Spectroscopic measurement of the refractive index of ion-implanted diamond

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We present the results of variable-angle spectroscopic ellipsometry and transmittance measurements to determine the variation of the complex refractive index of ion-implanted single-crystal diamond. An increase is found in both real and imaginary parts at increasing damage densities. The index depth variation is determined in the whole wavelength range between 250 and 1690 nm. The dependence from the vacancy density is evaluated, highlighting a deviation from linearity in the high-damage-density regime. A considerable increase (up to 5%) in the real part of the index is observed, attributed to an increase in polarizability, thus offering new microfabrication possibilities for waveguides and other photonic structures in diamond.

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Single-crystal diamond has attracted considerable attention in recent years in the photonics community due to the properties of its broad range of active luminescent centers, which offer promising opportunities in quantum cryptography and quantum information processing [1, 2]. The prospect of creating all-diamond integrated photonic structures has thus triggered interest in the possibility of fabricating optical waveguides [3] and other photonic structures [4] in diamond using ion implantation to modulate its refractive index. Moreover, an accurate control of refractive index variations is mandatory in all photonic applications that are based on ion implantation [5]. Despite this, a surprisingly small number of publications in the literature have addressed the problem of the index of refraction variation in diamond with ion irradiation [6–8]. Following the first systematic studies of damage-induced refractive index variation at a fixed wavelength [9] and the demonstration of waveguide fabrication in diamond with ion implantation [3], the dependence of refractive index variation upon structural damage needs to be systematically explored in a wide wavelength range for a broader spectrum of ion species and energies. In this Letter, we report on the use of variable-angle spectroscopic ellipsometry (VASE) [10] integrated with optical absorption measurement to assess refractive index and extinction coefficient variations as a function of damage density.

Ion implantation was performed on single-crystal chemical vapor deposition diamonds produced by Element-Six. The samples have 100 crystal orientation, size $3\,\mathrm{mm} \times 3\,\mathrm{mm} \times 0.5\,\mathrm{mm}$, and are classified as Type IIa, with two optically polished opposite large faces. Four samples were implanted with 180 keV B ions, at the Olivetti I-Jet facilities in Arnad (Aosta, Italy). The whole upper surface of the four samples was irradiated uniformly with fluences of 10^{13}, $5 \cdot 10^{3}$, 10^{14}, and $5 \cdot 10^{14}\ \mathrm{cm}^{-2}$ with an accuracy below 0.5%.

Ellipsometric characterization of the samples was performed using a Woollam M2000-FI variable-angle spectroscopic ellipsometer in the wavelength range from 246 to 1690 nm. For each sample, data were acquired at incidence angles of 63°, 65°, 67°, 69°, and 71° with respect to the surface normal.

An example of spectra of the measured ellipsometric angles Psi (Ψ) and Delta (Δ) at an impinging angle close to the Brewster angle of 67° is shown in Figs. 1(a) and (b) for the four implanted samples and compared to a reference spectrum for an unimplanted diamond sample. The detected oscillations increase with fluence, and are typical of the interference arising in thick transparent films on a substrate [10]. The optical transmission (OT) measurements were performed at normal incidence (beam spot size $1.5\,\mathrm{mm}^2$) with a PerkinElmer Lambda 950 spectrophotometer (spectral range 250–3300 nm, resolution 1 nm, accuracy 0.015% OT) [Fig. 1(c)].

The VASE data were fitted using Complete EASE v.4.17 software from Woollam Inc. to derive the depth variation of the index of refraction n. Having ascertained the small influence of absorption (see discussion below), a multilayer model for the damaged substrate was adopted with a Cauchy-type spectral dependence for $n(\lambda)$ with fixed layer thicknesses chosen between 30 and 50 nm, top surface roughness considered as a mixture of 50%–50% volume fraction for air [11] and diamond, and backside reflections included in the fit.

The obtained n values in the layers were thus compared to the vacancy density depth profiles, calculated by means of Monte Carlo simulations using the TRIM [12] code (with an atom displacement energy for diamond of 50 eV). To account for damage accumulation and saturation effects, the Crystal-TRIM (C-TRIM) code [13] was also employed. As an example, results for n versus depth z in sample 3 at $\lambda = 638$ nm are shown in Fig. 2. The consistency between experimental data and C-TRIM numerical results is very satisfactory, particularly considering that, in the analysis of the ellipsometric data, no preliminary assumptions were made about the variation of n. On the other hand, a discrepancy with TRIM results is

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