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Exciton states of the optical electrons of Al_2O_3 nanoparticles in dielectric matrix

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Abstract

The report presents and analyzes the experimental results luminescence study alumina and theoretical results showing that the dielectric nanoparticles have the exciton states of electrons with binding energy of several electron volts, which are excited by the weak optical laser radiation. Such materials with a wide spectrum of exciton states are important for creation: exciton lasers and optical emitters; receiving and emitting optical nano-antennas; control and processing information and signals; generation low-power optical solitons; optical computers etc.

Keywords: Dielectric nanoparticles; Exciton state; Luminescence; Optical nonlinearity

Introduction

In recent years, experimental investigations of the nonlinear optical properties of dielectric nanocomposites containing small concentrations of dielectric nanoparticles showed that they exhibit unique optical nonlinearity in low-intensity optical radiation fields [1−11]. The anomalous nonlinear optical properties are as follows: (I) Great value of bandgap gave reason to think that the nonlinear response of nanocomposite media occurs under ultraviolet light but it is observed for visible and infrared light [1]; (II) Nonlinear response occurs at radiation intensities below 1 kW/cm2 and can be observed under pulsed and cw laser modes. It reaches a maximum and disappears with increasing intensity [2−4]; (III) It takes place if transmission spectra of nanoparticles array have the broad bands of light absorption that are absent for the bulk sample [1,5,6,10]; (IV) Nonlinear optical properties take place at frequencies lying within the absorption band of light [5]. Typical dependences the nonlinear part of the absorption coefficient and refractive index on the intensity of radiation are presented in Fig. 1. The intensity threshold and nature of nonlinear response depend on characteristics of nanoparticles and matrix material as well as their size and shape. It was determined that dielectric nanoparticles have nonlinear response when the matrix has a static permittivity less than that of nanoparticles. These facts

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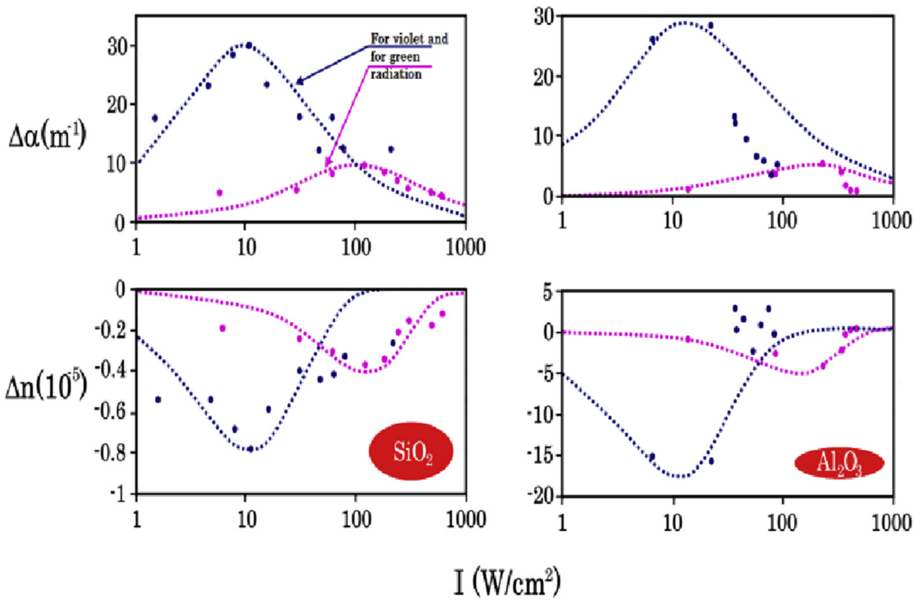

Fig. 1. Typical dependence the nonlinear part of the absorption coefficient and refractive index on the intensity of radiation. (points and curves are experimental and theoretical results, respectively).

are explained by photoexcitation of exciton states of the electrons of the nanoparticle. In the report presents and analyzes the experimental and theoretical results showing that the dielectric nanoparticles have the exciton states of electrons with binding energy of several electron volts, which are excited by the weak optical laser radiation [7].

Main part

The existence of nonlinear optical properties in dielectric nanocomposites points out that the electronic structure of nanoparticles dispersed in dielectric matrix differs significantly from the electronic structure of the bulk sample. Differences consist, first, of formation of the allowed energy levels for the charge carrier in the bandgap because the bandgap structure is connected with a complex form of nanoparticles and high density of surface defects in the crystal structure [8].

Moreover, the electrons of nanoparticles should have broad band of exciton states (Fig.2). A contribution of exciton states into optical properties is substantial if their Bohr radius is comparable to nanoparticle's size (or less than the size – the weak confinement regime). In contrast to the single-particle states, the accurate description of exciton states is impossible even for spherical nanoparticles. We can investigate an influence of nanoparticles' shape and size upon exciton energy spectrum more carefully by using an exactly solvable model of a nanoparticle represented as a system of two charge carriers – electron and electron hole, which exist inside an infinitely deep potential hole limited by paraboloid of revolution and sizes of real nanoparticles [9].

We estimate exciton energy spectrum taking into account only Coulomb interaction between electron and electron hole as well as quantum size effect in the effective mass approach. This assumption is reasonable due to comparatively small sizes of nanoparticles. Exciton's wave function $\Psi(\eta,\xi,\phi)$ in a parabolic coordinate system with the center in the center of gravity of electron–hole pair satisfies the next equation

$$\frac{4}{\xi+\eta}\left[\frac{\partial}{\partial\xi}\left(\xi\frac{\partial\Psi}{\partial\xi}\right)+\frac{\partial}{\partial\eta}\left(\eta\frac{\partial\Psi}{\partial\eta}\right)\right]+\frac{1}{\xi\eta}\frac{\partial^2\Psi}{\partial\varphi^2}+2\left(E+\frac{2}{\xi+\eta}\right)=0 \qquad (1)$$

Eq. (1) utilizes relative units where the Plank constant and a charge are equal to 1, masses of electron m_e, electron hole m_h and exciton $\mu=\frac{m_e m_h}{m_e+m_h}$ are chosen in accordance with the effective in accordance with the effective mass approach; as a length unit Bohr radius of the exciton$a_{ex}=\frac{\varepsilon_2}{\mu e^2}\hbar^2$. Parabolic coordinates are connected with Cartesian ones as it follows $x=\sqrt{\xi\eta}\cos\varphi \quad y=\sqrt{\xi\eta}\sin\varphi \quad z=\frac{1}{2}(\xi-\eta)$. Paraboloid of revolution around the OZ axis in parabolic coordinates system is represented with the equation