Amorphous Zn predeposition for growth of low-defect-density CdTe films and low-optical-loss Cd$_{1-x}$Mn$_x$Te magneto-optic waveguide on GaAs substrate

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Abstract

In order to reduce defect density in a CdTe film grown on GaAs, an amorphous Zn (a-Zn) layer was pre-deposited onto GaAs substrate. The a-Zn layer prevents a direct reaction of Te with Ga to form Ga$_2$Te$_3$, which induces defects. The thickness of a-Zn layer prior to the film growth can be reproducibly monitored from the intensity of reflection high-energy electron diffraction (RHEED) specular beam. Cd$_{1-x}$Mn$_x$Te waveguide grown on this CdTe buffer layer showed significantly reduced optical loss down to 4 dB/cm.

The Cd$_{1-x}$Mn$_x$Te magneto-optic waveguide grown on the GaAs substrate is important for monolithic integration of magneto-optic devices into III–V semiconductor optoelectronic circuits [1]. Low optical loss is an essential condition for practical application of Cd$_{1-x}$Mn$_x$Te waveguides. The high defect density causes high optical loss in the Cd$_{1-x}$Mn$_x$Te waveguide due to light scattering and light absorption [2]. It is known that for the epitaxial growth of II–VI film on III–V substrate, the defect density in the film is very sensitive to the substrate surface treatment and the initial growth conditions [3,4]. The case of ZnSe epitaxy on GaAs substrate has been well studied. An exposure of GaAs surface to a Zn beam prior to the ZnSe growth is a widely accepted recipe, which results in lowest stacking-fault density achieved so far [3,4]. The Zn exposure is believed to protect GaAs substrate against a reaction with Se atoms to form Ga$_2$Se$_3$ on the surface [5].

Here we propose to use amorphous Zn (a-Zn) predeposition prior to the growth of CdTe films on GaAs substrate to reduce defect density. The a-Zn layer is used to protect GaAs substrate against a reaction with Te atoms to form Ga$_2$Te$_3$ on the surface. In the proposed method, following low-temperature deposition, the a-Zn layer is desorbed at higher temperature. When Zn coverage of GaAs surface reaches a value of about 1 monolayer, the film growth started. Since Zn coverage of GaAs surface reaches a value of about 1 monolayer, the film growth started. Since the Zn coverage can be monitored by the reflection high-energy electron diffraction (RHEED) specular-beam intensity, the
optimum Zn coverage to grow high quality CdTe film can be obtained with a good reproducibility. Using a CdTe film grown with a-Zn predeposition method as a buffer layer, optical loss in Cd$_1-x$Mn$_x$Te waveguide is significantly reduced.

At first, we developed a method to monitor a deposition and a desorption of a-Zn layer on/from GaAs(001) substrate. The GaAs substrate was cleaned with atomic hydrogen at $T_{\text{sub}} = 420$°C. High-intensity streaky RHEED pattern and (3 x 1) reconstruction indicate smooth contamination-free GaAs surface. Next, the GaAs substrate was cooled down to 70°C and a-Zn layer was deposited. The RHEED specular-beam intensity was recorded during the deposition. Fig. 1 shows the RHEED specular-beam intensity as a function of the time (top horizontal axis). The thickness of a-Zn layer (bottom horizontal axis) was deduced from deposition time and calibrated a-Zn deposition rate. The deposition rate was determined from thickness of an amorphous-Zn film measuring by a Sloan DECTAC profilometer. The RHEED specular-beam intensity follows an exponential law $I = I_0 \exp(-kd)$, where $d$ is thickness of a-Zn layer and $k$ equals 0.362 Å$^{-1}$. This exponential dependence implies that for an electron beam diffracted on GaAs surface a-Zn layer can be treated as an absorption layer with thickness-independent absorption coefficient. During a desorption process the absorption coefficient was used to evaluate thickness of a-Zn layer.

The desorption process of a-Zn was studied by heating up the a-Zn layer on GaAs substrate up to 220–250°C. With heating the RHEED pattern of GaAs appeared again. Fig. 2 shows the RHEED specular-beam intensity as a function of the time. As mentioned above, the thickness of a-Zn layer was deduced from the RHEED specular-beam intensity: $d = -(1/k) \ln[I/I_0]$. The corresponding thickness of a-Zn layer as a function of the time is also shown in Fig. 2. The desorption rate of a-Zn layer is constant down to thickness of ~3–4 Å. Fig. 3 shows a-Zn layer desorption rate as a function of substrate temperature. The desorption rate was obtained from linear fitting of data of Fig. 2 in a range of a-Zn thickness from 4 to 10 Å. From data given in Fig. 3, the activation energy $E_a$ for a-Zn desorption is determined to be 0.99 eV.

To examine the effectiveness of a-Zn predeposition on a film quality, three samples with an identical structure were grown by molecular beam epitaxy on GaAs (001) substrate with different surface treatments. The sample structure was CdTe(1nm):ZnTe(1nm):GaAs. During CdTe (001) growth at $T_{\text{sub}} = 265$°C the Te and Cd fluxes were adjusted so that the surface showed (2 x 1)-weak a(2 x 2) reconstruction [6,7].

Sample 1 did not receive any special surface treatment of GaAs substrate. The ZnTe layer was deposited on a GaAs substrate, followed by a-Zn deposition at 420°C. The deposition rate was determined from thickness of an amorphous-Zn film measuring by a Sloan DECTAC profilometer.
grown with simultaneous opening of Zn and Te shutters at $T_{\text{sub}} = 265^\circ$C. For Sample 2, the GaAs substrate was exposed to Zn flux for 20 min before growth of the ZnTe ($T_{\text{sub}} = 265^\circ$C). For Sample 3 amorphous Zn predeposition was used. The growth of the ZnTe ($T_{\text{sub}} = 220^\circ$C) was started when the RHEED specular-beam intensity reached the value corresponded to Zn coverage of $3\,\AA$. After the ZnTe layer growth, the sample was heated up to $300^\circ$C under Cd flux. After a short time (typically 1 min) annealing, the substrate was cooled down to $T_{\text{sub}} = 265^\circ$C and the CdTe film was grown.

