Laser Letter

Losses in Metal-Clad Ion-Implanted GaAs Optical Waveguides

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We present an investigation of the optical interaction of metal cladding with guided waves in ion-implanted GaAs compound semiconductor waveguides under various implant conditions. At optical frequencies, such waveguides can be conveniently represented by a complex dielectric constant which depends on the carrier concentration in the implant region. The attenuation in these optical waveguides due to the free carrier absorption is compared with that due to propagation losses in metals.

1. Introduction

At optical frequencies, metals behave as very lossy dielectrics due mainly to the electron plasma resonances of most metals lying in the ultraviolet spectrum. But in the design of active integrated optical devices, metal electrodes are required for electro-optic and acousto-optic operation, and sometimes for polarization and mode filtering^{1,2)}.

Optical waveguides in III-V compound semiconductors are attractive as GaAs/GaAlAs crystal systems offer excellent electrical properties and a fairly good optical performance. The GaAs material system, apart from offering high-speed circuitry needed to drive optical modulators and switches, is potentially a good candidate for future integrated optical systems.

The optical interaction of the metal cladding with guided waves in lossless dielectric guiding layers was investigated^{3,4)}. Batchman and Peeler⁵⁾ studied the loss characteristics of dielectric waveguides using thin films of GaAs as a lossy cladding material. In this paper we consider the optical interaction of metal claddings with guided

waves in ion-implanted GaAs waveguides under various implant conditions. At optical frequencies, such waveguides can be conveniently represented by a complex dielectric constant whose real and imaginary parts are functions of the carrier concentration in the implant region. The knowledge of the attenuation and propagation characteristics of such metal-clad GaAs waveguides under various implant conditions is important in selecting the appropriate metal cladding structure and in determining the size of an optical device.

2. Metal-Cladded Waveguides

At optical frequencies, metals can be conveniently represented by a complex dielectric constant $\tilde{\epsilon}_r$ as $\epsilon'_r - i\epsilon''_r$, or by a complex refractive index $\tilde{n} = n' - in''$. The two parameters are related as

$$\tilde{\epsilon}_r = \tilde{n}^2; \text{ i.e. } \epsilon'_r = (n'^2 - n''^2), \epsilon''_r = 2n'n'' \quad (1)$$

Consider a planar optical waveguide sandwiched between two cladding layers, represented respectively by complex dielectric constants, $\tilde{\epsilon}_{r1}$, $\tilde{\epsilon}_{r2}$ and $\tilde{\epsilon}_{r3}$ as in Fig. 1. The complex character-

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Fig. 1. Three-layer planar optical waveguide structure.

istic equation for TE_m and TM_m is ³⁾:

$$kd = (\tilde{\epsilon}_{r1} - B)^{-1/2} \{ \arctan f [(B - \tilde{\epsilon}_{r2})/(\tilde{\epsilon}_{r1} - B)]^{1/2} + \arctan g [(B - \tilde{\epsilon}_{r3})/(\tilde{\epsilon}_{r1} - B)]^{1/2} + m\pi \} \quad (2)$$

where $f=g=1$, for TE modes;

$$f = \tilde{\epsilon}_{r1}/\tilde{\epsilon}_{r2}, \quad g = \tilde{\epsilon}_{r1}/\tilde{\epsilon}_{r3},$$

for TM modes; $B = (\tilde{\beta}/k)^2$,

$k = 2\pi/\lambda$ is the free space propagation constant and d is the thickness of the optical waveguide.

