MPCVD technology. Producers successfully achieved gem-sized single crystals with high fracture toughness and, through HPHT annealing treatments, demonstrated exceptional hardness properties. By 2012, the successful production of multi-carat near-colorless single crystals firmly established CVD diamonds as serious contenders in the gem market.²² The most recent phase has focused on industrial scaling and sophisticated characterization, with gemological laboratories expanding their identification capabilities as producers improved clarity, color control, and growth uniformity. Modern CVD technology now routinely produces single crystals exceeding 10 carats in rough form and faceted gems with three or more carats with excellent clarity, while offering unprecedented color control through deliberate impurity management and post-growth modification techniques.^{20,23} These developments have enabled CVD diamonds to achieve Type IIa purity with exceptional optical properties that often exceed mined diamonds, positioning them as high-quality, customizable alternatives in the contemporary jewelry landscape.

Optics

The broadband optical transparency and exceptional durability of CVD diamond make it a material of choice for robust optical components. Molars²⁴ described the progression from small planar windows to large-diameter (up to 120 mm) windows and hemispherical domes for use as infrared apertures in aerospace and defense systems. These components must withstand harsh environmental conditions, including rain and sand erosion, and relate their unsurpassed erosion resistance directly to the polycrystalline grain structure. Diamond's high transmissivity and dimensional stability also make it suitable for X-ray windows and lithography mask membranes.²⁵

Electronics

Diamond's large bandgap, radiation hardness, fast response time, and ability to operate at room temperature make it a nearly ideal material for detecting ionizing radiation. The history and development of diamond detectors for particle physics have been comprehensively reviewed, highlighting their unique resilience in high-radiation environments where conventional semiconductor detectors rapidly degrade.²⁶ A significant body of work has focused on developing detectors for alpha particles and X-rays. An alpha particle detector, reported in Zhang et al.²⁷ from a (100)-oriented HFCVD film, studying phenomena such as dark current, photocurrent, and the detrimental "polarization" effect. Similar devices were investigated by Bei-Bei et al.²⁸ The detector performance is intimately linked to material quality, as observed by (28) in a work that systematically showed that the performance of X-ray detectors, in terms of photocurrent and pulse-height distribution, improves significantly with increasing grain size. These effects are attributed to charge trapping at grain boundaries. The "priming" effect, whereby pre-irradiation fills deep traps and improves charge-collection efficiency, was also observed by Zhang et al.²⁹ The device architecture also plays a role; Galbiati et al.³⁰ characterized a coplanar electrode detector, which confines the electric field to the higher-quality growth side of the film, achieving a charge-collection efficiency of approximately 15%.

The high carrier mobility, high breakdown voltage, and unparalleled thermal conductivity of diamond make it a promising semiconductor for high-power, high-frequency electronics. A comprehensive review of diamond technology from an RF perspective³¹ concludes that despite technological challenges, diamond is a serious contender for RF power circuits. They highlighted achievements such as field-effect transistors (FETs) operating at 81 GHz and delivering extremely high power densities up to 30 W/mm. The successful synthesis and integration of metal-semiconductor FETs (MESFETs) based on delta-doped CVD diamond layers were reported by Schwitiers et al.³² For thermal management, diamond's role as a heat spreader is already commercially established. It is used to dissipate heat from high-power-density devices like laser diodes and GaAs monolithic microwave integrated circuits (MMICs). A case study on packaging GaAs MMICs in CVDD-enhanced plastic packages was described in Fabis.³³ Diamond is also employed in passive devices, such as surface acoustic wave (SAW) filters, and is being explored as an insulating substrate for silicon-on-insulator (SOI) technologies, potentially leading to silicon-on-diamond (SOD) devices with superior thermal performance, as explored by Aleksov et al.³⁴ and Mortet et al.³⁵

For electronic applications, controlled doping is essential. Boron doping provides reliable p-type conductivity, enabling devices like Schottky diodes and FETs.³⁶ In contrast, n-type doping proved to be a formidable challenge. Phosphorus is the most successful n-type dopant, but its deep donor level (0.6 eV) limits room-temperature conductivity. The search for a shallow donor continues to be a primary research focus.³⁷ A promising architectural workaround is delta-doping, which incorporates ultra-thin, heavily doped layers to create high-performance MESFETs.³²

