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New Carbon Materials: Biological Applications of Functionalized Nanodiamond Materials

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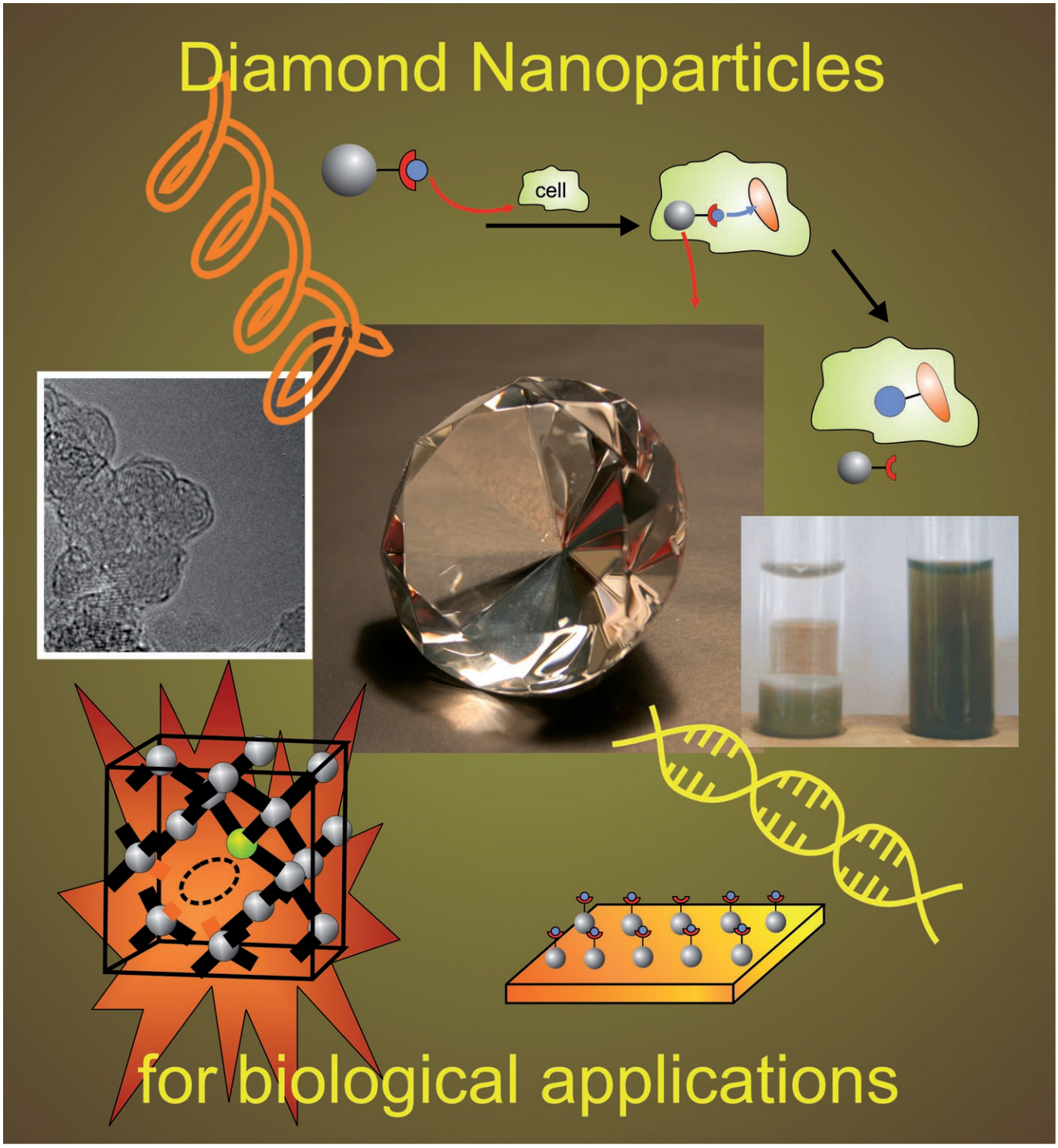

Abstract: Nanoscale diamond particles have become an interesting material. Due to their inertness, small size and surface structure, they are well-suited for biological applications, such as labelling and drug delivery. Here we discuss the surface structure and functionalisation of diamond nanoparticles. Non-covalent as well as covalent grafting of bioactive moieties is possible, and first applications of fluorescent diamond nanoparticles are described.

Keywords: biological applications · carbon · diamond · nanoparticles · surface chemistry

Introduction

In recent years diamond has become a widely investigated material for its remarkable properties, for example, hardness, thermal conductivity, dopability or optical transparency over a wide spectral range, to name only a few.[1] Diamond films, in particular, have become a focus of interest. Their production by chemical vapour deposition (CVD)[2] has evolved into a commercially available technique that is able to produce industrial amounts of surface coatings and free-standing films for a broad range of applications, such as electronic and electrochemical devices, sensors, protective coatings and optical windows.[3]

However, the family of diamond materials (Figure 1) includes additional members, such as the so-called diamond-like carbon (DLC),[4] sintered diamond phases[5] and diamond micro- and nanoparticles.[6] Closely related to diamond is a group of organic molecules, the diamondoids.[7] Although they are not real diamond materials (their properties differ significantly from those of true crystalline diamond due to their small size and electronic structure), they have interesting properties, which could eventually lead to new insights into the behaviour of nanoscale diamond materials. Especially their chemical properties are closely related to the surface chemistry of all kinds of diamond materials.[8]

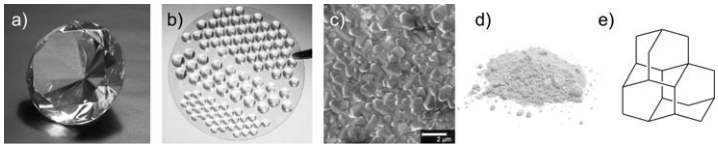

Figure 1. Different diamond materials: a) gem quality diamond, b) single-crystalline diamond film with microlens structures, c) polycrystalline diamond film, d) detonation diamond powder, e) triamantane, a diamondoid molecule.

In particular, the surface chemistry of nanoscale diamond particles should show close resemblance. This form of diamond carbon has recently come into the focus as a new potential material in quantum engineering, biological and electronic applications, as well as in composite materials.[9] Although considered as a "new" carbon material the production of nanodiamonds was invented decades ago. Besides the shock-wave transformation of graphite into sintered nanodiamond[10] nanoscale diamond can be obtained (even on an industrial scale!) by the detonation of certain explosives, for example, TNT–hexogene mixtures, in a closed container.[11] Due to the lack of oxygen the combustion of the explosive (which serves as source of energy *and* carbon) is incomplete and the resulting soot contains up to 80% diamond. This so-called detonation diamond consists of tiny diamond crystallites of about 5 nm in size.[12] They are covered with some graphitic and amorphous carbon and interconnected by soot-like structures.[13] In the present paper we discuss the properties and surface chemistry of this rediscovered material.

