Nanocrystalline Diamond Optical Planar Waveguides

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Abstract: We report about properties of nanocrystalline diamond planar waveguides. Design of the presented planar waveguides was done on the bases of modified dispersion equation and experimental samples were fabricated by microwave plasma enhanced chemical vapor deposition on silica-on-silicon substrates. Waveguiding properties of our samples were examined by prism coupling technique at 473 nm, 632.8 nm, 964 nm, 1310 nm and 1550 nm wavelengths. It was found that the diamond thin films guided one fundamental mode for all measured wavelengths.

Introduction

Nanocrystalline diamond (NCD) thin films have been of special interest for photonics application in the past few years because they exhibit beneficial chemical and physical properties. NCD thin films have high thermal conductivity, high density, large Young's modulus and high stability under extreme operating conditions [1-3]. Natural diamonds have also high refractive index. Though refractive index of synthetically prepared NCD film is usually lower than that of natural one, NCD deposited on silica-on-silicon substrate still has enough high refractive index contrast. The waveguides created this way are known as high index contrast (HIC) waveguides. Useful HIC waveguides can be used for small bending radius structures or compact and ultra dense photonics integrated circuits. One of the most important NCD thin films properties is its ability to act as a single photon source by incorporating N-V centres in diamond matrix. This opens a possibility of using NCD for quantum key distribution. Therefore development of waveguide in NCD films is an important first step towards a monolithic platform and all-diamond devices [4].

Design and fabrication of the NCD waveguides

In this paper we are going to describe design and fabrication of NCD planar waveguides deposited on silica-on-silicon substrate. The dimensions of the NCD planar waveguides were calculated by using modification dispersion equation. From the calculations it follows, e.g., that if we want the deposited film to guide one single mode, the thickness of the diamond film (h_{NCD}) should not exceed 200 nm at 632.8 nm, and for the 1550 nm the diamond film (h_{NCD}) should not be thicker than approx. 450 nm [5]. The thickness of the buffer SiO_2 film (h_{SiO2}) was set according to the calculated one, which ensures that the out-coupled energy of the evanescent wave would be less than 1 %. Calculations made clear that to ensure the above-mentioned conditions the thickness of the silica film should not be smaller than 900 nm for all considered wavelengths. Therefore we used silica-on-silicon substrate with thickness of the silica film to be around 1420 nm, which is fully sufficient.

After designing of the NCD planar waveguides we fabricated NCD waveguides by using microwave plasma enhanced chemical vapor deposition (MW PECVD) on silicon substrate bearing 1420 nm thick silica film. The NCD deposition was done from a gas mixture of methane and hydrogen (for NCD1 sample the hydrogen gas flow was 400 sccm and methane gas flow was 2 sccm while for the NCD2 sample the hydrogen gas flow was 500 sccm and methane gas flow was 1.5 sccm, resp.) in a MW PECVD reactor using an ellipsoidal cavity resonator [5, 6].

Results

Morphology of the NCD layers was investigated by Raman spectrometer (Renishaw InVia Reflex) with the excitation wavelength of 325 nm and the obtained data are shown in Fig. 1. Raman spectrum exhibits two sharp peaks, first one is centered at 521 cm^{-1} and it is assigned to the silicon substrate; the second one centered at 1332 cm^{-1} is well known as the so called diamond peak and it is related to sp^3

bonds. The wide band located at 1580 cm^{-1} is assigned to the G-band ("graphite-band") and is related to the sp^2 phases (i.e. amorphous phases) preferentially localized at grain boundaries [6]. The NCD2 sample was done at lower concentration of methane in the reaction mixture and it revealed lower rate of sp^2 ordering than NCD1.

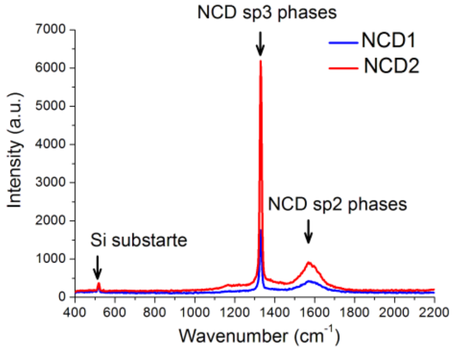

Fig. 1: Raman spectrum of the deposited NCD.

Waveguiding properties of the NCD films were measured by prism-coupling system using Metricon 2010 prism-coupler at five wavelengths: 473 nm, 632.8 nm, 964 nm, 1311 nm and 1552 nm. Measurements of the mode spectra for both polarizations (TE and TM) proved that the values of the refractive indices for TE and TM modes are almost identical. Based on this observation, we will in the following text for simplicity show only the TE modes. Refractive indices of the deposited films were calculated using the angles given for sample NCD1 in Fig. 2a, the wavelengths of the measurement and, if needed, the thickness of the NCD waveguiding films (380 nm). NCD2 sample that had lower rate of sp^2 we did not succeeded to get the refractive index value for 473 nm. Fig. 2b plots refractive indices of our NCD films against the values of natural diamond [8]. According to the calculations mentioned above it was expected that the deposited NCD film having a thickness of 380 nm will support 2 TE modes at the wavelengths of 964 nm and shorter. At the longer wavelengths there would be noticeable one TE mode only. However, the measurement showed that the deposited films actually supported always just one mode at all applied wavelengths. The value of the refractive indices of our NCD film much more resemble refractive indices of natural diamond than the films reported in [7], what make us to believe in high optical quality of our products.

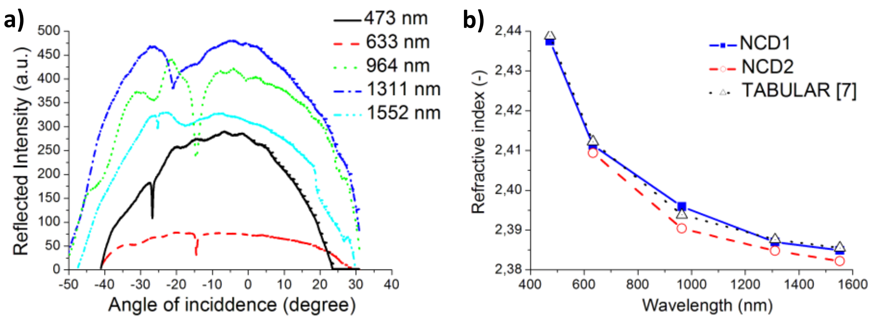

Fig. 2: a) TE guided mode spectrum for the NCD1 sample, b) Comparison of refractive indices of our NCD waveguides and natural diamond.

Conclusion

In this paper we presented a modified approach to deposit diamond thin layers. Waveguiding structure of our deposited layers was calculated for various operating wavelengths using modified dispersion equation. The NCD waveguides were fabricated by MW PECVD on silica on silicon substrate. The comparison with cited references [7] shows the merit of our work, as refractive index of our diamond is very close to natural diamond.

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