The complex waveguide propagation constant $\tilde{\beta}$ is represented by a real propagation constant, β' and an imaginary loss constant, β'' as

$$\tilde{\beta} = \beta' - i\beta'' \quad (3)$$

The attenuation rate, α of the propagating wave will then be given as

$$\alpha = 2\beta'', \quad \text{for } \beta'' > 0 \quad (4)$$

3. Ion-Implanted Waveguides

Ion-implanted optical waveguides in GaAs are fabricated by implanting with high-energy protons or other light ions. These implanted ions will produce displacements in the host crystal lattice which trap the free carriers, resulting a complex dielectric constant, $\tilde{\epsilon}_r$ whose real and imaginary parts are dependent on the number of free carrier density in the semiconductor. The trapping of free carriers leads to an increase in the real part ϵ_r' and a decrease in the imaginary part ϵ_r'' , a physical process known as the plasma depression effect.

At optical frequencies, the dielectric constant arises almost entirely from the electronic polarizability. The dipolar and ionic polarizabilities are small because of the inertia of the molecules and ions.

The electronic contribution arises from the displacement of electrons in an atom relative to the nucleus. So for ion-implanted waveguides operated at a wavelength far away from the absorption band edge, it can be shown⁷⁾ that

$$\epsilon_r' \simeq n_0^2 - \left[\frac{e^2}{\epsilon_0 m^* (2\pi c)^2} \right] N_c \lambda^2, \quad (5)$$

and

$$\epsilon_r'' \simeq \frac{e^3}{\epsilon_0 (m^*)^2 (2\pi c)^3} \left(\frac{N_c \lambda^3}{\mu} \right) \quad (6)$$

where N_c is the free carrier concentration, μ is the carrier mobility, n_0 is the real refractive index in the absence of free carriers (i.e. $N_c = 0$), e is the electronic charge, ϵ_0 is the free-space permittivity and m^* is the carrier effective mass. For n -type GaAs, $m^* = 0.068 m$, where m is the free electron mass.

The dependence of n_0 on the operating wavelength λ can be conveniently specified in the form of Sellmeier equations

$$n_0^2 = A + B/(\lambda^2 - C) - D\lambda^2 \quad (7)$$

Measured data for n_0 of intrinsic GaAs have been empirically fitted to the preceding equation and for our spectral region of interest (i.e. $1 \mu\text{m} < \lambda < 2 \mu\text{m}$), the resulting coefficients are⁷⁾: $A = 10.906$, $B = 0.97501$, $C = 0.27969$ and $D = 0.002467$.

The carrier mobility μ can be found experimentally as a function of the carrier concentration N_c . For n -type GaAs at 300°K and for N_c in the range of $10^{15} - 10^{19} \text{ cm}^{-3}$, the carrier mobility can be fitted using⁸⁾,

$$\mu = -1682 \log N_c + 33264 \quad (8)$$

where N_c is expressed in units of carriers per cm^3 , and μ is in units of $\text{cm}^2/\text{V-s}$.

From equations (5)–(8), the complex dielectric constants of an n -type ion implanted GaAs waveguide can be expressed in terms of two variables: the carrier concentration N_c in the implant region and the k parameter. Using equation (2), the propagation constant β' and the loss constant β'' are calculated at various N_c with aluminium cladding for TE₀ mode at $\lambda = 1.15 \mu\text{m}$ in a GaAs substrate of $N_s = 3.5 \times 10^{18}$

cm^{-3} as shown in Fig. 2. The graphs show that the waveguide attenuation increases with increasing N_c . The most important source of loss mechanism in GaAs waveguides in the $1 \mu\text{m}$ region is the free carrier absorption due to ϵ''_{r1} and ϵ''_{r2} . So the β'' curves in Fig. 2 show the attenuation is due to losses in the metal cladding and the free carrier absorption. Similar curves are calculated for TM₁ mode as shown in Fig. 3.

Fig. 2. The effect of carrier concentration N_c in the implant region on the propagation constant in an aluminium-clad ion-implanted GaAs waveguide for TE₀ mode.

Fig. 3. Similar curves as in Fig. 1 for TM₁ mode.

