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Optical confinement achieved in zinc oxide modified by energetic silicon ions beams

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ABSTRACT

Optical confinement was achieved in zinc oxide by silicon ions irradiation. Waveguide effects were found in all the irradiated samples. The optical properties and the field intensity distribution of the propagation mode, as well as the refractive index profile in the irradiated waveguide were studied and reconstructed accordingly. Achievement of optical waveguide structure in zinc oxide by silicon ions irradiation makes it possible to expand its application in modern optics and optical telecommunications in an attempt to control the propagation of light and to enhance the optical efficiency.

1. Introduction

Wide-bandgap semiconductors, especially for III-V semiconductors, such as gallium nitride, have come to the forefront in the past decade because of an increasing need photonic devices and high power/frequency optoelectronic devices. Zinc oxide is a member of II-VI semiconductor and has some similar properties as gallium nitride [1–3]. It is being proposed for the same applications and has several fundamental advantages over gallium nitride. Many researches and applications have currently attracted increased interest in this material [4–6]. Now, technological study of its powders and polycrystalline ceramics material is numerous, and can be extensively reviewed elsewhere [7,8]. Recent breakthroughs in producing high-quality single crystals have opened up a new possibility of producing a range of optoelectronic devices as well as devices for high-temperature/power electronics based on this material [9]. To realize this goal, many efforts of material processing have been performed. Bombardment of a material with energetic ions beams is one of the methods, which has been usually employed for doping or for electrical isolation [10–13]. Ion implantation/irradiation can also offer possibility of introducing any given impurity with accurate control of both the depth and lateral concentrations of the ions.

Waveguide structure is key elements of modern optics and optical telecommunications devices; many methods have been studied to be used in fabricating waveguide in different materials. With some advantages over other techniques, ion implantation/irradiation provides an efficient and flexible method to fabricate waveguide structure in crystal materials. In most cases implanted- waveguides are produced using energetic light ions (for instance, Hydrogen or Helium) [14,15], taking advantage of the effects caused by nuclear collision processes and displacement damage. This is usually achieved at the expense of using very high fluences, which reduces the practical utility of this method. However, waveguides fabricated by heavier ion irradiation, such as silicon, become more attractive recently. Compared with light ions, silicon has a much heavier atomic mass. Indices modification caused by lattice damage in crystal can be achieved by using heavier ion irradiation with low ion fluences. It is especially suitable for zinc oxide crystal, which shows highly resistive to irradiation [16,17]. Furthermore, the mechanism of the heavier ion-irradiated waveguide may shows difference to that of the light ion-implanted one.

In the present work, we report on the waveguide effect in silicon-irradiated zinc oxide. The guiding properties and the field intensity distribution of the propagation mode in the waveguide are investigated. The results show that silicon ions irradiation under appropriate conditions can be used not only for the modulation of electrical properties but also for the optical properties of zinc oxide. Bombardment with silicon ions beams may constitutes a very promising and controllable way to modify the optical properties of zinc oxide in the near-surface region.

2. Experiments

The zinc oxide was provided by Shanghai Daheng Optics & Fine Mechanics Co., Ltd., Chinese Academy of Sciences. The pure z-cut

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zinc oxide single crystals with $10 \times 5 \times 0.5\ \mathrm{mm}^3$ were optically polished and clean before irradiation. The energy of silicon ions were 6 MeV, and the ion doses were from 5×10^{13} to 5×10^{15} ions/cm^2. The samples were tilted by 7° off the incident silicon beam direction in order to minimize the channeling effect during the irradiation, shown in Fig. 1(a and b). The ion irradiation was performed at room temperature by a 1.7 MV tandem accelerator. The optical confinement effect was measured by end-face coupling method, as shown in Fig. 1(c). In this case, a microscope objective lens (×25) focuses the light beam into the facet of waveguide and another microscope objective lens (×25) collects the light from the output of end-face the sample, which is imaged onto a CCD camera. The waveguide modes properties in the near surface region were characterized by m-line technique [18,19] (via Metricon 2010 Prism Coupler, USA). During the measurement, a He–Ne polarized laser beam at wavelength of 633 nm struck the base of a precisely characterized rutile prism (with the refraction index of 2.58), and hence coupled into the waveguide region when corresponding condition was satisfied. The angle of incident laser beam could be varied by means of a rotary table. The intensity of reflected light striking the photodetector was plotted as a function of the incident angle, resulting in some “dips” (mode lines) in the intensity spectrum of the reflected light if the coupling conditions are satisfied. A sharp dip in intensity profile would correspond to a propagation mode. The measurement system was controlled with the computer.