High-resolution triple-axis X-ray diffraction was used to characterize the CdTe films. For (004) reflection the full-width-at-half-maximum (FWHM) of $\omega-2\theta$ scan (rocking curve) and FWHM of $\omega$ scan (mosaicity) were measured (Table 1). Following the method proposed in Refs. [8–10], an X-ray coherence length along [001] and [110] directions was derived from the two-dimensional X-ray reciprocal space map measured in vicinity of CdTe (004) reflection (Table 1). As the coherence of the incident beam is long (> $3\mu$m), the measured coherence length provide good estimate of average distance between defects [8–10]. For estimation of a twin density, a high-intensity low-resolution X-ray measurement setup was used which was equipped with a pinhole collimator and a graphite monochrometer. The diffracted beam intensity was measured as a function of the angle between diffraction plane and film normal ($\psi$) and the angle of sample rotation about its surface normal ($\pi$), while $2\theta - \omega$ angle was fixed for a CdTe (111) reflection. Fig. 4 shows a pole figure for Sample 1. Four peaks at $\psi = 54.7^\circ$ correspond to diffraction from (001) orientated CdTe, while four peaks at $\psi = 15.8^\circ$ correspond to diffraction from twins. From the integrated intensities of the peaks, twin density was estimated [11]. Sample 2 showed faint signal at $\psi = 15.8^\circ$ and Sample 3 was twin-free (Table 1).

In order to show the usefulness of the amorphous Zn predeposition method for device performance, Cd$_{1-x}$Mn$_x$Te waveguides were grown on top of CdTe layer and their optical loss was measured. Following the CdTe growth with the same procedures as were used for Samples 1, 2, and 3, a 3-µm-thick Cd$_{0.7}$Mn$_{0.3}$Te waveguide cladding layer and a 1.2-µm-thick Cd$_{0.85}$Mn$_{0.15}$Te waveguide core layer were grown. Fig. 5(a)

![Desorption rate of amorphous Zn (a-Zn) layer as a function of substrate temperature.](image)

**Table 1**

<table>
<thead>
<tr>
<th>Surface treatment of GaAs substrate</th>
<th>No treatment (Sample 1)</th>
<th>Zn-exposure (Sample 2)</th>
<th>Amorphous Zn predeposition (Sample 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FWHM $\omega-2\theta$ scan (rocking curve)</td>
<td>2.2 arcmin</td>
<td>1.4 arcmin</td>
<td>0.7 arcmin</td>
</tr>
<tr>
<td>FWHM $\omega$ scan (mosaicity)</td>
<td>11.4 arcmin</td>
<td>7.2 arcmin</td>
<td>5.1 arcmin</td>
</tr>
<tr>
<td>X-ray coherence length along (001)</td>
<td>137 nm</td>
<td>215 nm</td>
<td>430 nm</td>
</tr>
<tr>
<td>X-ray coherence length along (110)</td>
<td>49 nm</td>
<td>77 nm</td>
<td>100 nm</td>
</tr>
<tr>
<td>Twin density in CdTe films</td>
<td>0.2%</td>
<td>0.03%</td>
<td>0</td>
</tr>
<tr>
<td>Optical loss of Cd$_{1-x}$Mn$_x$Te waveguide</td>
<td>25 dB/cm</td>
<td>15 dB/cm</td>
<td>4 dB/cm</td>
</tr>
</tbody>
</table>
illustrates an experimental setup to evaluate optical propagation loss in the waveguide. A GaP prism was used to couple the laser light ($\lambda = 790$ nm) into the waveguide. A cooled charged-coupled device (CCD) TV camera collected light normally scattered from the film surface. Fig. 5(b) shows a streak of waveguiding light. Loss of waveguide mode was estimated by an exponential fit of the intensity of the scattered light as a function of distance between a scattering point and the prism. The results are shown in Table 1.

Table 1 shows that the a-Zn predeposition is effective to reduce defect density in CdTe films and optical loss in Cd$_{1-x}$Mn$_x$Te waveguide. The Zn-exposure is also effective to improve the film quality and the waveguide loss. It is not surprising, because of its successful use for growth of ZnSe-based laser diodes (LD) on GaAs [3,4]. However, as can be seen from Table 1 the a-Zn predeposition is more effective than the Zn-exposure.

Because of large lattice mismatch between CdTe and GaAs, the 60° dislocation is generated after growth of few monolayers of CdTe to relax the strains. They move through interface and recombine to form edge dislocation [12,13]. Any obstacle on interface (for example, Ga$_2$Te$_3$ compound) prevents the movement of the 60° dislocation and causes the threading dislocations and stacking faults nucleation [12,13]. In the case of Zn-exposure, the Zn coverage of GaAs is lower than 0.4 monolayer [14–16]. Therefore, Te atoms still can chemically react with Ga on GaAs surface that increases the number of defects in the film. In the case of the a-Zn predeposition, over 1 monolayer Zn coverage of GaAs can be easily obtained and it completely protects GaAs surface.

In conclusion, a new growth method to improve quality of CdTe films grown on GaAs substrate is proposed. Amorphous Zn layer is deposited at 70°C to prevent interaction of Te atom with GaAs surface. Zn coverage of surface can be controlled by monitoring RHEED intensity. The proposed method was proved to be effective in reducing of defect density in CdTe film and optical loss in Cd$_{1-x}$Mn$_x$Te optical waveguide.

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References