The Surface Structure of Nanodiamond

The structure of nanodiamond depends strongly on its production conditions. Nanoscale diamond particles that have been obtained by the destruction of bigger (natural or artificial) diamond crystals exhibit mainly the same surface features as their bulk-scale counterparts, whereas detonation diamond possesses significantly different features. Especially the extreme environment during the detonation produces a variety of surface functional groups on the particle surface. Usually a cooling gas (CO_2, H_2O or inert gases) has to be applied during the detonation in order to prevent the regraphitisation of the diamond crystallites as well as extensive soot formation.[12] Therefore, the reaction of dangling bonds with the surrounding medium causes the abundant functionalisation of the particle surface.[14] Additionally, the high temperature in the reactor persists even after the passing of the detonation wave, which results in at least partial graphitisation of the surface. Further modification occurs during the subsequent acid treatment. Usually, nitric acid and other oxidising acids are applied for this purpose.[15]

The resulting surface structure has extensively been studied by different techniques such as photoelectron,[16] IR[17] and NMR spectroscopy,[18] as well as by thermodesorption.[19] The most characteristic surface groups include carboxyl, hydroxyl and keto functions as well as anhydrides and lactones. Figure 2 shows a model of detonation diamond structure, in which the presence of surface groups and graphitic material open the way for various modifications of

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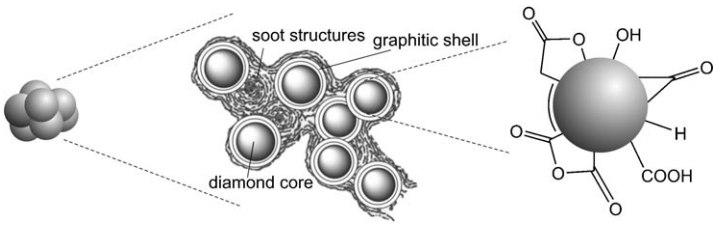

Figure 2. Cluster structure of detonation diamond and surface functional groups.

the materials properties. Surprisingly, the concentration of nitrogen-containing surface groups seems to be rather low although the starting materials usually are nitrogen-rich (vide supra) and the elemental analysis of pristine detonation diamond shows a nitrogen content of about 2%.[13,20] Apparently, most of this nitrogen is incorporated in the diamond particles, but not necessarily at lattice positions. The concentration of nitrogen defects is rather low.[21]

Functionalisation of the Diamond Surface

One of the most important and promising ways for materials modification is the surface functionalisation of the particles as it gives the opportunity to graft different functional moieties, for example, bioactive structures, polymerisable monomers or radical initiators, to name but a few. Two ways for the initial grafting have to be distinguished: the covalent and the non-covalent attachment of organic structures on the diamond surface. In the following chapters these two options will be discussed with regard to potential biological applications of the resulting materials.

Non-covalent Surface Modification

The bare diamond surface has proven to be very reactive towards adsorption of various kinds of small and larger molecules. For example, water forms a continuous layer on the diamond surface yielding interesting electronic surface properties described by the term "surface band bending".[22] Moreover, larger organic molecules and biological structures such as proteins can be immobilised on the diamond surface. The binding strength depends strongly on the surface termination of the considered diamond material. Due to the lack of polar interactions, for example, hydrogen bonding, hydrogen-terminated surfaces are much less likely to adsorb proteins and other biological items.[23]

Therefore, they do not show non-specific adsorption of bioactive molecules. On the other hand, oxidised diamond surfaces are prone to these interactions as the oxygen-containing surface groups participate in hydrogen bonds and other polar interactions with the adsorbed species.[24] There have been numerous reports on the non-covalent interaction between biomolecules and diamond surfaces. Among others, Bondar et al. showed the adsorption of apoobelin and luciferase,[25] Huang et al. reported on the immobilisation of cytochrome c[26] and Chung et al. on the application of protein lysozyme for the non-covalent surface modification of diamond nanoparticles.[27] The resulting materials were submitted to different tests of their applicability in biological systems. It was shown that these conjugates largely conserve the activity of the adsorbed biomolecules and that further functionalisation is possible on existing functional groups. In this way, Huang and Chang utilised the free amino groups of adsorbed poly-L-lysine to further modify their diamond–protein conjugate by covalently immobilising fluorescent dyes on the poly-L-lysine coating layer (Figure 3).[26] The resulting particles can be applied for labelling experiments (vide infra).

Covalent Functionalisation

The covalent surface modification of diamond films has recently developed into an active field of research. Different strategies for the covalent grafting of complex structures as

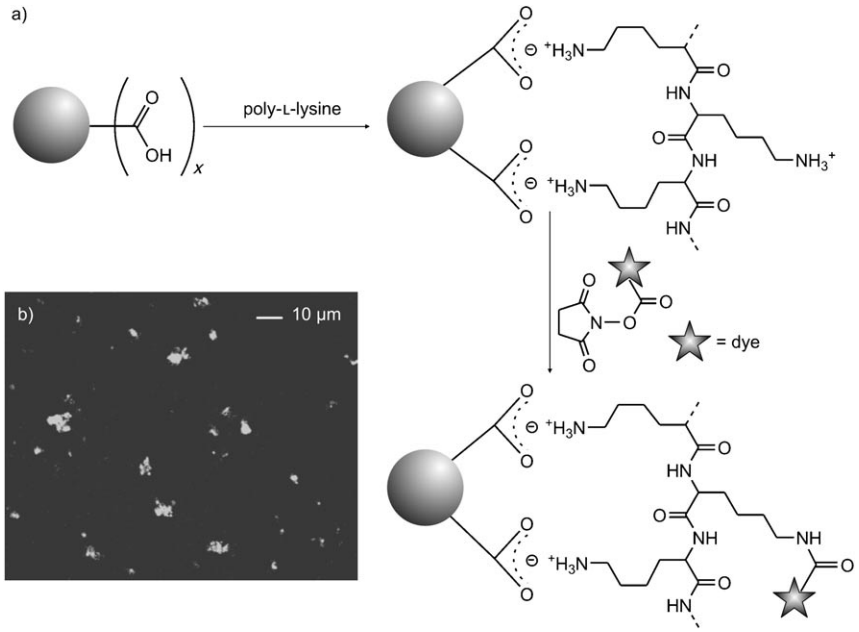

Figure 3. Non-covalent surface modification of nanodiamond particles. a) After the noncovalent coating with poly-L-lysine, the diamond particles are labelled with a fluorescent dye; b) fluorescence image of nanodiamonds labelled with Alexa Fluor 488. Reproduced with permission from *Langmuir* **2004**, *20*, 5879–5884. Copyright 2004 American Chemical Society.

well as for the tuning of hydrophobicity have been reported.[28] One method includes the photochemical reaction of hydrogen-terminated diamond films with organic compounds possessing a terminal vinyl group leading to stable C–C bonds at the diamond surface (Figure 4).[29] When bifunctional molecules are used, further functionalisation leads to ever more complex conjugates.

