Nonlinear Properties of Ion-Implanted Photonic Crystals

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Abstract Nonlinear refraction coefficients were measured for an ordered array of silica nanoclusters implanted with ions of Ge, Si and Er. Efficient nonlinear optical elements, as thin as the propagating wavelength, may now become a reality.

1. Introduction

Ordered arrays of nanosize spheres (photonic crystals) attracted many researchers for their linear and nonlinear properties and potential applications [1,2]. For example, one is able to design and realize imaging elements thinner than the propagating wavelength [3]. The optically confining environment of the structure is particularly attractive when embedded with nanosize clusters; a substantial enhancement in the nonlinear optical properties is expected. Si and Ge embedded and Er implanted structures are also known to exhibit photoluminescence, which is substantially enhanced by the opaline matrix. Here we present results on the linear and nonlinear optical properties of Ge, Si and Er implanted, ordered array of nanosize silica spheres (opal). Following annealing, Ge and Si material precipitate into nanosize crystallites within the nano-size silica spheres' matrix, to create a 'nano within nano' structure.

2. Experiment and Results

The opal was prepared by hydrolysis of TEOS (tetroethoxysilane) in a mixture of ammonium hydroxide, water and ethanol [4]. We prepared opal of various sizes, ranging from 100-nm to 400-nm. Ion implantation has been made at various energies and dosages. For example, ion implantation of the Ge ions was made at 150-KeV and a dose level ranging between $2x10^{14}$ to $2x10^{15}$ cm^{-2}. Si ions were accelerated at 400-KeV at a dose level of $6x10^{17}cm^{-2}$. The samples were then annealed at temperatures varying between 700-1100ºC. This step is required for Er implanted silica in order to activate the Er ions [5]. For Si and Ge implanted samples this step is needed to form the nanosize particulates. The nonlinear optical measurements were made with a Q-switched, mode-locked, doubled Nd:YAG laser (λ=532 nm, 10 nsec pulses @10 Hz) at various intensities. Ge and Er implanted opals did not exhibit an apparent damage after annealing at 1100ºC as can be seen for the 300-nm spheres' opal implanted with the higher dosage of Ge ions (Fig. 1). White light experiments (Fig. 2) confirmed the periodic structure in a perpendicular direction to the sample's surface and at the same time showed the resilience of opaline structures to high temperature annealing.

In Fig. 3, we show the transmission for Ge implanted opal as a function of light peak intensity. As was the case with Si implanted opal, there is a 'magic angle(s)' for which the nonlinear transmission is peaked. This occurs when the coupling of the light to the opaline structure is at resonance with the transverse periodicity, or, in general, when $|\boldsymbol{k}_n\text{-}\boldsymbol{K}|\sim\boldsymbol{k}_n$. Here, $\boldsymbol{k}_n$ is the optical wavenumber in the composite structure and $\boldsymbol{K}$ is the wavenumber of the opaline structure. For example from Fig 2 we can estimate that, n_{eff} ~2 for the Ge implanted sample implying a magic angle of _~20º. In the experiment we found _=22º (Fig. 3).

As the intensity varies, a typical nonlinear curve is obtained (Fig. 4) at the 'magic angle'. The characteristics of the nonlinear transmission may be explained by the nonlinear changes in the modulation index of the various gratings involved in the diffraction process [2]. The modulation index is quite high, m~7π, and the nonlinear refractive index changes may reach values as large as Δn~0.5. Nonlinear losses, due to resonantly enhanced transitions, are at least an order of magnitude smaller than the nonlinear refractive effect when compared at esu values.

3. Discussion and Conclusions

Nano size semiconductor clusters such as, Si and Ge clusters, exhibit a large spectrum of nonlinear refraction effects. At large pulse durations, such as presented here, the nonlinear effects are energy driven and may be related to carrier trapping in surface states. The nonlinear time constant, is relatively short, _~0.3-ns due to many recombination sites. Saturation occurs at relatively low peak intensities, I~100MW/cm^2. At shorter pulse durations such as, femptosecond or picosecond pulses, the transitions are driven by the pulse's field intensity. For these cases, nonlinear time constants were estimated at 20-ps. Wave propagation in photonic crystals may be viewed as the propagation of many spatial modes [3]. Self-imaging occurs when all of these modes are interfering coherently at some point. A substantial nonlinear effect occurs if these modes are coherently interacting with the nonlinear periodic structure. Large nonlinear effects may be tailored to the characteristics of the photonic crystals by incorporating an appropriate material, such as Er, or by an incorporating a nano-size semiconductor material such as, Ge or Si in the opal spheres. Thus, in general, the composite structure has the potential of being extremely efficient. Optical elements, as thin as the propagating wavelength, may now become a reality..

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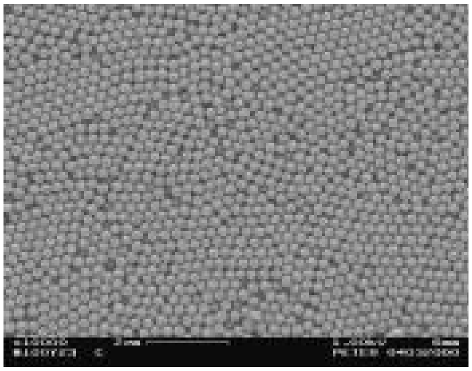

Fig. 1. Ge ion implanted 300-nm size spheres' opaline structure after annealing at 1100ºC.

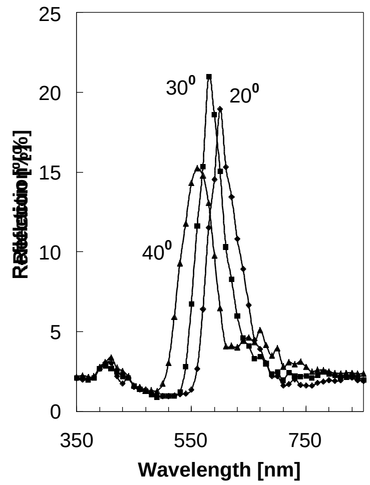

Fig. 2. White light reflection measurements on Ge implanted, 300-nm opal.

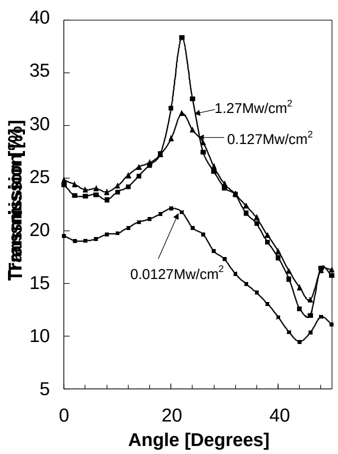

Fig. 3. Nonlinear transmission of 300-nm opal embedded with Ge nanoclusters at different intensities.

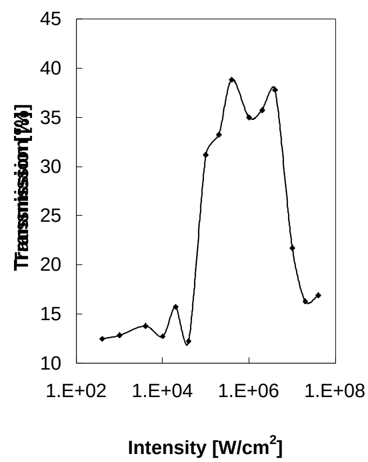

Fig. 4. Nonlinear transmission of 300-nm opal embedded with Ge nanoclusters as a function of peak intensity at the 'magic angle', _=22º.

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