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Application of two-stage thermal diffusion in the technology of buried channel waveguides

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In the paper, both theoretical analysis and experimental studies of the process of formation of channel waveguides buried during a two-stage thermal diffusion in glass are presented. In particular, the theoretical description of a simple mechanism of surface ion exchange, based on a single parameter characterizing the rate of the ion exchange process, has been proposed. The theoretical results have been verified experimentally for a two-stage exchange of $Ag^+ - Na^+$ in soda-lime glass. The effect of the parameters of the technological process on the modal properties of the structures obtained has been investigated.

1. Introduction

The technique of ion exchange in glass is a particularly simple and universal method of producing a wide class of passive integrated optical components. Through a proper selection of technological conditions – kinds of dopant ions, type of glass, time and temperature of the process – single-mode and multimode, planar and channel waveguides are obtained whose geometry and optical properties may change over a wide range [1].

The technology of buried channel waveguides is based mainly on a multi-stage ion exchange in the presence of an external electric field [1], [2]. This technology enables us to obtain, in a relatively short time, deep and symmetrical profiles of changes of the refractive index. Its shortcoming is the necessity of using a special technological stand ensuring electric insulation of the molten salts of the ions being exchanged [3].

There are relatively few papers on a technologically much simpler method of two-stage thermal diffusion which may be used particularly in the fabrication of single-mode structures [4], [5]. Neither is there a satisfactory theory of such ion exchange.

In this paper, an analysis of the process formation of two-dimensional distributions of the refractive index during two-stage thermal ion exchange in glass is presented. The effect of boundary conditions on the refractive index distribution profile has been determined and the modal properties of the structures obtained have been investigated.

2. Theory

In the first step of a two-stage thermal diffusion, the substituted ions (*a*), diffusing in the time t_D through a window of the width x_w, replace the ions (*b*) which are natural components of the glass substrate (it is assumed that these are the only active ions at the given temperature, substrate ions). The geometry of the process is shown in Fig. 1. The differences of the atomic size of the exchanging ions and their electronic polarizability lead to the formation of the refractive index distribution proportional to the preliminary concentration C_a^0 of the ions introduced.

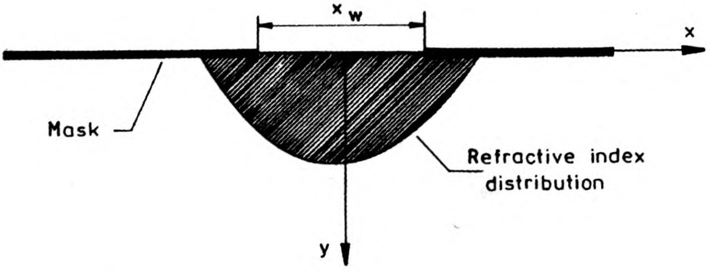


Fig. 1. Geometry of a masked ion exchange process

Carrying out in the next stage, after removing the mask, the diffusion of ions (*b*) in the time t_z we shall obtain the distribution of refractive index with the maximum separated from the surface of the glass substrate.

A two-dimensional distribution of the concentration $C_a(x, y)$ of ions (*a*), obtained in a two-stage process of thermal diffusion, proportional to the distribution function $dn(x, y)$ of the refractive index changes, is the solution of a nonlinear equation of diffusion [1]

$$\frac{\partial C_a}{\partial t} = \nabla \frac{D_a C_0}{C_0-(1-m)C_a} \nabla C_a, \quad C_a+C_b = C_0, \tag{1}$$

in which m is the ratio of mobility of the ions (*a*) and (*b*), D_a denotes self-diffusion coefficient of ions (*a*), C_b is the concentration of ions (*b*) and C_0 is the equilibrium concentration. The solution of Eq. (1) requires the establishing of a pair of suitable initial and boundary conditions.

