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High near-infrared transmittance and waveguide structures in polycrystalline ZnSe by carbon and proton implantation combined with photolithography

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ABSTRACT

We report on near-infrared (NIR) waveguide structures in polycrystalline ZnSe using the carbon ion implantation technique combined with standard lithography. High NIR transmittance is observed by the absorption spectra before and after carbon and proton implantation at room temperature. Two half-Gaussian curves are used to reconstruct the refractive index profile of the waveguides at a wavelength of 1539 nm. The results show that the numerically simulated mode by the finite difference beam propagation method (FD-BPM) is in good agreement with the experimental data by end-facet setup, which exhibits a high potential for designable NIR waveguide devices in polycrystalline ZnSe by carbon ion implantation.

1. Introduction

Infrared optical materials possess low absorption coefficient and high mechanical properties, which have been the subject of intense research for more than 50 years [1,2]. II–VI semiconductor crystals doped with transition metals, such as Cr, Mn and Fe, have a wide band gap and have been known to be effective infrared (IR) laser media [3,4]. Among the most attractive, ZnSe has high luminescence efficiency and excellent transparency in the infrared region [5]. ZnSe doped with Cr has been used as an infrared laser gain medium emitting at about 2.4 μm [6]. Mn-doped ZnSe is an excellent quantum dot material and have been also realized a potential candidate for highly emissive nanocrystals for bio imaging, wavelength tunable lasers, solar cells and diluted magnetic semiconductors for spintronics applications [5]. ZnSe belongs to the direct transition type semiconductor with a wide band gap of 2.7 eV and is widely used at IR band, which is used in designing optical elements for high-power CO_2 lasers at 10.6 μm, IR lens, blue light-emitting devices such as light-emitting diodes [7,8], and protective windows of devices detecting thermal signals in a broad spectral range, among others [9]. Optical waveguide structures could confine light propagation in one or two dimensions to small volumes, and the optical performance can be improved in comparison with bulk structures. In addition, channel waveguide structures that allow two-dimensional (2D) confinement of light, both laterally and in depth, can be easily connected with integrated photonic components in optical systems. Ion implantation is an excellent technique for material-property modification. With precise control of both the dopant's depth and refractive indices of the materials, ion implantation has been used to successfully produce visible and infrared waveguide structures. Ion implantation is a non-equilibrium process and creates an impact on crystals, glasses and semiconductors, which makes it suitable for waveguide formation at visible and infrared band in various substrate materials [10]. Additionally, ion implantation combined with standard lithography has been successfully used to fabricate channel waveguides in several optical materials at visible [11] and infrared band [12].

As reported, ZnSe waveguide structures have been fabricated by ultrafast laser inscription [13], vapor phase epitaxy [14], and particularly, proton implantation at visible band [15]. In addition, ZnSe crystal is transparent from visible to IR regimes, which makes ZnSe waveguide structures good candidates for guided-wave nonlinear application at IR band. Compared with single crystals, the polycrystalline ZnSe possesses substantially higher critical shear stress resistance, yield limit, and tensile strength [9], and these are good mechanical properties for practical applications. In this work, the planar and channel waveguides at near-infrared (NIR) wave band are fabricated first by carbon ion implantation into polycrystalline ZnSe combined with standard lithography. The

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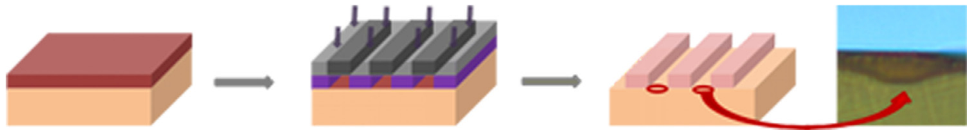

Fig. 1. The schematic plot of the fabrication process of the near-infrared channel waveguide in polycrystalline ZnSe crystal.

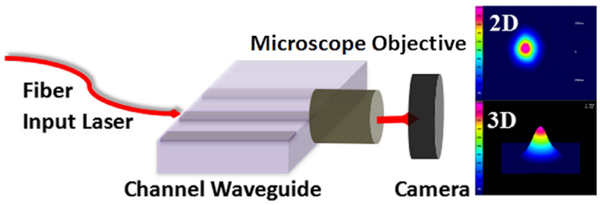

Fig. 2. The schematic of the experimental setup for end-facet setup in the NIR band with a diode laser (left); the images were collected by a CCD camera (right).

absorption spectra ranging from visible to IR band of polycrystalline ZnSe are measured before and after ion implantation.