Hydrogen-terminated diamond films can also be modified using electrochemical and radical reactions. In this way diazonium salts and azo-perfluoroalkyl compounds, respectively, can be grafted.[30] On the other hand, oxidised diamond films can be functionalised utilizing the existing surface groups. In the case of hydroxylated films, Delabouglise et al. reported on the covalent grafting of biotin.[31] Carboxyl groups on diamond films can be transformed into the corresponding acyl chlorides and are used for the covalent coupling with bioactive moieties. Ando et al. reported on the attachment of thymidine and the subsequent grafting of DNA strands (Figure 4).[32]

On the other hand, the covalent surface modification of nanoscale diamond particles has proven to be a challenging task. Although the surface is covered with a variety of initial surface groups (from production and purification treatment), there have not been too many reports on the selective grafting of bigger entities. One major obstacle is the surface inhomogeneity of the initial material.[33] It contains a variety of metal impurities as well as non-diamond carbon, which can nevertheless be removed to a great extent by acid and oxidative treatment.[34] Additionally, it is desirable to first chemically homogenise the surface. This can be done in a variety of ways: One option consists in the high-temperature treatment with oxidising mineral acids.[35] The diamond surface is then covered with carboxyl, keto and anhydride groups, with a majority of carboxyl groups. The further functionalisation of these surface groups has not been explored extensively yet.

The reaction of detonation diamond with different reactive gases has been studied (Figure 5). Spitsyn et al. reported on the surface modification with hydrogen, ammonia, chlorine and carbon tetrachloride.[36] This treatment not only lead to an improvement of sample purity, but also at least partially established the respective surface structures, namely NH_2, C–H and Cl. Chlorinated nanodiamond has also been obtained by Korolkov et al. They subjected these samples to reactions with different nucleophiles, for example, cyanide.[37] Sotowa et al. reported on the hydrogenation of submicron diamond powder followed by chlorination and amination using gaseous chlorine and ammonia.[38] The reaction with fluorine was studied by Khabashesku et al.[39] They found that the surface of detonation nanodiamond readily reacts with gaseous fluorine in the presence of hydrogen. The resulting fluorinated samples had a fluorine content of up to 8.6 at % and could be further functionalised by substitution with amines, amino acids and lithium organyls.

Another method to obtain more homogeneous nanodiamond surfaces is the reduction of surface carbonyl groups. Krueger et al. reported on the reaction with borane leading to hydroxylated diamond samples.[40] The resulting material can be modified in a variety of ways. Especially the grafting of trialkoxysilanes easily yields functionalised nanodiamond particles. The reaction can be carried out with different silanes, for example, trimethoxy and triethoxy 3-amino-propylsilane. Depending on the choice of alkoxy groups, the surface loading can be tuned between ≈ 0.3 and $1.5\ \mathrm{mmol\,g^{-1}}$.[41] The material's amino groups are accessible for further surface modification. Besides the build-up of a short model peptide on the diamond solid phase,[40] biotin was covalently immobilised on the particle surface by coupling it to the amino groups of the silane (Figure 6).[42] Its activity concerning the binding to streptavidin was demonstrated, making it a model for a bioactive moiety covalently grafted onto the diamond surface.

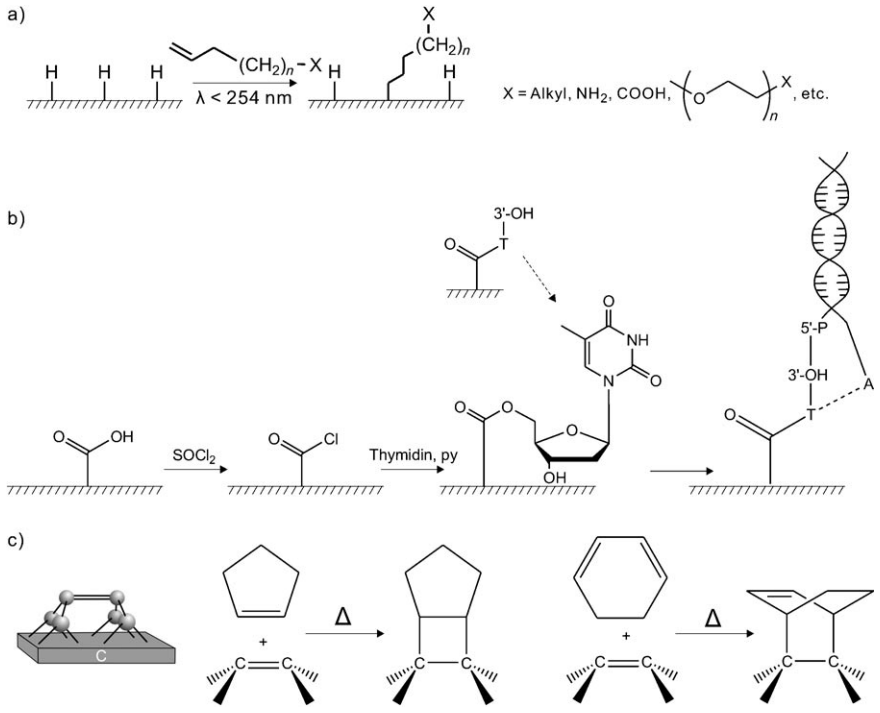

Figure 4. Surface functionalisation of diamond films: a) photochemical reaction of hydrogen-terminated films with vinyl compounds; b) reaction of oxidised diamond films with thymidine and subsequent grafting of DNA oligonucleotides; c) cycloaddition reactions on thermally annealed and reconstructed diamond surfaces; the 2+2 reaction is thermally allowed due to its stepwise character.

