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X-ray beam probing of tensile strains in the process of waveguide formation in zinc oxide

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ABSTRACT

Tensile strain and optical confinement in helium-implanted zinc oxide are investigated. High-resolution x-ray diffraction, prism coupling and end-face coupling technique are used to examine the implantation-induced structural changes and waveguide properties. The results show that tensile strain distribution is approximate follow the profile of lattice damage. Both contribute to the decrease of refractive index in zinc oxide. When an appropriate implantation depth is applied, laser beam can be confined between crystal surface and the reduced index layer.

1. Introduction

Zinc oxide (ZnO) attracts great interest due to its wide range of promising applications in a variety of devices [1–4]. It is an alternative to gallium nitride, another wide-gap semiconductor which is used for production of various optoelectronic devices. Many of applications of ZnO involves in polycrystalline or amorphous materials. However, the widespread usage of single crystal ZnO would greatly benefit for future integrated optical systems owing to its high radiation hardness, mature crystal growth processes, and advanced material modification technology [5,6].

Introduction of exotic ions into a host material will cause distinct change in microstructure and macroscopic properties, altering the material potentialities [7–9]. Ion implantation can be used to introduce ions into ZnO with accurate control over depth and lateral concentration. The application of ion irradiation for material processing includes not only integrated electronic circuits and ion slicing for film fabrication but also refractive-index tuning for waveguide. Optical waveguide is a basic component for the miniaturization of electro-optical devices and a primary objective in the development of optical communications [10,11]. In ion-implanted waveguide, radiation induced effects, including lattice strain, damage profile and index modification, are the significant contributing factors for formation of waveguide, which are of fundamental interest in investigating ion-implanted ZnO.

In this paper, strain distribution and waveguide properties are measured and analyzed by corresponding methods. This study can give insight into the mechanism of ion-crystal interaction and provide a reference for setting up optimum conditions for ZnO based devices.

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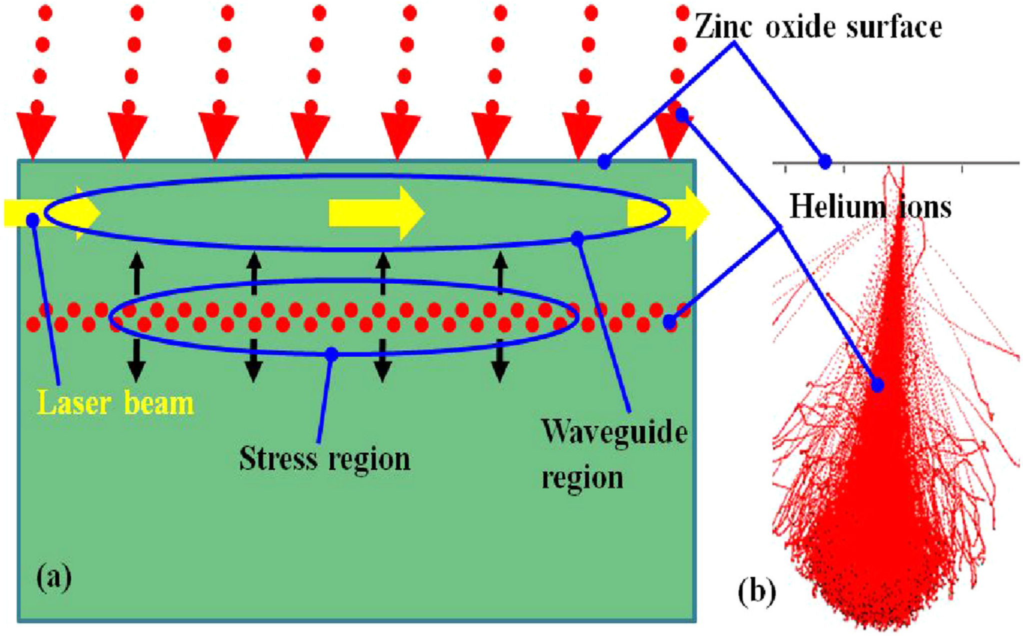

Fig. 1. (a) Schematic plots of waveguide formation in zinc oxide. (b) The range of helium ions in the near-surface region.

2. Experiments

Z-cut ZnO single crystals, with a size of $0.5 \times 5 \times 10\,mm^3$, are grown by the hydrothermal technique. Helium ions are implanted into the optically polished face of the samples, see Fig. 1. The energy of helium ions are 260 keV and 2 MeV, and the ion doses are 1×10^{16} and 2×10^{16} ions/cm^2, respectively. Ion implantation is performed in vacuum at room temperature by a 2×1.7 MV tandem accelerator at Peking University and an implanter at the Institute of Semiconductor, Chinese Academy of Sciences. After implantation, high resolution x-ray diffraction (HR-XRD) measurements are carried out in an AXS HRXRD D5005 system from Bruker Inc. with Cu-$K_{\alpha 1}$ radiation source. The classic m-line arrangement is used to investigate the properties of the waveguide. A prism coupling technique (via a prism coupler, Metricon 2010, USA) is used to measure the effective refractive indices of waveguide modes. The near-field image of waveguide is obtained via an end-face coupling setup. The laser intensity profile is imaged onto a CCD camera.

3. Results and discussion

Ion implantation is a effective method to modify material properties. Stopping and ranges of ions in matter (SRIM) code is used to simulate the process of helium implantation [12,13]. Fig. 2(a) shows the energy loss and the ion concentration of the helium implanted into ZnO. As we can see, helium ions lose most of their energies by electronic ionizations along the path of helium trajectory, usually with occurrence of the formation of point defects. At the end of the ions track, nuclear collisions result in lattice disorder and change of the material density. It can be seen that the deposited helium ions are mainly located at the track end at a depth of 0.95 μm. The relative atom displacement induced by implantation versus the penetration depth is presented in Fig. 2(b). For 260 keV sample, there is about 1% and 2% atom displacement at the ion track end for the implantation fluence at 1×10^{16} and 2×10^{16} ions/cm^2, respectively. When high energy 2.0 MeV ion is applied under the same ion fluence, atom displacement at the ion track end has the similar profile as that of 260 keV sample.

Lattice modification in the implanted ZnO was analyzed by using HR-XRD [14,15]. Bragg's Law is the theoretical basis of x-ray diffraction. According to the equation $n\lambda = 2d\sin\theta$, the change in the lattice constant Δd corresponds to the change in the position of a diffraction peak at $\Delta\theta$, which can be obtained by differentiating Bragg's equation $\Delta d/d = -\Delta\theta\cot\theta$. In an implanted ZnO, the interplanar space of the lattice can be modified by introducing helium ions and defects. Dilating the crystal lattice shifts the peak toward $\theta < \theta_{Bragg}$ (left side of the main sharp diffraction peak) owing to local lattice expansion by ion interstitials. This behavior is a characteristic of extended interplanar space along the surface normal direction. Fig. 3 shows the experimental HR-XRD roking curves from the two implantation z-cut ZnO samples and one unimplanted bulk one. All curves show a main sharp diffraction Bragg peak located at $2\theta = 34.4$, produced by diffraction of the unperturbed part of substrates. The main peak from unimplanted sample is much narrower than that of the helium implanted samples, showing that unimplanted ZnO has better single crystalline characteristics. The diffraction curves from implanted samples show some asymmetric broadened satellite peaks near Bragg peak. These oscillating fringes at $2\theta < 34.4$ are arised from diffraction of the damaged layer. The number of the satellite peaks is a measure of the strain in the implanted zone, and it