Quantum technologies

The NV center in diamond has evolved from a topic of fundamental investigation into a cornerstone of practical quantum technologies, a transformation critically enabled by progress in CVD diamond synthesis. The NV center's defining properties, optical addressability, long spin coherence at room temperature, and spin polarization, have positioned diamond as a versatile platform for quantum sensing, computing, and communication.³⁸ However, achieving scalable and high-performance devices required a parallel revolution in diamond materials engineering, shifting from natural and HPHT crystals to deliberately engineered "quantum-grade" substrates.³⁹

The historical trajectory of the field highlights this materials-driven evolution. In the early 2010s, NV centers became recognized as viable qubits for quantum networks and computing, supported by a growing body of experimental demonstrations and theoretical proposals.³⁸ Shortly thereafter, advances in nanoscale sensing extended the scope of NV-based detection from single centers to nanodiamond ensembles.⁴⁰ By the end of the decade, the community had converged on the need for wafer-scale, defect-controlled CVD growth, which established the framework for "quantum-grade" diamond materials emphasizing impurity suppression, isotopic purification, and oriented crystal synthesis.^{39,41} These developments provided the necessary foundation for reproducible, large-scale device fabrication and integration.

CVD materials engineering has been central to these achievements. Controlled in-situ nitrogen doping and post-growth defect engineering enabled the production of NV centers with tunable densities, from isolated single qubits to dense ensembles optimized for magnetometry.⁴² Enhancements in spin coherence through isotopic enrichment and refined annealing were complemented by methods for strain reduction and preferential NV orientation, which improved homogeneity and extended DC sensitivity limits.⁴³ Together, these advances culminated in compact, low-noise CVD diamond sensors demonstrating stable pico-Tesla magnetic field sensitivity, reflecting the technological maturity of diamond-based quantum platforms.⁴⁴

Progress has been driven by collaborative research networks uniting expertise in materials science, spin physics, and device engineering. Key contributions have originated from programs at Delft University of Technology and McGill University in spin control and quantum interfacing,³⁸ from the CNRS and University of Montpellier in quantum-grade CVD growth,³⁹ and from European and North American partnerships working toward wafer-scale integration and NV orientation control.^{41,45} This cross-disciplinary structure established a feedback loop between materials characterization, synthesis optimization, and device performance.

At present, CVD diamond underpins three primary application domains in quantum technology. In quantum sensing, engineered NV ensembles enable scalable magnetometers and thermometers with sub-picotesla precision.⁴² In quantum computing, diamond hosts optically addressable spin qubits and multi-spin registers, while laser-written NV arrays demonstrate the feasibility of scalable architectures.⁴⁶ In quantum communication, NV centers act as solid-state spin-photon interfaces for quantum repeaters and entanglement distribution.⁴¹ Across these fields, the interplay between materials control and quantum operation defines the current performance frontier.

Several synthesis challenges have shaped this trajectory. The mitigation of paramagnetic impurities in the spin bath required rigorous control of gas purity and substrate selection.³⁹ The balance between NV density and spin coherence was refined through optimization of doping, annealing, and charge stabilization.⁴⁰ Meanwhile, dislocation management and stress engineering reduced linewidth broadening, improving ensemble sensitivity and reproducibility.⁴⁷ These innovations established reproducible workflows linking growth parameters to device-level quantum metrics.