Other functionalisation techniques for diamond particles include the radical reaction

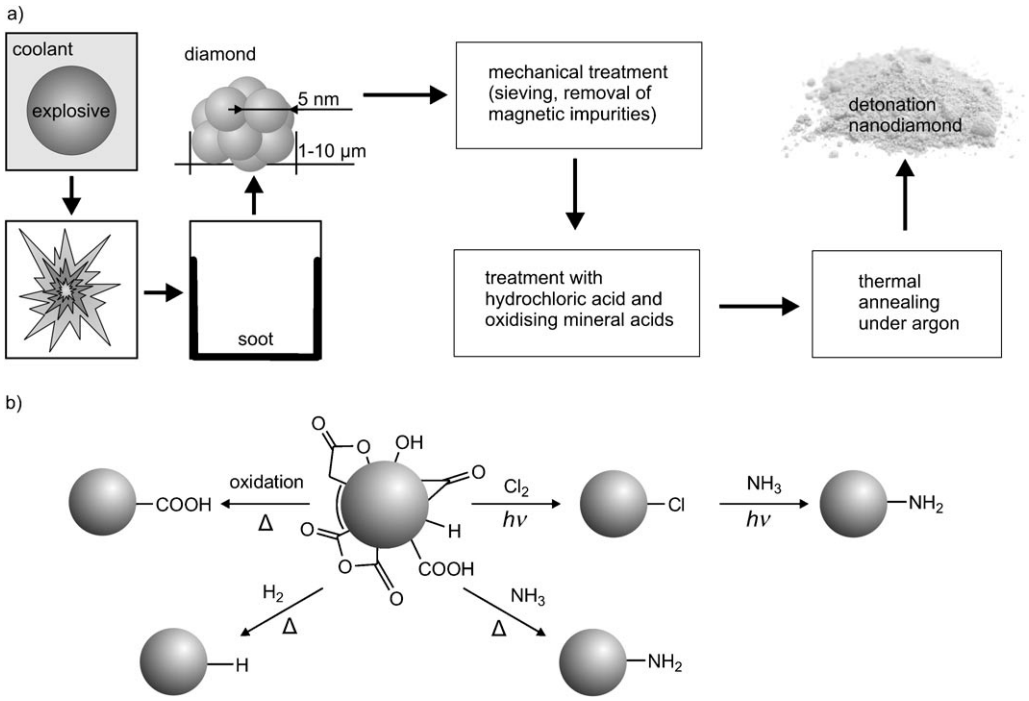

Figure 5. a) Production and purification of detonation diamond. b) Initial surface functionalisation by oxidative treatment or solid-phase reaction with gaseous reactants.

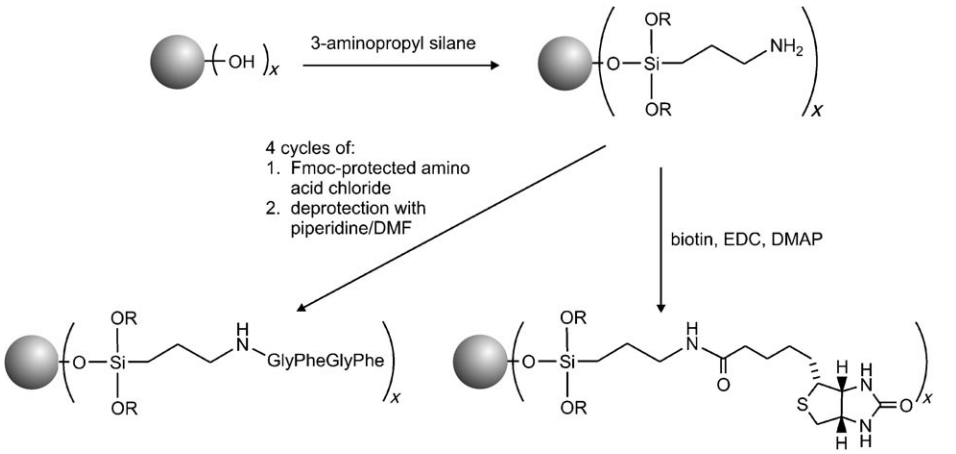

Figure 6. Covalent surface functionalisation using silanes and further modification on their terminal amino groups. Biotinylation and the build-up of a short peptide serve as a model for further more complex surface functionalisation with bioactive substances.

with acyloyl peroxides such as benzoyl and lauroyl peroxide (Figure 7b). Tsubota et al. reported on the covalent grafting of alkyl and aryl residues as well as on the formation of nitrile groups by the reaction of radical species on the diamond surface generated by these reagents.[43] Another reaction of radicals with the surface of diamond sub-micron particles was published by Nakamura et al. They used photochemically generated perfluoroalkyl radicals to modify the diamond surface (Figure 7c).[44] The material possesses a significantly increased hydrophobicity.

Stability of Functionalised Diamond Nanoparticles in Solution/Dispersion

One important issue for the applicability of nanoparticles in biological systems is the solubility or dispersibility of these objects in aqueous systems including buffer solutions. However, nanodiamond (especially the material from detonation synthesis) exists in the form of strongly bound agglomerates, due to the harsh conditions in the reaction chamber.[45] The particles are not only linked by the usual electrostatic interactions, but also through covalent bonds between surface functional groups as well as by soot structures surrounding each primary particle (Figure 2). Therefore, the production of colloidal solutions of primary particles of detonation diamond remains a challenging task.[13]

There have been only a few publications on the deagglomeration of this material. Chiganova reported on the production of nanodiamond hydrosols.[46] In that work first results regarding the influence of surface functional groups on the agglomerate stability have been described. Nevertheless, it remained unclear whether the investigated system contained true primary particles or small residual agglomer-

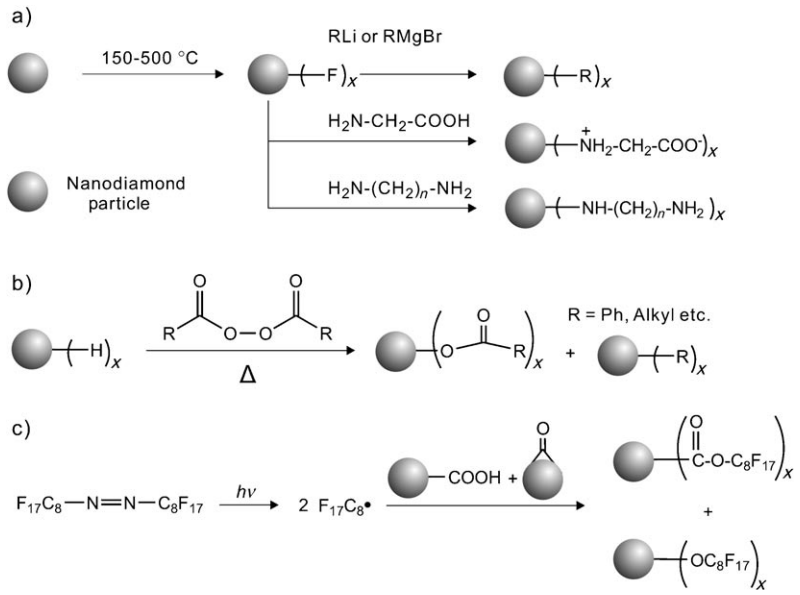

Figure 7. Further surface functionalisation techniques for diamond nanoparticles.

ates. Another approach using sodium oleate as a detergent has been taken by Xu et al.[47] The same authors reported on the mechanical dispersion of diamond particles yielding suspensions stabilised with detergents or inorganic salts.[48] Besides that, there have been accounts on surface graphitisation followed by surface oxidation as a means for the dispersion of detonation diamond leading to small agglomerates of about 50 nm.[49] In summary, most of the obtained suspensions contain at least a major fraction of remaining agglomerates.