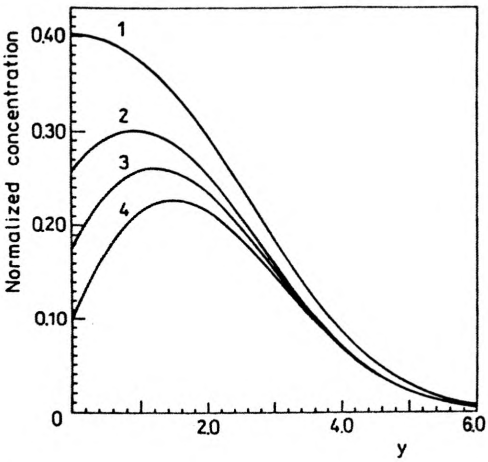
The initial condition for the concentration C_a is the function C_a^0, describing the distribution of the concentration of ions (*a*), formed in the preliminary diffusion. It is obtained by solving the equation of diffusion (1) for the function C_a^0 with the initial and boundary conditions in the form:

$$\begin{aligned} &C_a^0(x, y, t) = 0 \quad \text{for } t = 0, \\ &C_a^0(x, y, t) = C_0 \quad \text{for } x \in (-x_w/2, x_w/2), \quad y = 0, \end{aligned} \tag{2}$$

corresponding to the assumption of an infinite source of ions (*a*).

For the description of surface ion exchange (*a*)−(*b*) in the process of burying, a simple and physically justified assumption has been made that the flow of ions (*b*) through the substrate surface $j_{by}(y = 0)$ is proportional to the difference between the actual concentration of ions C_b and the equilibrium concentration, *i.e.*,

$$j_{by}(x, y, t) = s(C_0 - C_b) \quad \text{for } y = 0 \tag{3}$$



▲

Fig. 2. Numerically calculated normalized vertical profiles of the concentration $C_a(0, y)/C_0$ for the parameters of the technological process: $x_w = 1.7\,(D_a t_D)^{1/2}$, $m = 0.1$, $t_z/t_D = 1$ and various values of the parameter s (in μm/h): 1 – $s = 0.0$, 2 – $s = 0.5$, 3 – $s = 1.0$, 4 – $s = 2.0$. (y – profile depth in $(D_a t_D)^{1/2}$ units)

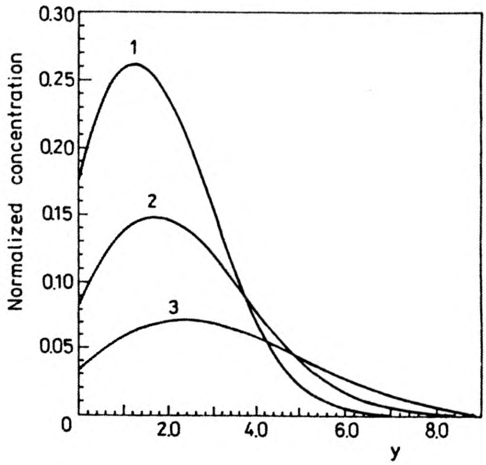


Fig. 3. Theoretical profiles of distribution of the normalized vertical concentration $C_a(0, y)/C_0$ for the technological parameters: $x_w = 1.7(D_a t_D)^{1/2}$, $m = 0.1$, $t_D = 1$ h, $s = 1$ μm/h and the various times of burying: 1 – $t_z = 1$ h, 2 – $t_z = 2$ h, 3 – $t_z = 4$ h. (y – profile depth in $(D_a t_D)^{1/2}$ units)

where s is the constant of proportionality characterizing the rate of surface ion exchange.

In Figure 2, the numerically calculated vertical profiles $C_a(0, y)$ are presented for the window width $x_w = 1.7(D_a t_D)^{1/2}$, $m = 0.1$, $t_Z/t_D = 1$ and the different values of the parameter s. The distribution for $s = 0$, corresponding to the unburied diffused