3. Results and discussion

The waveguide characterization was carried out using the prism coupling technique for the measurement of the effective indices of the guide modes. Figs. 2 shows the measured relative intensities of the transverse electric (TM) polarized light at a wavelength of 633 nm reflected from the prism formed by the waveguides after irradiation by silicon ions. Here, the refractive index of the substrate (n_{sub}) is labeled for comparison. Usually one drop of the intensity corresponds to one excited TM dark mode. Deep and sharp dip means a good confinement of the light, representing a real propagating waveguide mode. According to the prism-coupling results in Fig. 2(a), a sharper dip corresponding to real propagation mode was observed in as-irradiated 5×10^{13} ions/cm^2 sample. This means that it is a single-mode waveguide. It could be noted that the number of modes is increased with the increase of irradiation ions doses, shown in Fig. 2(b and c), and the first dip moves to left with increased effective index. The loss of confinement of the first mode attributes to the increased defects caused by irradiation with high ion doses. The second mode becomes more distinct in the waveguide formed by irradiation with higher ions doses. But in ion-irradiated waveguide the broader dip usually represents a leak mode.

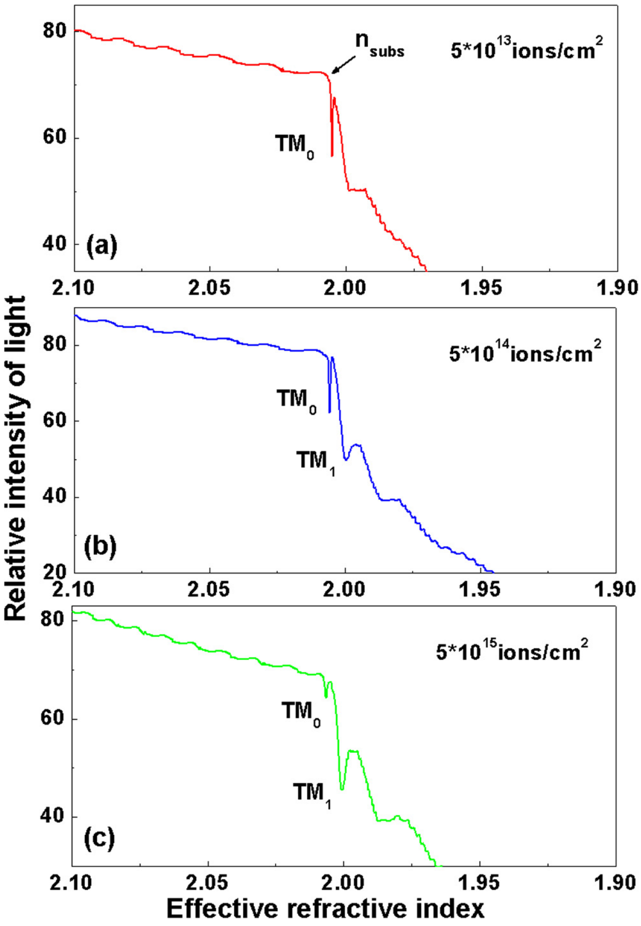

Fig. 2. The m-line results from silicon-irradiated waveguide by prism coupling measurement.

To investigate optical confinement near sample surface, a laser at 633 nm was coupled into one end-face of zinc oxide through a microscope objective lens. Take TM modes as example, the near-field intensity distributions from the output facet of the waveguide were recorded using a CCD camera in the end-face coupling experiment. The intensity profile is the overlap of all the transmission modes in waveguides. Fig. 3 shows the near-field intensity distribution of the TM polarized light through the waveguide, fabricated by ions irradiation at dose of 5×10^{13} ions/cm^2. The image is

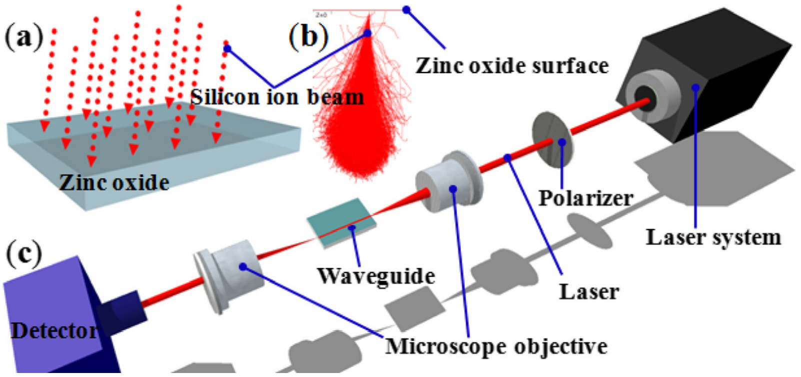

Fig. 1. (a) Schematic plots of waveguide fabrication in zinc oxide. (b) The range of silicon ions in the near-surface region. (c) Schematic of the end-face coupling arrangement used to investigate the optical properties of waveguide.