For the production of solutions of the primary diamond nanoparticles we have developed several techniques for efficient deagglomeration. The first is related to attrition milling (Figure 8a),[13] and uses small (30–50 μm) zirconia milling beads, which are stirred at very high speed. The diamond suspension is circulated through this stirred media bed, in which shear forces destroy the agglomerates. The resulting colloidal solutions contain isolated primary particles of detonation diamond (Figure 8c). Stable colloidal systems can be obtained in polar, protic solvents, for example, water, DMSO, methanol and mixtures thereof. The concentration of the diamond particles in solution can reach up to more than 10 wt % yielding highly viscous systems.

The second method, the so-called BASD technique (bead-assisted sonic disintegration) combines the shear force induced by the zirconia beads with the cavitation produced by ultrasound and proved very efficient for the deagglomeration (Figure 8b,d) and in situ functionalisation of small quantities of detonation diamond.[50] As for the milled-

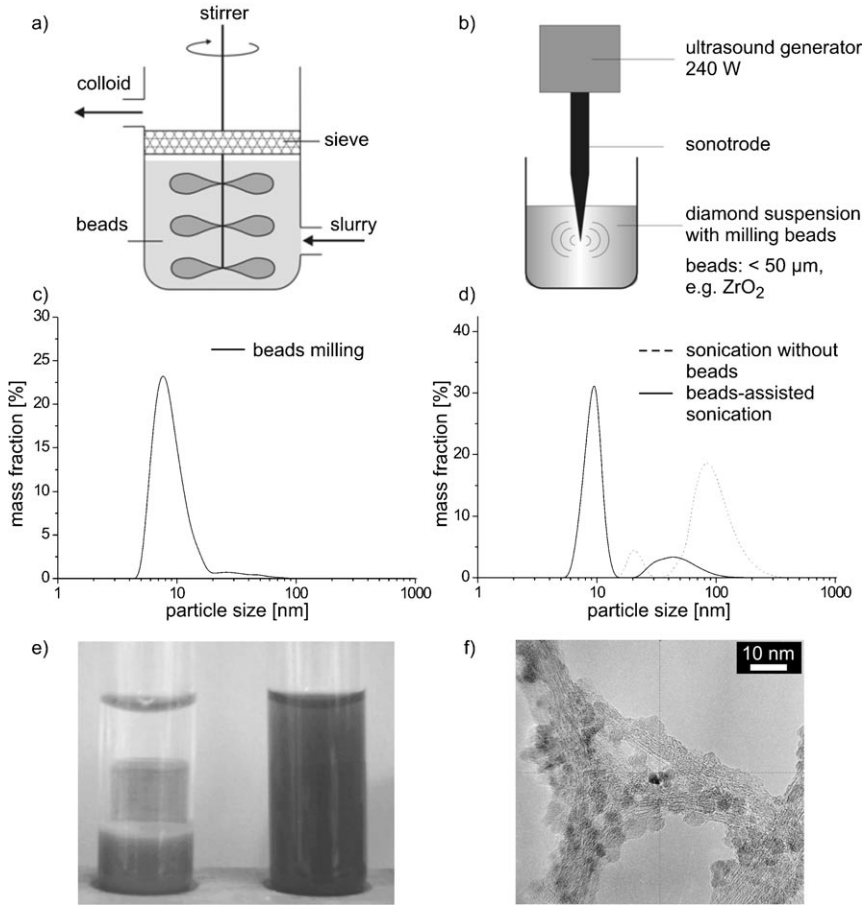

Figure 8. Deagglomeration of detonation diamond. a),c) Setup and particle size distribution for attrition milling; b),d) setup and particle size distribution for beads-assisted sonic disintegration (BASD); e) aqueous suspension before and colloidal solution of detonation nanodiamond after beads milling; f) HRTEM image of deagglomerated detonation nanodiamond deposited on single-walled carbon nanotubes (adapted from Figures 2 and 3 in reference [41]).

bead samples, the stability of the colloidal solutions from BASD is depending on the polarity and hydrogen bonding ability of the solvent with best results obtained for DMSO and water. Aqueous colloids exhibit a zeta potential of $\approx+35$ mV and are stable within a pH range between 3 and 7. The positive surface charge most likely originates from positively charged surface groups, whose nature remains unclear so far, though hydroxyl groups could be a potential candidate.

Biological Applications of Functionalised Nanodiamond Materials

Recently nanoscale diamond particles were applied for a variety of biological applications. The newly developed production, purification and functionalisation techniques enable the material to be used in numerous ways. Additionally, the apparent low cytotoxicity (vide infra) makes it an attractive alternative to other widely used nanoparticles such as cadmium-containing quantum dots. There have been several reports on the use of nanodiamond as an adsorbent for large biomolecules, for example, proteins. This can be useful for the detection of these substances in dilute solutions by MALDI-TOF mass spectrometry.[51] The adsorption strength on nanodiamond due to hydrophilic and hydrophobic interactions is so high that a very efficient capture of proteins such as cytochrome *c*, myoglobin and albumin occurs. After coating with poly-L-lysine, nanodiamond particles can also serve for the detection of DNA oligonucleotides by the same method.[52] The adsorption on the nanodiamond surface can also be used for the efficient separation and purification of proteins, as Bondar et al. have shown for apoobelin and luciferase.[25] The adsorption of biomolecules has also been used for the immobilisation of antibodies for sensor applications. Huang et al. have described a system for the detection of *Salmonella typhimurium* and *Staphylococcus aureus*.[53] The construction of a biochip with a coating of nanodiamond particles carrying immobilised bacterial luciferase has also been reported (Figure 9).[54] There have also been activities towards the application of nanodiamond for gene and drug delivery into living cells. In a first example Kossovsky et al. used cellobiose-coated diamond nanoparticles for the immobilisation of mussel adhesive protein (MAP) to generate antibodies in rabbits.[55]

