$Cd_{1-x}Mn_xTe$ magneto-optical waveguide integrated on GaAs substrate

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The refractive indices of diluted magnetic semiconductor $Cd_{1-x}Mn_xTe$ films on sapphire substrates have been determined by *m-line* spectroscopy to precision 0.001 at the wavelengths $\lambda=670$, 785, and 1150 nm. Using these data, we designed double-layer $Cd_{1-x}Mn_xTe$ structures on a GaAs substrate, achieving the integration of the magneto-optical waveguide on a semiconductor substrate. Good optical confinement of the waveguide mode was confirmed. © *1997 American Institute of Physics.* [S0003-6951(97)00119-8]

Progress in optical communication systems requires an ever higher level of integration of different optical elements. The optical isolator is an essential component of such integration. It protects the laser diodes and optical amplifiers from unwanted reflections and is necessary to ensure source stability, especially when fast switching and large bandwidth are important. Recently, hybrid optical integration of the planar optical isolator based on garnet magneto-optical film has been successfully demonstrated on a silicon substrate.[1] Because most of the active optical elements (such as laser diode, optical amplifier, modulator, optical gate) are produced on GaAs or InP substrates, it is desirable to integrate monolithically all optical circuits on these types of substrate. We know of no successful attempts to grow a magneto-optical waveguide on GaAs or InP.

$Cd_{1-x}Mn_xTe$ is a very attractive magneto-optical material for integrated optical isolator.[2,3] It has the zinc-blende-type crystal structure of GaAs and InP, and high-quality single crystal $Cd_{1-x}Mn_xTe$ films can be grown directly on GaAs substrates. Due to the exchange interaction between the band electron and the localized d electron of Mn^{+2}, this material exhibits a huge Faraday effect near the absorption edge (typically 2500 °C/cm at 10 kG).[4,5] The absorption edge varies from 1.6 to 2.1 eV as Mn concentration changes.[2] This makes the $Cd_{1-x}Mn_xTe$ magneto-optical waveguide suitably compatible with AlGaInP:GaAs optoelectronics devices operating at wavelengths in the range 600–800 nm. For long wavelength optoelectronics devices ($\lambda=800$–1500 nm), $Cd_{1-x-y}Mn_xHg_yTe$ films[6,7] can be used as magneto-optical waveguides. A bulk optical isolator using these materials has been recently achieved.[6]

In designing a $Cd_{1-x}Mn_xTe$ waveguide on GaAs, one must take note of the fact that GaAs usually has a higher refractive index than II–VI semiconductors.[8,9] As will be shown below, the refractive index of $Cd_{1-x}Mn_xTe$ is typically less by 0.7–0.9 than the GaAs value ($n_{GaAs}=3.4$–3.8 at $\lambda=1150$–600 nm). Therefore, total internal reflection at the interface between GaAs and $Cd_{1-x}Mn_xTe$ does not occur. To obtain a $Cd_{1-x}Mn_xTe$ waveguide on GaAs substrate, the low-refractive index cladding layer should be grown first. Moreover, the step of the refractive index between core and cladding layers must be large enough to isolate the waveguide mode from the GaAs substrate. However, to our knowledge, there is no reliable data for the refractive index of $Cd_{1-x}Mn_xTe$.

A number of optical techniques, such as interferometry, ellipsometry, and transmission and reflection spectroscopy, can be used to determine the refractive index of the film. However, most of them do not provide accurate values, because usually the precision of the measurement of the refractive index depends critically on the precision of the film thickness determination.

The method of *m-line* spectroscopy is perhaps the most precise and reliable option for determining the refractive index of the films. As has been shown by Ulrich and Torge,[10] if the waveguide contains more than ten modes, the refractive index can be obtained to within 0.000 1 precision. In the *m-line* spectroscopy of the $Cd_{1-x}Mn_xTe$ films, a nonabsorbing low-refractive-index substrate is required. Sapphire substrates (n=1.75–1.77 at $\lambda=1150$–600 nm) are suitable for this purpose.[11]

In this letter, the refractive index of $Cd_{1-x}Mn_xTe$ has been determined by the technique of one-prism *m-line* spectroscopy. Using these data, double-layer $Cd_{1-x}Mn_xTe$ waveguides on GaAs substrates were designed and studied.