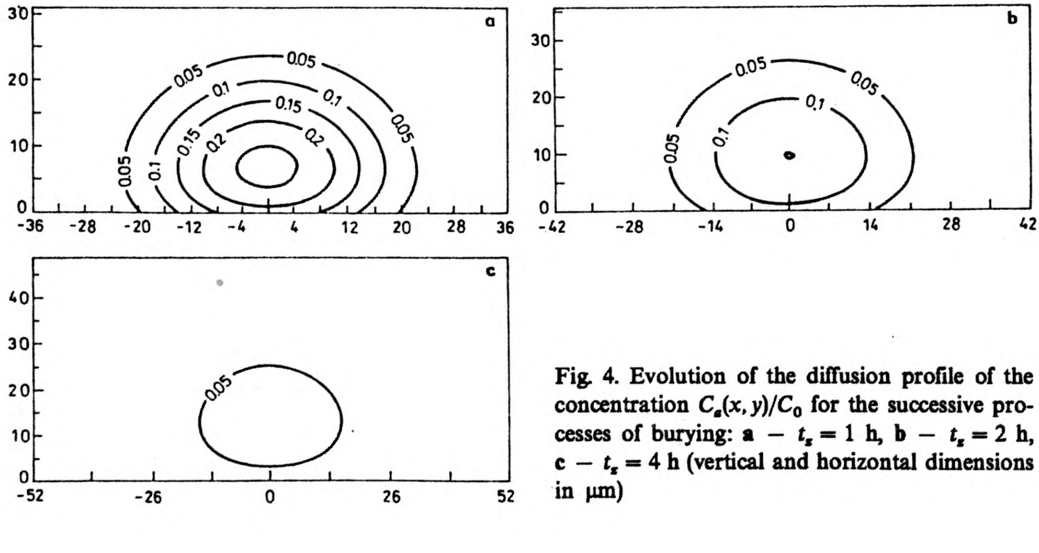


Fig. 4. Evolution of the diffusion profile of the concentration $C_a(x, y)/C_0$ for the successive processes of burying: **a** – $t_z = 1$ h, **b** – $t_z = 2$ h, **c** – $t_z = 4$ h (vertical and horizontal dimensions in μm)

waveguide structure, restricts the spatial dimensions of the buried profiles. The rate of the surface exchange s is decisive as far as the depth and the value of the distribution maximum are concerned.

The distribution functions presented in Fig. 3 were calculated for the technological parameters: $x_w = 1.7(D_a t_D)^{1/2}$, $s = 1$ μm/h, $t_D = 1$ h and different times of burying. An increase of the time of burying influences, in an essential way, both the value of the maximum and dimension of the distribution profile, while less – the separation of the maximum from the substrate surface.

The evolution of the diffusion profiles of the concentration ($m = 0.1$, $s = 1$ μm/h, $(D_a t_D)^{1/2} = 5.6$ μm, $x_w = 10$ μm) for the successive processes of burying is described in Fig. 4. In this way, it is possible to achieve index distribution profile close in its geometry to a circular one.

3. Experimental results

To verify the theoretical model, the process of two-stage diffusion $Ag^+ - Na^+$ into soda-lime glass has been carried out, including preliminary diffusion of Ag^+ ions from molten $AgNO_3$ ($t_D = 1$ h, temperature $T = 350$°C) through aluminium masks of different widths, and burying for $T = 350$°C and $t_z = 1$ h, 2 h, for Na^+ ions from molten $NaNO_3$.

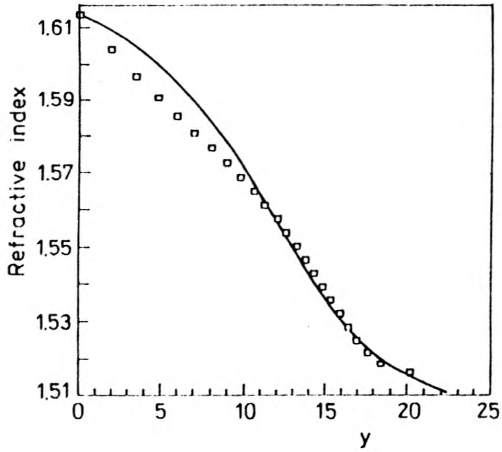


Fig. 5. Comparison of the theoretical planar profile (solid line) with the experimental results determined by IWKB method (□ – points), for $Ag^+ - Na^+$ ion exchange in soda-lime glass ($t_D = 1$ h, $T = 350$°C); y – profile depth (in μm)

The technological parameters of ion exchange – D_a, m and the maximum change of refractive index $dn_{\max}$ were determined on the basis of analysis of the respective planar waveguide profile. In Figure 5, a typical distribution of the refractive index determined by IWKB method is presented, for a planar waveguide obtained during the diffusion of Ag^+ ions ($t_D = 1$ h, $T = 350$°C). The experimental values were approximated by a theoretical curve which was a solution of one-dimensional equation of diffusion (1) with conditions (2). The best matching was obtained for the parameters of the process $D_a = 31$ μm²/h, $m = 0.1$, $dn_{\max} = 0.1$.