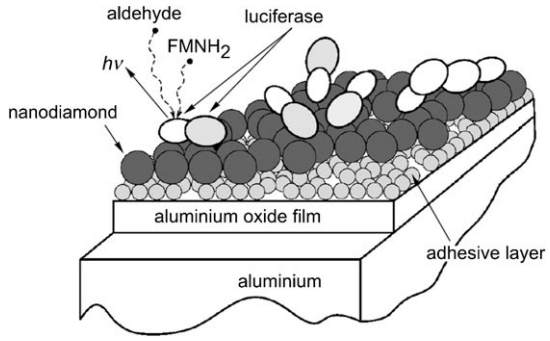

Figure 9. Luminescent biochip with nanodiamond–recombinant bacterial luciferase conjugate (with permission of Springer Business Media group; $FMNH_2$: reduced form of flavin mononucleotide).[54]

Another very attractive opportunity for the application of nanodiamond particles in biological systems is their ability to be doped with different elements. The resulting point defects exhibit interesting luminescence properties. In the case of nitrogen doping and the generation of negatively charged N-V centres by irradiation and annealing, the fluorescence wavelength is located in the far-red ($\approx$700 nm) with an absorption at $\approx$560 nm.[56] Therefore it is possible to observe the luminescing nanoparticles by fluorescence microscopy. Yu et al. have reported on the use of proton-irradiated and annealed, nitrogen-containing nanodiamonds in kidney cells.[57] Besides the strong red luminescence in the cells, they did not observe any photobleaching nor cytotoxicity. This makes the material a valuable alternative for other fluorescence labels. The applicability was demonstrated with poly-L-lysine-coated nanodiamond particles that are able to directly interact with DNA.[58] In the same work the authors described the tracking of a single fluorescent diamond particle within a live HeLa cell. These recent advances add a new class of carbon nanoparticles to the range of those sp^2-hybridised carbon dots that have been recently used for labelling purposes and drug delivery.[59] Compared to these materials the diamond particles exhibit valuable properties like crystallinity, chemical and physical inertness of the core, no porosity, low toxicity (vide infra), dopability and so forth; therefore they represent progress in the quest for carbon materials for biological applications.

Toxicity of Diamond Materials

The toxicity of a material is a very important issue when it comes to biological applications. Especially for nanoparticles, adverse effects on cells or body tissues have to be investigated very thoroughly. Two aspects have to be considered. On the one hand, the pristine material contains a considerable amount of potentially toxic impurities,[60] which can be removed by an appropriate purification procedure (vide supra). On the other hand the inherent cytotoxicity of the diamond nanoparticles has to be investigated. The work of Bakowicz and Mitura shows that nanocrystalline diamond has close to no adverse effect in living species such as rats.[61] Also their investigation of the in vitro biocompatibility of nanodiamond showed that the material does not cause cytotoxic effects. Similar results were obtained by Schrand et al.[62] A comprehensive discussion can be found in reference [63]. In summary, to the best of the available knowledge, nanocrystalline diamond is not cytotoxic and thus a promising candidate material for biological applications.

Future Challenges and Developments

The research on biological applications of nanocrystalline diamond has begun only recently, raising many unanswered questions. One of the most challenging issues is the stabilisation of biofunctionalised primary particles of single-digit nanometric size in physiological media. Efforts to control the surface charge and the agglomeration ability have to be made. On the other hand, grafting techniques that improve the hydrolytic stability of the conjugates are highly desirable. Hence, the direct C–C coupling of the diamond surface with a linker molecule is of great interest. Experiments to use photochemical and cycloaddition reactions to achieve this goal are under way. The selective grafting of just one functional unit per diamond particle is also of importance. So far, the particles are usually functionalised statistically with a bigger number of moieties. For certain applications that rely on quantitative analysis, it is absolutely necessary to obtain 1:1 conjugates.

In conclusion, nanodiamond is a material that can be obtained in bulk scale and can easily be purified. It possesses a variety of surface functionalities that can be used to adsorb or graft functional groups or much more complex moieties, for example, proteins or DNA, onto the diamond surface. It can be solubilised in aqueous or other polar media and forms stable colloids. To the best of the available knowledge nanodiamond is biocompatible and not cytotoxic and can be used in a variety of biological applications. These include adsorptive separation, purification and analysis of proteins; vehicles for drugs, genes and antibodies; and the fluorescence labelling with luminescent diamond nanocrystals. In the future, functionalised diamond materials will most likely become one of the widely used substrates for bio-applications.