Looking ahead, the prospects for CVD diamond remain expansive. Commercialization pathways are already emerging for industrial magnetometers and thermometers,⁴² while biomedical applications exploit the biocompatibility and ambient operation of nanodiamond-based NV sensors.⁴⁰ Broader directions include energy systems diagnostics and the exploration of analogous defect-spin platforms in other wide-bandgap semiconductors.⁴⁶ Central to these developments is the established materials-to-device feedback cycle, integrating precise growth control, advanced characterization, and scalable fabrication to transform laboratory discoveries into deployable quantum technologies.⁴⁵

Other emerging applications

The application landscape for CVD diamond continues to expand. In MEMS, its hardness and chemical inertness are leveraged. A molding technique to create intricate diamond microstructures from silicon masters is described in Bjorkman et al.,⁴⁸ developed for use in microfluidics and as molds for polymers. In electrochemistry, boron-doped diamond (BDD) electrodes are utilized for electroanalysis and wastewater treatment due to their wide electrochemical window and corrosion resistance. Furthermore, the ability to grow high-quality, thick diamond layers via MPCVD provides an economically attractive route to produce synthetic diamond anvils for high-pressure research, as demonstrated by Israel et al.¹¹ and McCauley and Vohra.⁴⁹

THE BRAZILIAN CHAPTER

The global advancement of CVD diamond technology found a resonant and productive echo in Brazil, largely driven by research at the National Institute for Space Research (INPE), spanning over three decades, and provides

a microcosm of the field's evolution, reflecting global trends while focusing on challenges pertinent to the Brazilian industrial and technological context.

The initial phase of Brazilian research, mirroring global efforts, focused on solving the fundamental problem of adherent diamond film growth on technologically relevant metal substrates. Early work by Trava-Airoldi et al.⁵⁰⁻⁵⁶ concentrated on molybdenum and Ti6Al4V alloy, both crucial for aerospace and biomedical applications. They pioneered surface modification techniques to enhance diamond film adhesion. For molybdenum, they achieved remarkable adhesion through nitrogen ion sub-implantation, creating a thin interfacial layer of nitrides and complexes that acted as a diffusion barrier and improved chemical bonding. For Ti6Al4V, studies involved detailed analysis of residual stress using micro-Raman spectroscopy and X-ray diffraction.⁵³

Barbosa et al.⁵⁷ established the activation energy for NCD films grown by HFCVD using Ar/H₂/CH₄ mixtures, showing that NCD and MCD share a similar growth mechanism, with activation energies around 10 kcal/mol. This finding indicated that both structures are governed by carbon incorporation via C₁ species rather than distinct processes. Building on that foundation, refined the control of HFCVD parameters such as filament temperature, gas composition, and substrate distance, correlating them to grain size distribution and film uniformity. These works provided critical insights into diamond nucleation dynamics, the transition between nanocrystalline and microcrystalline regimes, and the influence of substrate temperature on film morphology. Together, they laid the scientific and technological groundwork for subsequent developments at INPE, enabling the transition from polycrystalline coatings to the controlled homoepitaxial growth of single-crystal diamond by MPCVD.

In the work developed by Campos et al.,⁵⁸ the authors developed freestanding NCD windows with low surface roughness (Ra ≈ 20 nm) without the need for polishing, which is crucial for preserving the beam's spatial coherence. These windows, fabricated with thicknesses from 200 nm to 40 μm, exhibited excellent X-ray transparency and sufficient mechanical strength to withstand a pressure gradient of 1 atm, showcasing their viability for use in vacuum environments.

The following phase of research reflects a move towards sophisticated, multifunctional systems and advanced manufacturing techniques. The challenge of depositing diamond on steel was tackled with innovative interlayers. Research conducted by Damm et al.⁵⁹⁻⁶¹ focused on vanadium carbide (VC) interfaces deposited via thermomdiffusion and, more recently, laser cladding, which created a robust, composite intermediate layer that effectively mitigated residual stress and enabled the growth of high-temperature CVD diamond on steel substrates. The group also developed hybrid structures like BDD coated on carbon nanotubes for advanced electrochemical applications.⁶²

