Single photon sources based on HPHT nanodiamonds

N S Kurochkin\textsuperscript{1,2}, S P Eliseev\textsuperscript{1,2}, V V Sychev\textsuperscript{2}, A V Gritsienko\textsuperscript{1,2}, V S Gorelik\textsuperscript{2} and A G Vitukhnovsky\textsuperscript{1,2}

\textsuperscript{1}Moscow Institute of Physics and Technology (State University), 9 Institutskiy Per., 141700 Dolgoprudny, Russia
\textsuperscript{2}P.N. Lebedev Physical Institute of Russian Academy of Sciences, 53 Leninsky Pr., 119991 Moscow, Russia
E-mail: elst.conference@gmail.com

Abstract. Color centers in nanodiamonds are promising candidates for the creation of high-speed sources of single photons without blinking and degradation. Color centers in HPHT nanodiamonds have been investigated. The luminescence decay curves of color centers have been measured. Second order correlation functions were measured for nanodiamonds with sizes from 50 nm to 250 nm. Conclusions about the energy structure of color centers were made based on the correlation functions.

1. Introduction

Promising materials for creating sources of single photons are quantum dots and nanoplates [1-4], color centers in 2D materials and diamonds [5]. Ultrafast radiation sources can be obtained by coupling emitters with a nanocavity [6-8]. Among the sources of single radiation, the color centers in diamonds are the most stable. The most famous color centers in diamonds are nitrogen vacancy (NV) and silicon vacancy (SiV) luminescence centers in diamond. These centers can arise both naturally and as a result of ion implantation followed by annealing.

Most quantum-optical applications use photoluminescence of NV\textsuperscript{−} centers, which has been used to demonstrate coherent optical effects such as electromagnetically induced transparency [9] and coherent population capture [10]. A single NV center was used to implement a secure communication system at a distance of several tens of meters [11]. Also potential applications of NV centers are used in areas such as biosensing and biomarking [12], sub-diffraction imaging (for example, by STED lithography method [13, 14]) and many other scientific and technical areas (biology, neuroscience, fundamental physics [15]).

Two main methods are used to make synthetic single crystal diamonds: high pressure, high temperature (HPHT) and chemical vapor deposition (CVD). In turn, nanodiamonds can be obtained by crushing synthetic (e.g. HPHT) diamonds or by detonating carbon.

Crystal structure of HPHT nanodiamonds is preserved during their creation. This is a significant advantage of this type of nanodiamonds as sources of single photons over other types of nanodiamonds.

2. Results and discussion

In our work, we investigated the sources of single photons was carried out in HPHT nanodiamonds with characteristic sizes of 50 nm, 150 nm and 250 nm. For this, we recorded and analyzed the second-order correlation functions $g^{(2)}(\tau)$ according to the Hanbury Brown-Twiss scheme.
The photoluminescence was recorded using a scanning laser confocal microscope. Correlation functions of the 2nd order were measured using a CW laser source with a wavelength of 532 nm and an excitation power of about 1 mW. Photoluminescence was recorded using a broadband filter that transmits in the wavelength range of 600-800 nm. To obtain the photoluminescence kinetics, a pulsed supercontinuum laser source in the range of 500-700 nm was used.

Figure 1 shows the obtained functions $g^{(2)}$ for three types of nanodiamonds with different size. The graphs show dips in the correlation function, which indicates the quantum nature of radiation with a small number (up to 5) emitters. The number of emitters $n$ was estimated from the relation $g^{(2)}(0) = 1 - 1/n$. In this case, bunching of photons ($g^{(2)} > 1$) is observed for nanodiamonds with a size of 150 nm and 250 nm at delay times more than 10 ns. This is typical for NV centers in diamond due to the presence of a metastable level thermally coupled to the excited level. In this case, the system is not described by a simple two-level model. It is necessary to consider a three-level model of the system. The approximation of the correlation functions in figure 1 (b, c) was carried out according to the equation [16]:

$$g^{(2)}(t) = 1 + c_2 e^{-t/\tau_2} + c_3 e^{-t/\tau_3}$$

Here $\tau_2$ and $\tau_3$ are characteristic short and long decay times, $c_2$ and $c_3$ are exponential contribution coefficients. Coefficient $c_2 < 0$, $c_3 > 0$. The second term in the equation describes the dynamics of the $g^{(2)}(t)$ dip. The third term in the equation describes the damping of the correlation function wings. All four coefficients depend on the pump power of the NV center.