Acknowledgements

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[1] G. E. Harlow, R. M. Davies, *Elements* **2005**, *1*, 67–70.
[2] M. P. D'Evelyn in *Handbook of Industrial Diamonds and Diamond Films* (Eds.: M. A. Prelas, G. Popovici, L. K. Bigelow), Marcel Dekker, New York **1998**, and references therein.
[3] T. Soga, Y. Hayashi, T. Sharda, *in A. A. Balandin, K. L. Wang, Handbook of Semiconductor Nanostructures and Nanodevices, Vol. 2*, American Scientific, Stevenson Ranch, USA **2006**, pp. 149–179; N. Ali, E. Titus, J. Gracio, W. Ahmed, E. Ahmed, *Recent Res. Dev. Mater. Sci.* **2004**, *5*, 55–83; O. A. Williams, M. Nesladek, *Phys. Status Solidi A* **2006**, *203*, 3375–3386.
[4] A. Erdemir, C. Donnet, *J. Phys. D* **2006**, *39*, R311-R327.
[5] T. M. Alam, *Mater. Chem. Phys.* **2004**, *85*, 310–315.
[6] A. V. Palnichenko, A. M. Jonas, J.-C. Charlier, A. S. Aronin, J.-P. Issi, *Nature* **1999**, *402*, 162–165; H. Sugimura, K. Ushiyama, Y. Sato, O. Takai, Y. Sakamoto, M. Takaya, N. Nakagiri, *J. Vac. Sci. Technol. B* **1999**, *17*, 1919–1922; J.-Y. Raty, G. Galli, *Nat. Mater.* **2003**, *2*, 792–795.
[7] J. E. Dahl, S. G. Liu, R. M. K. Carlson, *Science* **2003**, *299*, 96–99.
[8] A. A. Fokin, B. A. Tkachenko, P. A. Gunchenko, D. V. Gusev, P. R. Schreiner, *Chem. Eur. J.* **2005**, *11*, 7091–7101; B. A. Tkachenko, N. A. Fokina, L. V. Chernish, J. E. P. Dahl, S. Liu, R. M. K. Carlson, A. A. Fokin, P. R. Schreiner, *Org. Lett.* **2006**, *8*, 1767–1770.
[9] *Ultrananocrystalline Diamond: Synthesis, Properties, and Applications* (Eds.: O. A. Shenderova, D. M. Gruen), William Andrew, Norwich **2006**.
[10] L. F. Trueb, *J. Appl. Phys.* **1968**, *39*, 4707–4716.
[11] V. Yu. Dolmatov, *Russ. Chem. Rev.* **2001**, *70*, 607–626.
[12] O. A. Shenderova, V. V. Zhirnov, D. W. Brenner, *Crit. Rev. Solid State Mater. Sci.* **2002**, *27*, 227–356.
[13] A. Krüger, M. Ozawa, F. Kataoka, T. Fujino, Y. Suzuki, A. E. Aleksenskii, A. Ya. Vul', E. Osawa, *Carbon* **2005**, *43*, 1722–1730; A. E. Aleksenskii, M. V. Baidakova, A. Ya. Vul', V. I. Siklitskii, *Phys. Solid State* **1999**, *41*, 668–671.
[14] V. L. Kuznetsov, M. N. Aleksandrov, I. V. Zagoruiko, A. L. Chuvilin, E. M. Moroz, V. N. Kolomiichuk, V. A. Likholobov, P. M. Brylyakov, G. V. Sakovich, *Carbon* **1991**, *29*, 665–668.
[15] K. Ushizawa, Y. Sato, T. Mitsumori, T. Machinami, T. Ueda, T. Ando, *Chem. Phys. Lett.* **2002**, *351*, 105–108.
[16] P. I. Belobrov, L. A. Bursill, K. I. Maslakov, A. P. Dementjev, *Appl. Surf. Sci.* **2003**, *215*, 169–177.
[17] T. Jiang, K. Xu, *Carbon* **1995**, *33*, 1663–1671.
[18] N. Komatsu, N. Kadota, T. Kimura, E. Osawa, *Chem. Lett.* **2007**, *36*, 398–399.
[19] Yu. V. Butenko, V. L. Kuznetsov, E. A. Paukshtis, A. I. Stadnichenko, I. N. Mazov, S. I. Moseenkov, A. I. Boronin, S. V. Kosheev, *Fullerenes, Nanotubes, Carbon Nanostruct.* **2006**, *14*, 557–564.
[20] P. Chen, F. Huang, S. Yun, *Carbon* **2003**, *41*, 2093–2099.
[21] K. Iakoubovskii, G. J. Adriaenssens, K. Meykens, M. Nesladek, A. Ya. Vul, V. Y. Osipov, *Diamond Relat. Mater.* **1999**, *8*, 1476–1479; S. N. Mikov, A. V. Igo, V. S. Gorelik, *Phys. Solid State* **1999**, *41*, 1012–1014.
[22] S. Ji, T. Jiang, K. Xu, S. Li, *Appl. Surf. Sci.* **1998**, *133*, 231–238; J. B. Cui, J. Ristein, L. Ley, *Phys Rev. Lett.* **1998**, *81*, 429–432.
[23] D. A. Tryk, H. Tachibana, H. Inoue, A. Fujishima, *Diamond Relat. Mater.* **2007**, *16*, 881–887; M. C. Granger, M. Witek, J. Xu, J. Wang, M. Hupert, A. Hanks, M. D. Koppang, J. E. Butler, G. Lucazeau, M. Mermoux, J. W. Strojek, G. M. Swain, *Anal. Chem.* **2000**, *72*, 3793–3804; R. J. Narayan, W. Wei, C. Jin, M. Andara, A. Agarwal, R. A. Gerhardt, C. C. Shih, C. M. Shih, S. J. Lin, Y.-Y. Su, R. Ramamurti, R. N. Singh, *Diamond Relat. Mater.* **2006**, *15*, 1935–1940.
[24] D. Steinmüller-Nethl, F. R. Kloss, M. Najam-Ul-Haq, M. Rainer, K. Larsson, C. Linsmeier, G. Köhler, C. Fehrer, G. Lepperdinger, X. Liu, N. Memmel, E. Bertel, C. W. Huck, R. Gassner, G. Bonn, *Biomaterials* **2006**, *27*, 4547–4556; B. Rezek. D. Shin, T. Nakamura, C. E. Nebel, *J. Am. Chem. Soc.* **2006**, *128*, 3884–3885; G. P. Bogatyreva, M. A. Marinich, E. V. Ishchenko, V. L. Gvyazdovskaya, G. A. Bazalii, *Sverkhtverd. Mater.* **2002**, 10–15.
[25] V. S. Bondar', I. O. Pozdnyakova, A. P. Puzyr', *Phys. Solid State* **2004**, *46*, 758–760.
[26] L.-C. L. Huang, H.-C. Chang, *Langmuir* **2004**, *20*, 5879–5884.
[27] P.-H. Chung, E. Perevedentseva, J.-S. Tu, C. C. Chang, C.-L. Cheng, *Diamond Relat. Mater.* **2006**, *15*, 622–625; T.-T.-B. Nguyen, H.-C. Chang, V. W.-K. Wu, *Diamond Relat. Mater.* **2007**, *16*, 872–876.
[28] M. Lu, T. Knickerbocker, W. Cai, W. Yang, R. J. Hamers, L. M. Smith, *Biopolymers* **2004**, *73*, 606–613; J. B. Miller, *Surf. Sci.* **1999**, *439*, 21–33; R. J. Hamers, S. Coulter, J. S. Hovis, M. D. Ellison, D. F. Padowitz, M. P. Schwartz, C. M. Greenlief, J. N. Russell, Jr., *Acc. Chem. Res.* **2000**, *33*, 617 624; G. T. Wang, S. F. Bent, J. N. Russell, Jr., J. E. Butler, M. P. D'Evelyn, *J. Am. Chem. Soc.* **2000**, *122*, 744 745.
[29] T. Knickerbocker, T. Strother, M. P. Schwartz, J. N. Russell, Jr., J. Butler, L. M. Smith, R. J. Hamers, *Langmuir* **2003**, *19*, 1938–1942; M. Lu, T. Knickerbocker, W. Cai, W. Yang, R. J. Hamers, L. M. Smith, *Biopolymers* **2004**, *73*, 606–613.
[30] S. Q. Lud, M. Steenackers, R. Jordan, P. Bruno, D. M. Gruen, P. Feulner, J. A. Garrido, M. Stutzmann, *J. Am. Chem. Soc.* **2006**, *128*,

