Chapter

Introductory Chapter: Some Aspects of Diamonds in Scientific Research and High Technology

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1. Introduction

Nowadays, the diamond is the most promising and unused semiconductor material in electronics and photonics due to the technological limitations of large sample production [1]. However, diamond is used for drilling, grinding, and polishing hard rocks and structural materials. Diamond itself can be mechanically processed using the difference of its wear resistance for different crystallographic directions.

In addition to the diamond mining industry, the volume of synthesized rough diamonds is steadily increasing. Alrosa Group of Companies (Yakutia, Russia) is the world largest natural diamond supplier. It mines about 35–40 million carats (7–8 tons) per year [2], which makes up about 28% of world production. At the same time, diamond plants located in China annually produce ~10 billion carats (~2000 tons) of synthetic diamonds, which are mainly used as abrasive material [3].

Natural diamond is a mineral that was formed at high pressures and high temperatures (HPHT) and annealed under HPHT conditions for a long time. Usually, natural diamond contains a large amount of nitrogen in the form of polyatomic impurity-defective centers [4]. In addition, the natural stones have a size of 0.1–1 mm usually, and large diamonds have a big value in jewelry. Due to these reasons, natural diamond is not considered as a material for high-tech applications.

The main methods for producing synthetic diamonds are the HPHT temperature gradient method [5], chemical vapor deposition (CVD) [6], and detonation synthesis [7]. The latter method is also called shock-wave method and produces the diamond nanopowder. It is economically viable in the field of conventional explosive weapon recycling. This nanopowder is used for seeding substrates for CVD synthesis of diamond [8], in adaptations of quantum key distribution algorithms [9], medical research [10], etc.

HPHT synthesis allows obtaining diamond crystals up to 20 mm in size. Using laser cutting from these stones, diamond substrates with a thickness of 0.25–3 mm are obtained. At present, diamond substrates with dimensions of 15 × 15 mm^2 [11] are commercially available. Unfortunately, large-size HPHT diamonds are characterized by an inhomogeneous distribution of impurities (N, Ni, etc.) in volume due to the inhomogeneous incorporation of impurities during the growing process into various growth sectors [12]. However, the HPHT method enables to synthesize diamond samples in which, using radiation-thermal treatment, it is convenient to create the necessary concentrations of spin- and optically active NV centers, which are intensively studied for applications of quantum cryptography [13], quantum computing [14], spintronics [15], and magnetometry [16]. The very important application of HPHT diamonds is a role of substrates for the deposition of high-quality thin films and bulk diamond samples using CVD method.

The priority of the first CVD synthesis patents relates to the 1950s of the last century [17, 18]. But only at the end of the century CVD diamond technology has developed enough to deposit graphite-free epitaxial diamond film on a diamond substrate [19]. At the time being CVD synthesis is a method for producing single-crystal diamonds of the highest quality, superior to the best jewelry brilliants. Depending on the choice of the substrate, the CVD method can produce both single crystals on substrates of diamond [20] and iridium [21], as well as polycrystalline samples on substrates of silicon [22, 23], copper [23], iron [23], etc.

The highest thermal conductivity of diamond (4–5 times higher than that of SiC and copper) enables to divert tens to hundreds of watts of heat generated from electronic devices, which determined the use of this material as a heat sink/radiator for powerful electronic devices [24]. For example, the use of CVD diamond as a substrate for GaN-based heterostructures provides a low thermal resistance at the material interface and the absence of thermal greases [25, 26]. At the same time, the diamond may serve as a passive element itself (heat sink) or as the basis of the active element, simultaneously performing the heat sink function.

The low dielectric constant of diamond means a high propagation velocity of electromagnetic radiation in the material and lower dielectric losses at high frequencies, due to lower parasitic capacitances. This fact additionally makes the use of diamond attractive for developing microwave and extremely high-frequency electronics, optoelectronics, and photonics devices of the future. Such integrated devices will be less energy intensive compared to devices based on traditional semiconductors. These characteristics, combined with high heat dissipation properties, makes diamond very attractive for creating electronic components for avionics of supersonic and hypersonic aircraft and spacecraft, i.e., where the problem of overheating is very important [27].

The size of polycrystalline CVD diamonds already reaches 120 mm in diameter [28]. But they are characterized by a high degree of roughness of the growth surface (0.1–10 μm). The nucleation surface of the CVD diamond substrate is smoother (0.01–0.1 μm) but more defective, which impairs its thermal, electronic, and optical properties. Difficulties in the mechanical processing of diamond led to the development of laser methods for its processing. In addition to laser cutting [29], separating the substrate [30], and polishing the surface [31], laser methods have found their application in the creation of antireflection structures on the surface of the diamond [32], which is important for the problems of radiation extraction from a material with a high refractive index and its significant dispersion (2.40–2.47 in the visible range).

Diamond is characterized by high bipolar mobility of charge carriers and is inferior only to gallium arsenide in electron mobility. In diamond, the mobility of electrons exceeds the mobility of holes by tens of percent, while in other semiconductors this difference can reach tens of times. High mobility of charge carriers in the material indicates a high rate performance of the device based on it. To obtain p-type conductivity, diamond is doped with boron in the deposition process, which is a well-established process from a technological point of view [33]. To obtain n-type conductivity, the diamond is doped with phosphorus [33]. But the quality of the phosphorus-containing diamond layers is significantly inferior to boron-containing ones because of the higher value of mechanical stresses, because phosphorus is usually incorporated into diamond in the form of impurity-defective complexes PV and PV_2 (where V is a vacancy) [34]. To reduce the value of mechanical stresses during the doping diamond with phosphorus, lithium is used as a co-impurity [35].

The electrical properties of diamond are significantly affected by the charge of the surface states of the sample. Depending on the type of chemisorbed elements, the electronic affinity of the diamond surface is changeable [36, 37]. The detection of negative electron affinity of the diamond surface (downward bending of zones, the absence of a potential barrier) determined the studies on the creation of cold cathodes and electron emitters based on diamond coatings [38].

Due to the strong covalent bonds, diamond is a chemically inert material and is suitable for medical and biotechnological applications [10]. In this case, such diamond properties as low cost of nanoparticles, the possibility of surface activation by photochemical methods, high photoluminescence yield and its resistance to photobleaching, low cytotoxicity, and, as a consequence, environmental safety are used.

The collection of scientific chapters proposed to the reader reflects some of the aspects, mentioned above. This collection will be useful to students, graduate students, and researchers who are interested in such disciplines as the synthesis of carbon and superhard materials, carbon electronics and photonics, surface chemistry, etc.

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