Diffusion and Interface Effects during Manufacturing of Compact Microstructured Optical Fibers

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Compact Microstructured Optical Fibers (CMOFs) enable very flexible optical waveguide designs with high geometrical precision by stacking of various doped silica rods. The geometrical parameters (pitch to diameter ratio, core to pitch ratio) shift during sintering of the interstitial cavities of the initially imperfect filled preform. We modeled geometrical shift effects and compared it with manufacturing results. Additionally, refractive index modulating dopants, e.g. Germanium or Fluorine, can develop dissociative reactions. In that case gassing reactions are followed by undesired void formation during the thermal processing steps. The paper shows simulations of thermally treated Germanium and Fluorine doped silica rod arrangements. The model results were confirmed by dopant and void profile measurements of manufactured CMOFs. The investigated geometrical disturbances in stretched canes or drawn fibers emphasize the importance of a sufficient thick barrier layer. The minimal undoped silica barrier layer thicknesses of Germanium and Fluorine doped package rods are approximated to be about 12 µm and 40 µm, respectively, for a typical single drawing step procedure at 1900°C.

1 Introduction

Compact Microstructured Optical Fibers (CMOFs) show a better mechanical strength and atmospheric corrosion resistance compared with typical holey structured Photonic Crystal Fibers (PCFs). Moreover CMOFs allow easy splicing and coupling techniques. The light propagation in CMOFs is based on Total Internal Reflection (TIR) or Photonic Band Gap effect (PBG). The required modulation of refractive index (RI) structure is realized by defined arrangement of undoped and doped silica rods. Typical dopants are Germanium, Phosphorus to increase the RI, Fluorine and Boron for its depression. Diffusion effects change the dopant profiles during the preform preparation, e.g. Modified Chemical Vapor deposition (MCVD), Outside Vapor deposition (OVD). Also thermal sintering and collapsing procedures cause changes of the dopant profiles. Thermal dissociation and evaporation of dopant components decrease the effective dopant concentration. A typical example for the effect is the central dip in single and multimode fibers. In extreme case decreases the Germanium concentration in the preform center to zero by starting with maximum dopant concentration [1]. Otherwise the high pressure of evaporated species causes geometrical disturbances and voids during sintering procedure of packed rod arrangements.

2 Reactions and Diffusion approximation

Thermal procedures like stretching or drawing (typically between 1600°C and 2000°C) force the following dissociations:

Germanium dopants follow the reaction:

$$GeO_2 \leftrightarrow GeO\,(g)\uparrow + \tfrac{1}{2}O_2\uparrow \qquad (1)$$

Fluorine dopants leave the glass matrix by [2]:

$$4SiO_{1.5}F \leftrightarrow SiF_4\,(g)\uparrow + 3SiO_2 \qquad (2)$$

Figure 1 shows the calculated partial pressure of the evaporated species SiF_4 und GeO, starting with high silica glass matrices, doped with10 mol% GeO_2 (reaction 1) and 10 mol% $SiO_{1.5}F$ (reaction 2) [3]. At drawing temperature (about 1900°C) the dopants originate GeO or SiF_4 partial pressure in the percent range of atmospheric pressure by surface evaporation.

The dopant diffusion depends on geometrical, kinematical and thermal processing parameters as well as dopant concentration. The diffusion coefficient was approximated for GeO_2 doping to be about $10^{-10.5}$ cm²/s, for Fluorine doping to be about 10^{-9} cm²/s at drawing temperature of about 1900°C [4, 5].

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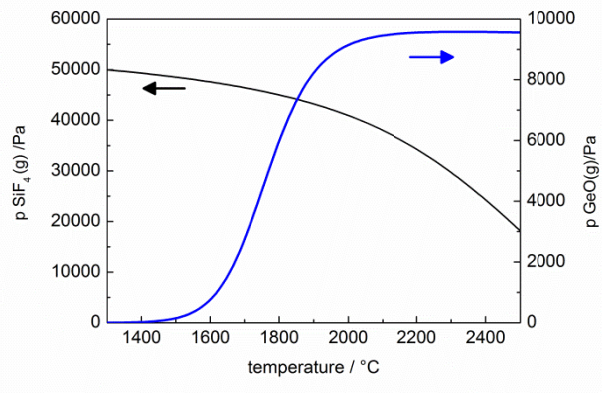

Figure 1 *Calculated partial pressure of SiF_4 and GeO depending from temperature according to reactions (1) and (2), [3]*

Figure 2 shows the resulting diffusion concentration profiles starting with a uniform dopant concentration of 10 mol%. The simulation assumes complete surface dopant evaporation. The process time is about 16 min, which is typical for drawing a microstructured preform with a diameter of about 20 mm.

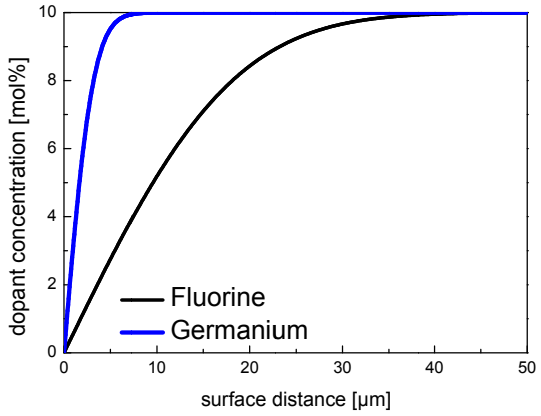

Figure 2 *Simulated diffusion profiles assuming complete surface evaporation of GeO_2 and SiF_4 for a typical single drawing step at 1900°C*

As a result it means, that a minimum undoped silica barrier layer of 12 µm (40 µm) is essential for stretching/drawing of Germanium (Fluorine) doped package rods. Figure 3 shows two samples of undesired dopant evaporation effects. The voids at the CMOF interfaces are caused by insufficient thickness of the SiO_2 barrier layer surrounding the Germanium and Fluorine packaging rods.

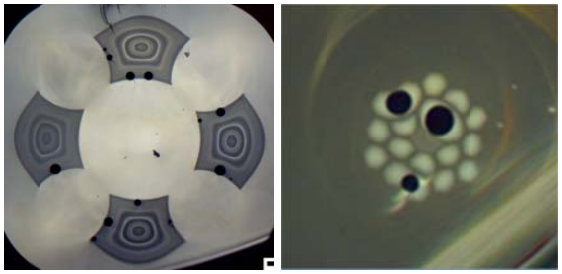

Figure 3 *Voids and bubbles (black areas) at interfaces of a Fluorine doped CMOF (left) and Germanium doped CMOF (right)*

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