2. Experimental

The polycrystalline ZnSe used in our work was carved into dimensions of 10 mm × 10 mm × 1 mm with the largest facets optically polished. The waveguides were produced by carbon and proton ion implantation at room temperature, which was performed at the 1.7 MV tandem accelerator of the Peking University and the Institute of Semiconductors, Chinese Academy of Sciences, respectively. To ensure a uniform effect on the whole sample, the ion beam was electronically scanned, tilting by 7° off the ion beam during interaction. Fig. 1 depicts the schematic plots of the fabrication process of the near-infrared channel waveguide. Before implantation, a photoresist mask with thickness of about 5 μm was deposited on the largest side of one sample by a standard lithographic technique. A mask of Cr stripes overspread the largest surface during the subsequent UV exposure, and the sample was post-baked at 120 °C for 30 min to remove the remaining water in the photoresist. With this processing, the mask was composed of a series of specially designed stripe patterns with a lateral width of ~43 μm, which were used to block the incident ions during implantation. At the same time, there were open stripes forming uncovered regions with a width of ~7 μm between adjacent photoresist stripes. The sample with such mask stripes was implanted by carbon ions at an energy of 6.0 MeV and fluences of 1×10^{15} ions/cm^2. Another sample undisposed was implanted by 500 keV and 550 keV proton at fluences of 1×10^{16} ions/cm^2, respectively.

A Jasco U570 spectrophotometer was used to record the absorption spectra of the polycrystalline ZnSe waveguide and substrate from the UV to IR band. To investigate the NIR band properties of the waveguide structure, the distinguished *m*-line method was used to measure the dark mode spectroscopy of the planar waveguide at 1539 nm by a prism coupler (Metricon, Model 2010, USA). The end-face coupling investigation with a continuous wavelength from 1260 nm to 1630 nm was performed with a tunable laser diode. During the measurement, a tapered fiber with the light at NIR band was coupled into the waveguide structure to stir up the guided modes, and the NIR light from the opposite facet of the waveguide structure was collected through another microscope objective lens (×25), which was imaged onto a CCD camera (Fig. 2).

The refractive index profile was a crucial parameter for waveguide structure and designing waveguide devices with practical applications and this was difficult to determine by direct measurement. Based on the measured dark-mode spectra, several methods, such as inverse Wentzel–Kramer–Brillouin (i-WKB) [16], reflectivity calculation method (RCM) [17], and intensity calculation method (ICM) [18] were developed to reconstruct the refractive index profiles of waveguides. In this work, we assumed that two half-Gaussian curves can be used to depict the refractive index profile of the planar waveguide. This assumption was discussed detail in Ref. [19] and with this, the refractive index profiles have been successfully reconstructed for several materials, such as stoichiometric lithium niobate [19], Nd:$Y_3Ga_5O_{12}$ [20], among others. For reconstructing the refractive index profile, the following parameters were adjusted until the theoretical effective index of the modes matched the experimental ones within an acceptable error rate: the refractive index of the waveguide surface (n_{sur}) and optical barrier (n_{bar}), the FWHM of the two half-Gaussian curves and the depth of the optical barrier (D). With the above-adjusted parameters, a refractive profile was supposed to approximately depict the refractive index behaviors in the planar waveguides. The refractive index distribution of the channel waveguides was constructed by carefully considering the shape of the section and the index.

3. Results and discussion

Determined by intrinsic and extrinsic absorption mechanisms, the absorption coefficient, Eq. (1), is defined as the relative decrease in the radiation intensity along the propagation direction [9]:

$$\alpha = \frac{1}{I\,(h\upsilon)} \frac{d\,\{I\,(h\upsilon)\}}{dx} \tag{1}$$

As reported by Pankove [21], free-carrier absorption has a monotonic, featureless spectrum, and the free carriers make a significant contribution to the absorption in ZnSe crystals. To explore the optical transmission properties of the polycrystalline ZnSe that may have been affected by carbon and proton implantation, the absorption spectra of the 1-mm thick sample were measured by a Jasco U570 spectrophotometer before and after implantation at room temperature, as shown in Fig. 3. The solid line is the polycrystalline ZnSe, and the dashed lines are the waveguide after carbon and proton ion implantation. For exact results, the other largest facets of the samples, except the implantation ones, were optically polished. As recorded, the absorption spectra exhibited good transparency from visible to IR band. Compared with the three lines in Fig. 3, there is no obvious change after carbon and proton ion implantation, especially in IR band. The results indicate that implantation had almost no influence on the absorption, which indicates the possibility for IR devices applications of ion-implanted waveguide structures.

Polycrystalline ZnSe is an excellent transmissive optical material at the NIR band, and so it is significant to research the optical properties of the waveguide structure at the NIR band. The dark mode spectroscopy of the waveguide structure on polycrystalline ZnSe formed by 6.0 MeV C ion implantation at 1539 nm is investigated by the conventional prism-coupling method, which is omitted in our work. The surface refractive index (n_{sur} = 2.4563) is sightly higher than the bulk index (n_{sub} = 2.4559), and one drop of the intensity corresponds to one excited mode at 1539 nm. For further understanding of the implantation-induced modifications in the polycrystalline ZnSe, we reconstructed the 3D index profile (Fig. 4) of the planar waveguide through two half-Gaussian curves, following the dark mode spectroscopy at 1539 nm. The results show that the index profile is a typical barrier-confined distribution, which has a maximum negative index change for the optical barrier from the surface to the depth of ~4.95 μm inside the wafer. Owing to