The refractive index distribution in the channel waveguide cross-section was determined by the shearing interferometry method [7]. The method requires sample preparation in a shape of a thin slice, cut off perpendicularly to the waveguide axis and polished on both sides. The sample thickness in the lightwave area was measured with an error less than 1%. An interference fringe pattern, defining a refractive index distribution, was registered by interferometer microscope "Biolar PI", set up on a uniform field interference [7].

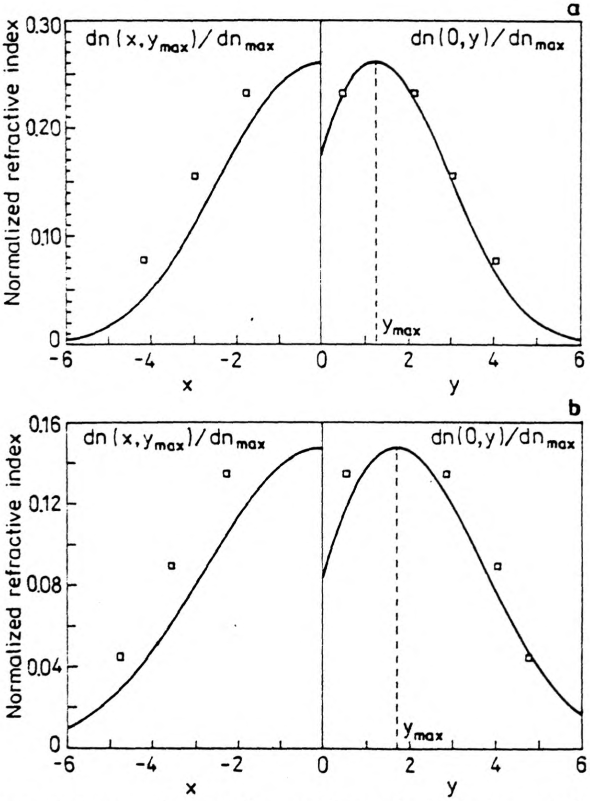


Fig. 6. Comparison of the experimental results (□ – points) with theoretical ones (solid line) for the normalized refractive index distribution parallel ($dn(x, y_{max})/dn_{max}$) and perpendicular $dn(0,y)/dn_{max}$) to the substrate surface (x, y in $(D_a t_D)^{1/2}$ units). **a** – $t_z = 1$ h, **b** – $t_z = 2$ h

A comparison of the typical experimental profiles of channel waveguides measured by the interferometric method with the theoretical results is presented in Fig. 6 **a**,**b**, for the distributions parallel $dn(x, y = y_{max})$ and perpendicular $dn(x = 0, y)$ to the surface of the substrate. The channel waveguides were made in the process of two-stage diffusion (preliminary diffusion $t_D = 1$ h, $T = 350°C$, the burying $t_z = 1$ h, 2 h, $T = 350°C$) through the window of the 10 μm width. The best fitting of both distribution curves was achieved for the rate of surface exchange $s \simeq 1$ μm/h. A certain broadening of the distribution profiles for the directions parallel to the substrate surface may be explained by the difference of the electrochemical potentials of the substituted ions Ag^+ and ions Al^+ forming the metallic mask [6]. The tangential component of the electric field, associated with this difference, accelerates the migration of Ag^+ ions along the surface and contributes to the widening of the distribution for the parallel directions. The substitution of the metallic mask by a dielectric one should limit this effect.