For the function $g^{(2)}(t)$ in figure 1 (a), the coefficient $c_3$ was set equal to 0, the system is described by a two-level model. The value $g^{(2)}(0) < 0.5$ for this nanodiamond unambiguously indicates that it is a source of single photons. For the other two nanodiamonds the number of NV centers in them can be more than one since $g^{(2)}(0) \geq 0.5$. In all three nanodiamonds from the analysis of the correlation functions the characteristic short decay time of luminescence is about 10 ns, which correlates with the luminescence time of NV$^-$ centers in bulk diamond crystals and indicates their predominance in these HPHT diamonds. Measurement of the kinetic luminescence decay curve of a 300 µm HPHT diamond crystal (figure 2) also shows that the luminescence decay time of color centers in the bulk crystal is about 10 ns.
3. Conclusion

HPHT nanodiamonds are promising sources of single photons due to their stable crystal structure. In the future it is possible to use them in devices for quantum-optical applications. Here we demonstrated single photon sources based on color centers in HPHT nanodiamonds with sizes from 50 nm to 250 nm.

References
[1] Eliseev S, Vitukhnovsky A, Chubich D, Kurochkin N, Sychev V and Marchenko A 2016 JETP Lett. 103(2) 82
[2] Kurochkin N, Katsaba A, Ambrozevich S, Vitukhnovsky A, Vaschenko A and Tananaev P 2018 J. Lumin. 194 530
[3] Kurochkin N, Eliseev S, Gritsienko A, Sychev V and Vutukhnovsky A 2020 Nanotechnology 31(50) 505206
[4] Selyukov A, Danilkin M, Eliseev S, Kuznetsov A, Grafova V, Klimonsky S, Vainer Yu, Vasilev R and Vitukhnovsky A 2020 Quantum Electron. 50(3) 252
[5] Bolshedvorskii S. et al. 2017 Opt. Mater. Express 7(11) 4038
[6] Eliseev S, Kurochkin N, Vergeles S, Sychev V, Chubich D, Argyrakis P, Kolymagin D and Vitukhnovsky A 2017 JETP Lett. 105(9) 577
[7] Kurochkin N, Eliseev S and Vitukhnovsky A 2019 Optik 185 716
[8] Gritsienko A, Kurochkin N, Vitukhnovsky A, Selyukov A, Taydakov I and Eliseev S 2019 J. Phys. D: Appl. Phys. 52 325107
[9] Wilson E., Manson N and Wei C 2003 Phys. Rev. A 67(2) 023812
[10] Santori C. et al. 2006 Phys. Rev. Lett. 97(24) 247401
[11] Alléaume R, Treussart F, Messin G, Dumeige Y, Roch J, Beveratos A, Brouri-Tuelle R, Poizat J and Grangier P 2004 New J. of Phys. 6(1) 92
[12] Balasubramanian G, Lazarie A, Arumugam S and Duan D 2014 Curr. Opin. Chem. Biol. 20 69
[13] Vitukhnovsky A, Chubich D, Eliseev S, Sychev V, Kolymagin D and Selyukov A 2017 J. Russ. Laser Res. 38(4) 375
[14] Eliseev S, Korolkov A, Vitukhnovsky A, Chubich D and Sychev V 2016 Nanotechnol. Russ. 11(3) 200
[15] Aharonovich I, Castelletto S, Simpson D, Su C, Greentree A and Prawer S 2011 Rep. Prog. Phys. 74(7) 076501
[16] Kurtziefer C, Mayer S, Zarda P and Weinfurter H 2000 Phys. Rev. Lett. 85(2) 290