For the refractive index measurements, zinc-blende $Cd_{1-x}Mn_xTe$ single crystal films were grown on sapphire [0001] substrates by the molecular beam epitaxy (MBE) method. For Mn concentration x less than 0.6, the single layer films were grown directly on the sapphire substrates. Direct growth of films with higher Mn concentration induces mixing of the NiAs-type $Cd_{1-x}Mn_xTe$, such that in order to obtain zinc-blende-type single crystal films with $x>0.6$, it was necessary to use a 100-nm-thick $Cd_{0.5}Mn_{0.5}Te$ buffer layer.

Figure 1 shows the setup for the one-prism *m-line* spectroscopy experiment. The light is reflected from the film through the GaP prism. Because the refractive index of the prism ($n=3.09$–3.30 at $\lambda=1150$–600 nm) is higher than the refractive index of the $Cd_{1-x}Mn_xTe$ film ($n=2.6$–3.0 at $\lambda=1150$–600 nm), the light propagation constant inside the prism can be equal to the propagation constant of the waveguide mode. When this is the case, the light is coupled from the prism to the optical waveguide. A short-focus lens (f=5 mm) produced a wide range of incidence angles. At the

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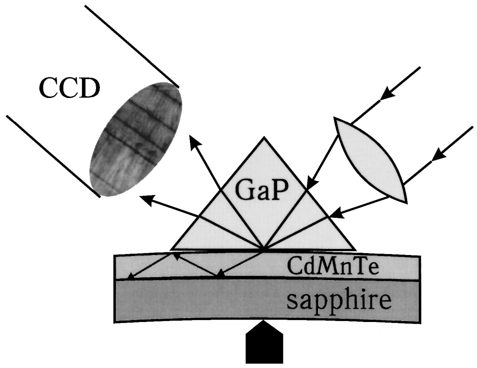

FIG. 1. One-prism *m-line* spectroscopy.

angles where the propagation constant inside the prism coincides with the propagation constant of the waveguide, the light is efficiently absorbed into the film and is not reflected. This causes the dark lines in reflected light. From output angles of these lines, we deduced the propagation constants of the waveguide modes, from which the film parameters were calculated. The precision of the refractive index was estimated to be 0.001.

As laser sources, two 5 mW semiconductor laser diodes at wavelengths 670 and 784 nm, and a 5 mW He-Ne laser at wavelength 1150 nm were used. Output angles of the *m-lines* were measured by using two types of GaP prism: 45-45-90° and 60-60-60°. By measuring the *m-line* spectra from the same film with different prisms, the refractive index of the prisms could be precisely determined. We obtained for GaP the values 3.083 at $\lambda = 1150$ nm, 3.194 at $\lambda = 784$ nm, and 3.267 at $\lambda = 670$ nm.

Figure 2 shows the refractive index of $Cd_{1-x}Mn_xTe$ as a function of Mn concentration at these three wavelengths. At $\lambda = 1150$ nm and $x = 0$, this data coincides with data for the refractive index of CdTe.[8]

As can be seen from Fig. 2, the refractive index of $Cd_{1-x}Mn_xTe$ decreases rapidly with increasing Mn concentration. For all investigated wavelengths this change is about 0.03–0.05 per 0.1 change of Mn concentration. Thus, good optical confinement can be achieved by using the $Cd_{1-x}Mn_xTe$ buffer layer with Mn concentration only about 0.1–0.2 higher than Mn concentration of the waveguide core layer.

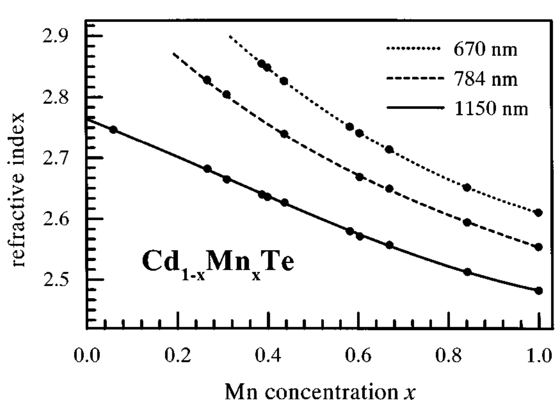

FIG. 2. The refractive index of $Cd_{1-x}Mn_xTe$ as a function of Mn concentration.

