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Exciton-polariton state in nanocrystalline SiC films

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HIGHLIGHTS

- Research of optical resonance absorption in films of nanocrystalline SiC.
- It shows that maximum position and intensity of absorption depends on the structure and thickness of the nc-SiC films.
- Resonance absorption model based on excitation of exciton polaritons in a microcavity has been proposed.

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ABSTRACT

We studied the features of optical absorption in the films of nanocrystalline SiC (nc-SiC) obtained on the sapphire substrates by the method of direct ion deposition. The optical absorption spectra of the films with a thickness less than ~500 nm contain a maximum which position and intensity depend on the structure and thickness of the nc-SiC films. The most intense peak at 2.36 eV is observed in the nc-SiC film with predominant 3C-SiC polytype structure and a thickness of 392 nm. Proposed is a resonance absorption model based on excitation of exciton polaritons in a microcavity. In the latter, under the conditions of resonance, there occurs strong interaction between photon modes of light with λ_{ph} =521 nm and exciton of the 3C polytype with an excitation energy of 2.36 eV that results in the formation of polariton. A mismatch of the frequencies of photon modes of the cavity and exciton explains the dependence of the maximum of the optical absorption on the film thickness.

1. Introduction

Observation of exciton-polariton state in nanocrystalline SiC layers at room temperature [1] is of a great scientific and practical interest in connection with perspectives of investigations of exciton-polariton Bose condensate [2] in high-stability SiC matrix [3]. The quantum effect of exciton-polariton superposition in solids was discovered more than 50 years ago [4,5]. However, intense experimental investigations of the properties of excitonic polaritons are being carried out during 15 years, after the first report on strong photon-exciton interaction of excitonic polaritons in microcavities [6]. Studies of the properties of Bose condensate of polaritons in microcavitiy with excitons on ZnO quantum dots [7] have recently resulted in development of a low-threshold polariton source of coherent radiation [8] which does not require pumping necessary for photonic lasers. As a physical analog of specially created planar semiconductor microcavities with quantum wells between the Bragg mirrors there may be used thin semiconductor films in which stable excitonic polaritons are excited at sufficiently high exciton binding energy E_b ($E_b > kT_{room}$) [9]. The excitation energy for excitonic polaritons both in the scheme with quantum points and in semiconductor layers is defined by the spectrum of exciton energy, and this imposes certain restrictions on the possibility to control the energy of polaritons. In this connection, it seems promising to use SiC as an active medium. This wide-gap semiconductor has many polytypes with different exciton width of the forbidden band, that may provide variation of exciton ground state energy within a range of ~1 eV [10]. Nanodimension of crystalline SiC may create one more degree of freedom for controlling the energy spectrum of polaritons excitation in the nanocrystalline layer due to the influence of the dimensional factor. Quantum confinement of electrons shifts the spectrum of electron excitation energy towards the short-wavelengths region [11], high concentration of defect states in the nanocrystals modifies the spectrum of electron excitation energy [12]. The increase of the oscillator strength of the electronic transitions in the nanocrystals may give rise to the effect of giant exciton-polariton superposition in the nanocrystals even under the condition of weak quantum confinement [13].

In the present paper we consider the possibility of excitation of polaritons at room temperature in nanocrystalline SiC (nc-SiC) layers obtained by the method of direct ion deposition which

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makes it possible to obtain nc-SiC films of different polytypes [14].

2. Experimental

A series of nc-SiC films with a thickness of 200–800 nm was obtained by the method of direct ion deposition [14] on monocrystalline Al_2O_3 substrate. One of the expected properties of excitonic polaritons in nc-SiC films is an essential rise of nonlinear response of electromagnetic radiation in the region of resonance excitation [15]. Therefore, the present investigations were performed on nanocrystalline films of the cubic and rhombohedral polytypes earlier found to have high values of nonlinear susceptibility [16]. The films were deposited under the same conditions: the substrate temperature was 1100 °C, the average ion energy was 100 eV, the pressure in the chamber did not exceed $3 \cdot 10^{-3}$ Pa. Thereat, the deposition duration was different. So, there were obtained nc-SiC films with different thickness, but their structure was identical. The thickness of the films was determined by the method of optical interferometry from interference of the reflection spectra. The structure of nc-SiC films formed under nonequilibrium conditions of ion deposition is a mixture of the main and additional polytypes with close values of the formation temperature [17]. Fig. 1 shows a typical spectrum of X-ray diffraction (XRD) of nc-SiC film from Series 7500 with a thickness of 338 nm deposited at 1100 °C.