For an implant region with $N_c = 1.0 \times 10^{18} \text{ cm}^{-3}$ in a GaAs substrate of $N_s = 3.5 \times 10^{18} \text{ cm}^{-3}$, the propagation constant for TE and TM modes are shown in Fig. 4 and the loss constant shown in Fig. 5. The graphs show that TE modes are less affected by the metal-cladding than TM modes. The TE_m modes have propagation constants very close in the TM_{m+1} modes. The TM_0 mode, also called the surface plasma mode, is

Fig. 4 The propagation constant for TE and TM modes for aluminium-clad GaAs waveguide with an implant carrier concentration N_c of $1.0 \times 10^{18} \text{ cm}^{-3}$.

very lossy at optical frequencies³⁾. The free carrier absorption due to the loss constants ϵ''_{r1} and ϵ''_{r2} was found to have no significant effect on β' . Fig. 5 also shows the loss constants for TE_m and TM_m modes with and without taking the free carrier absorption into account.

As kd increases (i.e. far from cut-off), the loss due to metal cladding will tend to zero as shown in the lower curves of Fig. 5, while the upper curves will approach the free-carrier absorption loss in the waveguide given as⁹⁾.

$$\alpha = k \epsilon_{r1}'' / \sqrt{\epsilon_{r1}'} \quad (9)$$

From equations (5) and (6), this leads to

$$\alpha \approx - \left[\frac{e^3}{\epsilon_0 (m^*)^2 4 \pi^2 c^3} \right] \left(\frac{N_c \lambda^2}{\mu n_0} \right) \quad (10)$$

The attenuation rate is a measure of the number of optically active defects produced by the ion bombardment. The production of these optical defects is a non-linear function of the dose range or anneal temperature¹⁰⁾. In general the ion bombardment is used to create high-resistivity wave-guiding layers and so the free carrier distribution is not uniform along and perpendicular to the direction of optical propagation, due to non-uniform radiation damages in

Fig. 5. The loss constant for TE and TM modes with $N_c = 1.0 \times 10^{18} \text{ cm}^{-3}$. Dotted curves show losses due to metal cladding. Solid curves include free-carrier absorption effects.

the crystal. This detrimental effect can be alleviated by using a post-bombardment annealing at temperatures in the range 250—600°C to achieve a compromise between the resistivity and the optical attenuation^{10,11}. Garmire¹¹ found that the optical mode shape has been broadened after annealing, due mainly to changes in the carrier concentration profile. It was suggested⁹ that part of the observed attenuation results from the free carrier absorption of photons in the "tail" of the optical mode which extends well into the substrate. We shall consider such non-uniform carrier concentration in ion-implanted waveguides in a later article.

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References

- 1) T. E. Batchman and S. C. Rashleigh: IEEE J. Quantum Electron **8** (1972) 848.
- 2) K. H. Rollke and W. Sohler: IEEE J. Quantum Electron. **13** (1977) 141.
- 3) I. P. Kaminow, W. L. Mammel and H. P. Weber: Appl. Opt. **13** (1974) 369.
- 4) S. C. Rashleigh: Opt. and Quantum Electron **8** (1976) 49.
- 5) T. E. Batchman and J. R. Peeler: IEEE J. Quantum Electron. **14** (1978) 327.
- 6) See for example, F. C. Brown, The Physics of Solids, Benjamin, New York, 1967.
- 7) B. O. Seraphin and H. E. Bennet: "Optical Constants" in Semiconductors and Semi-metals, Vol. 3, New York, Academic Press, 1967.
- 8) H. Kressel and J. K. Butler: Semiconductor Lasers and Heterojunction LEDS, New York, Academic Press, (1977).
- 9) V. Evtuhov and A. Yariv: IEEE Trans. on Microwave Theory and Tech. **23** (1975) 44.
- 10) J. C. Dymont, J. C. North and L. A. D'Asaro: J. Appl. Phys. **44** (1973) 207.
- 11) E. Garmire, H. Stoll, A. Yariv and R.G. Hunsperger: Appl. Phys. Lett. **21** (1972) 87.