16884–16891; T. Nakamura, M. Hasegawa, K. Tsugawa, T. Ohana, M. Ishihara, Y. Koga, *Diamond Relat. Mater.* **2006**, *15*, 678–681.
[31] D. Delabouglise, B. Marcus, M. Mermoux, P. Bouvier, J. Chane-Tune, J.-P. Petit, P. Mailley, T. Livache, *Chem. Commun.* **2003**, 2698–2699.
[32] T. Ando, K. Nakagawa, M. Nishitani-Gamo, *Oyo Butsuri* **2001**, *70*, 1447–1451.
[33] L. A. Bursill, A. L. Fullerton, L. N. Bourgeois *Int. J. Mod. Phys. B* **2001**, *15*, 4087–4102; D. K. Saha, K. Koga, H. Takeo, *Surf. Sci.* **1998**, *400*, 134–139.
[34] J.-B. Donnet, C. Lemoigne, T. K. Wang, C.-M. Peng, M. Samirant, A. Eckhardt, *Bull. Soc. Chim. Fr.* **1997**, *134*, 875–890.
[35] V. F. Loktev, V. I. Makal'ski, I. V. Stoyanova, A. V. Kalinkin, V. A. Likholobov, *Carbon* **1991**, *29*, 817–819.
[36] B. Spitsyn, J. L. Davidson, M. N. Gradoboev, T. B. Galushko, N. V. Serebryakova, T. A. Karpukhina, I. I. Kulakova, N. N. Melnik, *Diamond Relat. Mater.* **2006**, *15*, 296–299.
[37] V. V. Korolkov, B. N. Tarasevich, I. I. Kulakova, G. V. Lisichkin, *Sverkhtverd. Mater.* **2006**, 11–17.
[38] K.-I. Sotowa, T. Amamoto, A. Sobana, K. Kusakabe, T. Imato, *Diamond Relat. Mater.* **2004**, *13*, 145–150.
[39] Y. Liu, Z. Gu, J. L. Margrave, V. N. Khabashesku, *Chem. Mater.* **2004**, *16*, 3924–3930.
[40] A. Krüger, Y. Liang, G. Jarre, J. Stegk, *J. Mater. Chem.* **2006**, *16*, 2322–2328.
[41] A. Krueger, M. Ozawa, G. Jarre, Y. Liang, J. Stegk, L. Lu, *Phys. Status Solidi A*, **2007**, *204*, 2881–2887.
[42] A. Krueger, J. Stegk, L. Lu, G. Jarre, unpublished results.
[43] T. Tsubota, O. Hirabayashi, S. Ida, S. Nagaoka, M. Nagata, Y. Matsumoto, *Phys. Chem. Chem. Phys.* **2002**, *4*, 806–811; T. Tsubota, S. Ida, O. Hirabayashi, S. Nagaoka, M. Nagata, Y. Matsumoto, *Phys. Chem. Chem. Phys.* **2002**, *4*, 3881–3886.
[44] T. Nakamura, M. Ishihara, T. Ohana, Y. Koga, *Chem. Commun.* **2003**, 900–901.
[45] A. E. Aleksenskii, V. Yu. Osipov, A. T. Dideikin, A. Ya. Vul', G. J. Adriaenssens, V.V. Afanas'ev, *Tech. Phys. Lett.* **2000**, *26*, 819–821; G. L. Bilbro, *Diamond Relat. Mater.* **2002**, *11*, 1572–1577.
[46] G. A. Chiganova, *Colloid J.* **1997**, *59*, 87–89; G. A. Chiganova, *Colloid J.* **2000**, *62*, 238–241.
[47] X. Xu, Z. Yu, Y. Zhu, B. Wang, *Diamond Relat. Mater.* **2005**, *14*, 206–212.
[48] X. Xu, Y. Zhu, B. Wang, Z. Yu, S. Xie, *J. Mater. Sci. Technol.* **2005**, *21*, 109–112; X. Xu, Z. Yu, Y Zhu, B. Wang, *J. Solid State Chem.* **2005**, *178*, 688–693.
[49] K. Xu, Q. Xue, *Phys. Solid State* **2004**, *46*, 633–634.
[50] M. Ozawa, M. Inakuma, M. Takahashi, F. Kataoka, A. Krueger, E. Osawa, *Adv. Mater.* **2007**, *19*, 1201–1206.
[51] X. L. Kong, L. C. L. Huang, C.-M. Hsu, W.-H. Chen, C.-C. Han, H.-C. Chang, *Anal. Chem.* **2005**, *77*,259–265.
[52] X. Kong, L. C. L. Huang, S.-C. V. Liau, C.-C. Han, H.-C. Chang, *Anal. Chem.* **2005**, *77*,4273–4277.
[53] T. S. Huang, Y. Tzeng, Y. K. Liu, Y. C. Chen , K. R. W alker, R. Guntupalli, C. Liu, *Diamond Relat. Mater.* **2004**, *13*, 1098–1102.
[54] A. P. Puzyr', I. O. Pozdnyakova, V. S. Bondar', *Phys. Solid State* **2004**, *46*, 761–763.
[55] N. Kossovsky, A. Gelman, H. J. Hnatyszyn, S. Rajguru, R. L. Garrell, S. Torbati, S. S. F. Freitas, G.-M. Chows, *Bioconjugate Chem.* **1995**, *6*, 507–511.
[56] A. Gruber, A. Dräbenstedt, C. Tietz, L. Fleury, J. Wrachtrup, C. von Borczyskowski, *Science* **1997**, *276*, 2012–2014.
[57] S.-J. Yu, M.-W. Kang, H.-C. Chang, K.-M. Chen, Y.-C. Yu, *J. Am. Chem. Soc.* **2005**, *127*, 17604–17605.
[58] C.-C. Fu, H.-Y. Lee, K. Chen, T.-S. Lim, H.-Y. Wu, P.-K. Lin, P.-K. Wei, P.-H. Tsao, H.-C. Chang, W. Fann, *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 727–732.
[59] Y.-P. Sun, B. Zhou, Y. Lin, W. Wang, K. A. S. Fernando, P. Pathak, M. J. Meziani, B. A. Harruff, X. Wang, H. Wang, P. G. Luo, H. Yang, M. E. Kose, B. Chen, L. M. Veca, S.-Y. Xie, *J. Am. Chem. Soc.* **2006**, *128*, 7756–7757; A. Yan, B. W. Lau, B. S. Weissman, I. Külaots, N. Y. C. Yang, A. B. Kane, R. H. Hurt, *Adv. Mater.* **2006**, *18*, 2373–2378.
[60] V. S. Bondar', A. P. Puzyr', *Phys. Solid State* **2004**, *46*, 716–719.
[61] K. Bakowicz, S. Mitura, *J. Wide Bandgap Mater.* **2002**, *9*, 261–272.
[62] A. M. Schrand, H. Huang, C.a Carlson, J. J. Schlager, E. Osawa, S. M. Hussain, L. Dai, *J. Phys. Chem. B* **2007**, *111*, 2–7.
[63] V. P. Grichko, O. A. Shenderova, in *Ultrananocrystalline Diamond: Synthesis, Properties, and Applications* (Eds.: O. A. Shenderova, D. M. Gruen), William Andrew, Norwich **2006**, pp. 529–557.

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