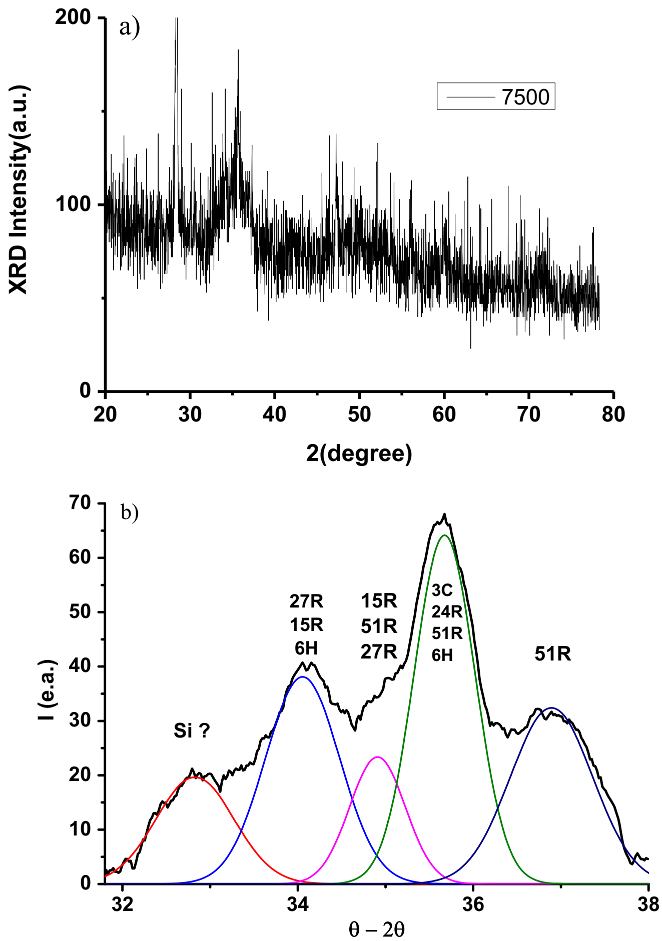

Fig. 1. (a) XRD spectrum of nc-SiC film of 7500 series deposited at 1100 °C with a thickness of 338 nm, (b) approximation of the X-diffraction peak near 36 angular degrees.

As seen from approximation of the XRD maxima and their qualitative analysis, for the nc-SiC film deposited at 1100 °C the main polytypes are the cubic 3C, the rhombohedral 24R and 27R, with the presence of the rhombohedral 15R, 51R and the hexagonal 6H polytypes. Thereat, from the XRD data it is difficult to establish the quantitative ratios between the polytypes. *Silicon nanocrystals are also present in a small amount in the films in addition to nanocrystals SiC* [17]. Fig. 2 shows electron-microscopic typical images of parts of the film from Series 7500: (a) SEM image of the surface morphology and (b) TEM image of a thin section of the film with microdiffraction from it, in this part it corresponds to electron diffraction from the crystallographic planes in the polytype 24R. The average size of the nanocrystals estimated from the two-dimensional TEM image is ~15–50 nm. The nanocrystals are shaped as irregular polyhedrons. The thicknesses of the investigated samples of nc-SiC films are presented in Table 1.

The spectra of optical density (OD) of the samples were measured by a spectrophotometer L-35 at room temperature.

3. Experimental results and discussion

In our earlier works we paid much attention to studying the optical properties of nc-SiC films with different nanocrystalline parameters, polytypes and thickness on the order of 500 nm and more, as their absorption and scattering spectra yield essential information on the structure and electronic properties of the material. The absorption spectra of such films were found to have features typical of nanodimensional materials and contained the region of fundamental absorption, power absorption edge and exponential absorption tail [18,19].

A typical optical density spectra of nc-SiC film with a thickness exceeding 500 nm is shown in Fig. 3 (series 7463). In the said investigations the film thickness did not play a significant role, as it did not influence the energy characteristics of the spectra. However, the absorption spectra of the films with a thickness less than

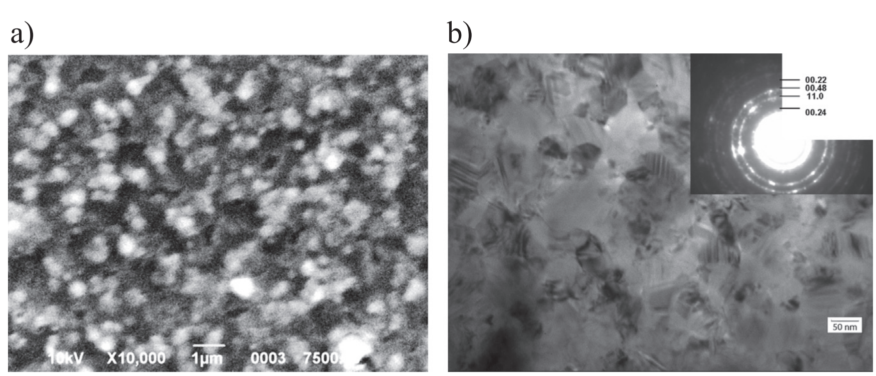

Fig. 2. (a) SEM image of the morphology of nc-SiC film of Series 7500 deposited at 1150 °C, (b) TEM micrograph and microdiffraction pattern of thin area of film.