The group at INPE had progressively advanced in the development of diamond CVD technology through a series of studies focused on adhesion, structure, and stress control in coatings deposited on WC-Co substrates. The work led by Fraga et al.^{63,64} studied effective pretreatment routes using Murakami and aqua regia solutions to remove cobalt from WC-Co, combined with nanodiamond seeding to improve nucleation. These studies compared nano-, micro-, and UNCD coatings grown by HFCVD, showing that adhesion and morphology depended strongly on substrate preparation and grain size. Vieira et al. expanded these findings by developing multilayer architectures alternating micro-, nano-, and ultrananocrystalline layers, achieving smoother surfaces, better adhesion, and reduced internal stress.⁶⁵ Subsequently, Silva Neto⁶⁶ optimized MPCVD growth parameters, achieving polycrystalline films with growth rates up to 20 μm/h and low residual stress through improved substrate holder design and high-power plasma stability. More recently, Pentian Junior et al.⁶⁷ combined laser texturing with HFCVD to engineer surface microstructures that enhanced mechanical interlocking and stress relief in diamond-coated WC-Co tools. Collectively, these works established the experimental and technological foundation at INPE for transitioning from polycrystalline coatings to controlled single-crystal diamond growth, paving the way for the subsequent PhD research that achieved gem-grade single-crystal CVD diamond in Brazil. Alongside this work on polycrystalline and nanocomposite films, the group also made forays into the high-end domain of single-crystal diamond.

The PhD work of Silva Neto⁶⁸ enabled the production of the first gem-grade single-crystal CVD diamond in Brazil, as can be seen in Fig. 1. Homoepitaxial growth of the 1.8 mm gemstone was performed in two stages on a yellow type Ib single-crystal HPHT diamond seed. This approach was necessitated by the loss of epitaxial surface area to lateral polycrystalline diamond growth, which required the sample to be removed for laser cutting between growth steps.

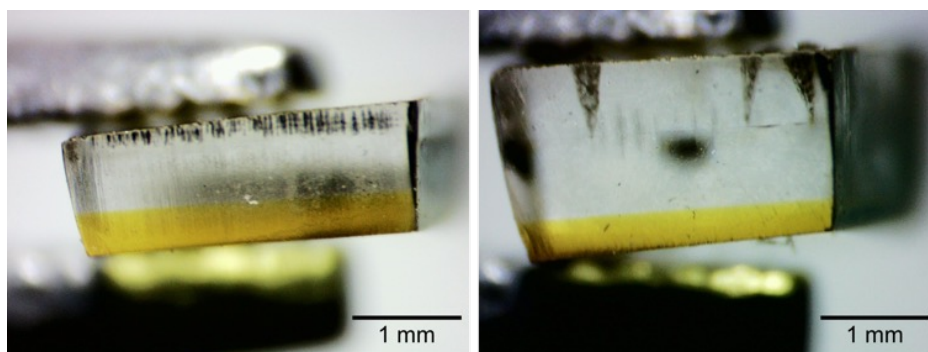


Figure 1: First gem-grade single-crystal CVD diamond grown in Brazil. The two-stage homoepitaxial growth was performed on a type Ib HPHT diamond seed using a high-power MPCVD reactor developed at INPE. The image highlights the interface between the seed (yellow) and the colorless CVD layer, marking a milestone in the national development of single-crystal diamond synthesis.

Source: Silva Neto JV.⁶⁸

This achievement was a necessary step to ensure the structural and optical quality required for subsequent studies involving sulfur doping to assess the viability for its use as an n-type dopant. The research focused on the controlled homoepitaxial growth of diamond using MPCVD with sulfur added to the conventional CH_4/H_2 gas mixture, aiming to investigate its influence on the structural, optical, and chemical characteristics of the resulting material. A comprehensive methodology was developed at INPE, including the design and optimization of the reactor, precise temperature control, plasma stability, and gas flow management. This work marked a pioneering advancement in Brazil, consolidating the country's capability to produce single-crystal CVD diamond suitable for both technological and gemological applications.