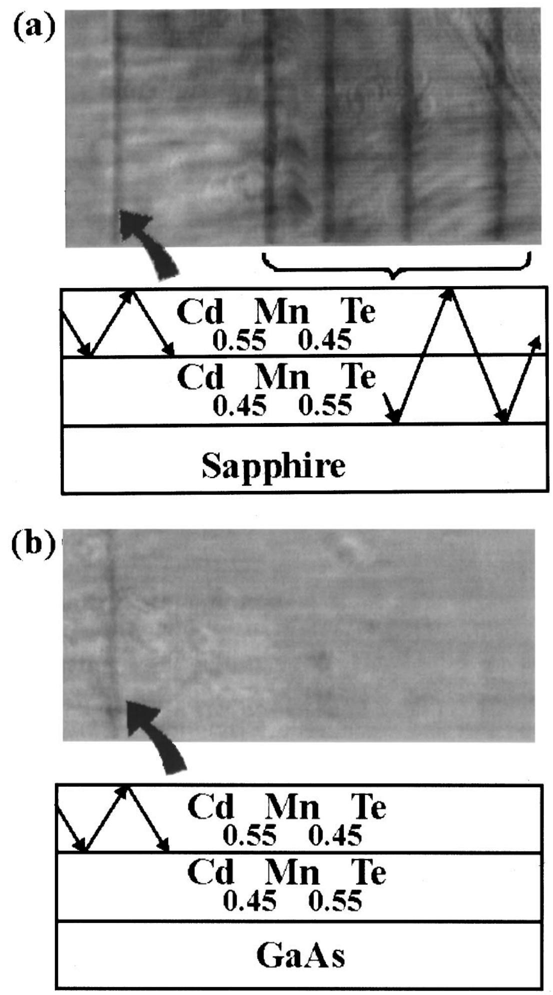

FIG. 3. (a) Doublelayer $Cd_{1-x}Mn_xTe$ waveguide on sapphire substrate, and its *m-lines*. (b) Doublelayer $Cd_{1-x}Mn_xTe$ waveguide on GaAs substrate, and its *m-line*.

The double-layer waveguide was grown simultaneously on sapphire and GaAs [001] substrates. A 1.5-μm-thick $Cd_{0.45}Mn_{0.55}Te$ cladding layer, and a 1.5-μm-thick $Cd_{0.55}Mn_{0.45}Te$ core layer were used. Figure 3(a) shows the *m-lines* from the waveguide on the sapphire substrate. Several *m-lines* appeared. They can be classified into two groups, i.e., four right-side *m-lines* and one left-side *m-line*. The distance between the adjacent four right-side *m-lines* systematically decreases. This behavior of the *m-lines* is typical for the multimode single-layer waveguides. Because the refractive index step between two $Cd_{1-x}Mn_xTe$ layers is small, these *m-lines* correspond to the waveguiding propagation between the air and the sapphire substrate [see Fig. 3(a)]. The other ''separated'' *m-line* corresponds to the waveguiding propagation only in the upper $Cd_{0.55}Mn_{0.45}Te$ layer. By contrast, the waveguide on the GaAs substrate showed only one *m-line* [Fig. 3(b)]. The position of this *m-line* corresponds to the position of the separated *m-line* of Fig. 3(a). Here the light propagates only in the upper layer, because of the higher refractive index and larger optical absorption of GaAs. The fact that the *m-line* is identically positioned for both waveguides is evidence for good optical confinement in the $Cd_{1-x}Mn_xTe$ waveguide.

The optical loss of the waveguide on GaAs substrate was 70 dB/cm at $\lambda = 1150$ nm, and more than 150 dB/cm at $\lambda = 784$ and $\lambda = 670$ nm. Because the waveguide on sapphire substrate showed a very small loss, i.e., ~ 0.3 dB/cm at $\lambda = 1150$ nm, it is clear that the high loss is not intrinsic to $Cd_{1-x}Mn_xTe$ waveguides. By improving the film growth process, damping by waveguides on GaAs substrate can be reduced by at least 20 times.[12]

In summary, we have reported the refractive index of $Cd_{1-x}Mn_xTe$ at wavelengths of 670, 784, and 1150 nm measured to within 0.001 precision. We successfully demonstrated the monolithic integration of the $Cd_{1-x}Mn_xTe$ magnetooptical waveguide on the GaAs substrate.

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