4. Effective indices of refraction

The analysis of the optical properties of the presented waveguide structures was based on the effective index method, developed in [8] for channel waveguides. Solving the integral equation, for x from the interval determined by the dimension of the channel waveguide

$$2k_0 \int_{y_{t_2}}^{y_{t_1}} [n^2(x,y)-(N^2_{\mathrm{eff}_n}(x)]^{1/2}dy = 2n\pi + \Phi_{y_{t_1}} + \Phi_{y_{t_2}}, \quad n = 0,\ 1,\ 2,\ \ldots \tag{4}$$

in which $n(x,y) = n_b + dn(x,y)$ is the distribution function of the refractive index in the substrate with the refractive index n_b, y_{t_1} and y_{t_2} are the turning points of the mode determined from the equation $n(x,y_t) = N_{\mathrm{eff}_n}(x)$, $\Phi_{y_{t_1}}$ and $\Phi_{y_{t_2}}$ describe the phase changes associated with the reflection from the waveguide boundaries at the turning points, k_0 is the wave number in the free space, we find the function $N_{\mathrm{eff}_n}(x)$ representing the effective index of refraction of the equivalent one-dimensional planar waveguide. The same method used again for the equivalent planar waveguide index distribution $N_{\mathrm{eff}_n}(x)$ determines the effective index $N_{\mathrm{eff}_{nm}}$ and the propagation constant β_{nm} of two-dimensional waveguide $N(x,y)$:

$$2k_0 \int_{-x_t}^{x_t} [N^2_{\mathrm{eff}_n}(x) - N^2_{\mathrm{eff}_{nm}}]^{1/2}dx = 2m\pi + \Phi_{x_{t_1}} + \Phi_{x_{t_2}}, \tag{5}$$

$$N_{\mathrm{eff}_n}(x_t) = N_{\mathrm{eff}_{nm}}, \quad \beta_{nm} = N_{\mathrm{eff}_{nm}} k_0, \quad m = 0,\ 1,\ \ldots\ .$$

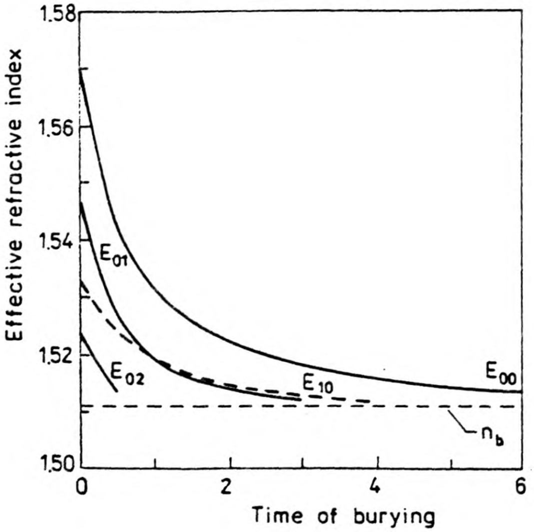


Fig. 7. Effective index of buried channel waveguide modes E_{nm} for the parameters of the technological process $(D_a t_D)^{1/2} = 0.8$ μm, $x_w = 4$ μm, $m = 0.1$, $s = 1$ μm/h in the function of the time of burying t_z, (t_z in t_D units)

Figure 7 presents the numerically calculated effective index of a few basic modes E_{nm}, guided in a channel waveguide obtained in the process with the parameters ($(D_a t_D)^{1/2} = 0.8$ μm, $x_w = 4$ μm, $m = 0.1$, $s = 1$ μm/h), in the function of the time of burying. An increase of the time of burying results in an increase of the dimension of the channel waveguide, but at the same time the maximum of the index distribution decreases. As illustrated by the numerical results, the latter factor is more essential and a decrease of the $N_{\mathrm{eff}_{nm}}$ value is observed. The effect described may be used for the optimization of the waveguide parameters.

5. Conclusions

In this paper, both theoretical analysis and experimental studies of the process of two-stage thermal diffusion including preliminary diffusion and burying were presented.

The theoretical model was based on a simple mechanism of surface ion exchange, described in the boundary conditions by a single parameter characterizing the rate of the exchange process and being a function of the kind of the substituted ions and the type of glass used.

The theoretical results were compared with the experimental ones analysing by interferometric methods the diffusion profiles of distribution of the refractive index, obtained during the two-stage exchange of $Ag^+ - Na^+$ ions in soda-lime glass. The conformity of the theory with the experiment should be considered to be good.

In further studies, the effect of the parameters of the technological process (time and temperature of preliminary diffusion and burying) on the effective index of some basic modes has been determined. The results obtained may find application both in the optimization of the optical properties of multimode buried channel waveguides, and in designing single mode structures.

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