In the homoepitaxial growth of diamond, the step-flow growth mode is essential for achieving high crystalline perfection. This process, driven by the lateral migration of atomic steps, often enhanced by a substrate misorientation of 3° to 4° off-axis, fundamentally influences crystal quality. The dynamics of these steps are critical, as smooth, continuous progression not only promotes the termination of threading dislocations to reduce defect density but also provides ordered lattice sites that minimize the incorporation of point defects like nitrogen.⁶⁹ Consequently, mastering step-flow growth, where the surface morphology evolves towards triangular hillocks, is vital for producing high-purity diamond films with superior electronic properties. Building on this principle, the homoepitaxial growth of diamond via MPCVD was investigated, specifically examining how high methane and nitrogen concentrations influence step-flow behavior. By correlating changes in surface morphology with spectroscopic data, their work provides critical insight into controlling defect and impurity incorporation for high-quality single-crystal diamond.⁷⁰

This work created the foundation for the growth of a diamond crystal that, after being cut and polished into a round brilliant shape, yielded a weight of 2.5 carats pictured in Fig. 2, exhibited a visually estimated color in the near-colorless range, and an approximate clarity of VS, although it was not submitted to an official grading laboratory.



Figure 2: First gem-quality single-crystal CVD diamond produced in Brazil (2.5 ct). The crystal was grown homoepitaxially on a type Ib HPHT seed in two MPCVD stages, laser-cut, and cut and polished into a round brilliant.

Source: Elaborated by the authors.

The team's most recent milestone is shown in Fig. 3. The research group has further advanced its capabilities and can now produce optical-quality diamond crystals with thicknesses of a few millimeters and lateral dimensions of up to 15 × 15 mm, significantly expanding the potential for applications requiring larger, bulk-like diamond components.

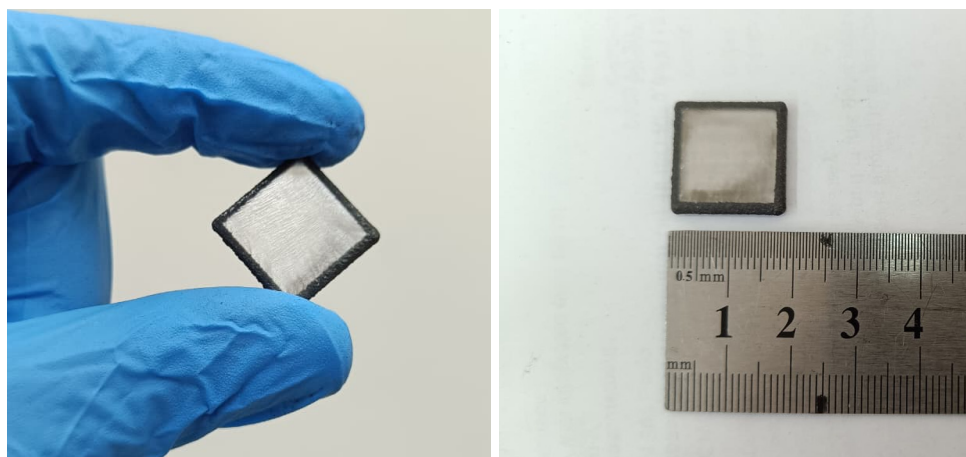


Figure 3: Optical-quality single-crystal CVD diamond produced at TCarbon with dimensions of approximately 15 × 15 mm and 2 mm in thickness. The images show the transparent crystal held by hand (left) and placed beside a ruler for scale (right).

Source: Elaborated by the authors.

This trajectory, from solving basic adhesion to engineering complex multifunctional coatings and exploring high-quality single-crystal growth, mirrors the global maturation of the field and positions Brazil as a significant contributor in specialized niches, particularly in tribology, advanced interlayer technology, and foundational research on SCD.

CONCLUSIONS

The journey of CVD diamond from a laboratory curiosity to a commercially viable engineered material has been remarkable. As of the mid-2000s, the landscape was one of robust growth and maturing technology. By the late 1990s and early 2000s, CVD diamond had firmly established itself in several niches. Chalker et al.⁷¹ correctly anticipated that thermal management would be a leading commercial application, and this has indeed come to pass, with polycrystalline diamond for heat spreading becoming a commodity material. Radiation detectors for high-energy physics and niche nuclear applications are a reality, with ongoing development to improve their performance and longevity.⁷² Cutting tools with CVD diamond coatings are widely available and provide superior performance in specific machining operations. The synthesis technology has matured considerably, with the production of large-area, high-quality polycrystalline wafers being routine,⁷³ and the synthesis of single-crystal diamond unlocked the highest performance tiers for electronic devices.⁷⁴ Research into NCD and hybrid materials has expanded the property space and application potential.⁷⁵

Despite significant progress, several challenges persist. The cost of high-quality CVD diamond, particularly single-crystal material, remains high compared to conventional semiconductors like silicon or silicon carbide. Precise and reliable n-type doping, as well as achieving high activation ratios for both n- and p-type dopants, continues to be an area of active research essential for fully realizing bipolar devices. For polycrystalline diamond, grain boundaries still act as traps and scattering centers, limiting charge carrier mobility and lifetime. Improving crystal quality and developing techniques for heteroepitaxy on foreign substrates remain important goals.⁷⁶ Additionally, processing diamond, including etching, patterning, and forming low-resistance ohmic contacts, is more difficult than with traditional semiconductors, necessitating specialized fabrication techniques.

The future of CVD diamond appears bright, built upon the foundation laid by the research summarized in this review. Key directions for future development include its application in ultra-high-power electronics, where diamond-based devices are poised to play a critical role in managing and switching very high power levels in applications

like electric vehicles and renewable energy systems. Diamond with specific color centers is also a leading platform for quantum sensing, quantum computing, and quantum communication, with CVD being the primary method for producing these engineered crystals. The integration of NCD into MEMS and nano-electro-mechanical systems (NEMS) will enable devices with unparalleled performance in terms of frequency, power handling, and robustness. Furthermore, diamond's biocompatibility and chemical inertness make it a promising material for biomedical implants, biosensors, and electrochemical electrodes. The ultimate promise of diamond lies in its ability to combine multiple extreme properties in one material, potentially enabling future systems where a single diamond chip performs sensing, computation, heat dissipation, and power handling simultaneously.

The evolution of CVD diamond from a scientific curiosity to a cornerstone of modern materials engineering is a testament to decades of global, interdisciplinary research. The journey has taken us from understanding the metastable growth of diamonds at low pressures to achieving unprecedented control over their structure, from rough polycrystalline coatings to atomically smooth single-crystal layers and sophisticated nanocomposite diamond films.

Intertwined with this global narrative is the history of the development of this technology in Brazil, as documented by the prolific research at INPE. The work chronicles a path from addressing fundamental challenges of adhesion on industrial metals to the forefront of multifunctional nanocomposite coatings for space and biomedical applications, and even to foundational investigations into the growth of single-crystal diamond. This Brazilian chapter demonstrates how a focused national research program can not only follow global trends but also establish world-leading expertise in specific, high-impact areas, contributing practical solutions and innovative materials to the international community.

CVD diamond unequivocally transcended its identity as gemstones or mere laboratory subjects. It is now a pivotal engineering material, enabling technologies that operate at the extremes of power, temperature, pressure, and biological compatibility. As synthesis and processing technologies continue to mature, the integration of these extraordinary carbon materials into the core of 21st-century technology is set to expand even further with the rise of CVD diamond in quantum technology applications driving innovation across the scientific and industrial landscape for years to come. The full spectrum of their usage, much like the story of their development, continues to be written by a global community of scientists, with Brazil holding a well-established place among them.

CONFLICT OF INTEREST

Nothing to declare.

AUTHOR CONTRIBUTIONS

Conceptualization: Silva Neto JV, Gómez JS, and Rosales MJC; **Formal Analysis:** Trava-Airoldi VJ; **Investigation:** Silva Neto JV, Gómez JS, and Rosales MJC; **Resources:** Silva Neto JV, Gómez JS; **Supervision:** Corat EJ, Trava-Airoldi VJ; **Validation:** Gómez JS, Trava-Airoldi VJ; **Data curation:** Silva Neto JV; **Writing:** Silva Neto JV; **Final approval:** Trava-Airoldi VJ, Silva Neto JV.


DECLARATION OF USE OF INTELLIGENCE ARTIFICIAL TOOLS

ChatGPT and SciSpace were employed to improve writing and enhance the search for updated literature, respectively.

AVAILABILITY OF DATA AND MATERIALS

The data will be made available upon request.

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