Technology for photonic components in silica/silicon material structure

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Abstract

The main objectives of this thesis were to develop a low temperature PECVD process suitable for optoelectronic integration, and to optimize silica glass composition for UV-induced modifications of a refractive index in PECVD fabricated planar devices. The most important achievement is the successful development of a low temperature silica deposition, which for the first time makes it is possible to fabricate good quality low loss integrated components while keeping the temperature below 250°C during the entire fabrication process. Two strong absorption peaks that appear at 1.5 µm communication window due to N-H and Si-H bonds have been completely eliminated by process optimization. This opens possibilities for monolithic integration with other, temperature sensitive devices, such as semiconductor lasers and detectors, or polymer-based structures on the common silicon platform. PECVD technology for low loss amorphous silicon in application to SiO$_2$/Si based photonic crystal structures has been also optimized to remove hydrogen incorporated during the deposition process, responsible for the porosity of the deposited material and creation of similar to silica absorption bands.

Change of the refractive index of germanium doped silica under UV irradiation is commonly used for fabrication of UV induced fiber Bragg gratings. Here we describe our achievements in fabricating of fiber Bragg gratings and their application to distributed sensor systems. Recently we have built up a laser lab for UV treatment in application to planar technology. We have demonstrated the high photosensitivity of PECVD deposited Ge-doped glasses (not thermally annealed) even without hydrogen loading, leading to a record transmission suppression of 47dB in a Bragg grating photoinduced in a straight buried channel waveguide. We have also used a UV induced refractive index change to introduce other device modifications or functions, such as phase shift, wavelength trimming and control of polarization birefringence.

The developed low temperature technology and the UV processing form a unique technology platform for development of novel integrated functional devices for optical communication systems.

A substantial part of the thesis has been devoted to studying different plasma deposition parameters and their influence on the optical characteristics of fabricated waveguides to find the processing window giving the best trade-off between the deposition rate, chamber temperature during the process, optical losses and presence of absorption bands within the interesting wavelength range. The optimal conditions identified in this study are low pressure (300-400 mTorr), high dilution of silane in nitrous oxide and high total flow (2000 sccm), low frequency (380 KHz) RF source and high RF power levels (800-1000 W).

The thesis provides better understanding of the plasma reactions during the deposition process. RF Power is the key parameter for increasing the rate of surface processes so as to accommodate each atomic layer in the lowest energy state possible. All the process conditions which favor a more energetic ion bombardment (i.e. low pressure, low frequency and high power) improve the quality of the material, making it more dense and similar to thermal oxide, but after a certain point the positive trend with increasing power saturates. As the energy of the incoming ion increases, a competing effect sets in at the surface: ion induced damage and resputtering.

Finally, the developed technologies were applied for the fabrication of some test and new concept devices for optical communication systems including multimode interference (MMI)-based couplers/splitters, state-of-the-art arrayed waveguide grating-based multi/demultiplexers, the first Bragg grating assisted MMI-based add-drop multiplexer, as well as more research oriented devices such as a Mach-Zehnder switch based on silica poling and a Photonic Crystal-based coupler.

Keywords: silica-on-silicon technology, PECVD, plasma deposition, photonic integrated circuits, planar waveguide devices, UV Bragg gratings, photosensitivity, arrayed waveguide gratings, multimode interference couplers, add-drop multiplexers.
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B. L. Wosinski, R. Stubbe and M. Breidne "Distributed sensing with grating reflectors in optical fibers", invited talk on European Optical Society First Annual Meeting EOSAM-93, Zaragoza, Spain, July 6-9, 73 (1993).


**List of abbreviations**

1D - one dimensional (category of photonic crystals)
2D - two dimensional (category of photonic crystals)
AWG - arrayed waveguide grating
Bg - Bragg grating
BRW - Bragg reflection waveguide
CVD - chemical vapour deposition
DWDM - dense wavelength division multiplexing
e-beam - electron beam
ECR - electron cyclotron resonance
EDFA - erbium doped fiber amplifier
FHD - flame hydrolysis
FTIR - Fourier transform infra red (spectrometry)
HDP - high density plasma
ICP - inductively coupled plasma
LPCVD - low pressure chemical vapour deposition
MEMS - micro electro-mechanical system
MMI - multi mode interference
MZI - Mach – Zehnder interferometer
OADM - optical add-drop multiplexer
OSA - optical spectrum analyzer
PECVD - plasma enhanced chemical vapour deposition
PLC - planar lightwave circuit
RIE - reactive ion etching
RF - radio frequency
TDM - time division multiplexing
ULSI - ultra large scale of integration
UV - ultra violet
WDM - wavelength division multiplexing
1. Introduction

1.1. Background and general view

Research and development in the area of optical communication has experienced an enormous progress during the last decade and has generated the largest investments of international capital into the optical communication industry ever seen. The increasing demand for telecommunication capacity on the other hand is driving development of new integrated optoelectronic devices in research laboratories all over the world.

Fiberoptic communication, optoelectronic circuits, as well as optical sensors, operating at a speed of light, are paving the way for ever faster information transmission and processing. The evolution from single fiber point-to-point communication links towards wavelength division multiplexing (WDM)-based networks helps to meet the growing demands for capacity increase of the communication networks.

WDM technology relies on the fact that optical fibers can carry many wavelengths of light simultaneously without interaction between each wavelength. Thus, a single fiber can carry many separate wavelength signals or channels simultaneously. This capacity to wavelength multiplex signals in one fiber has led to the tremendous increase in bandwidth available to power the Internet around the globe.

Besides tuneable laser sources, several wavelength selective key products are required to make WDM possible. Wavelength multiplexers allow the insertion of all the separate wavelength laser signals to be combined into a single fiber. Arrayed waveguide grating (AWG)-based multiplexers are state-of-the-art devices, which combine the separate wavelength signals into one fiber. At the opposite end of the system from a transmission laser, a wavelength demultiplexer (which is a mirror image of the multiplexer) separates the signals into separate wavelength channels.

For the purpose of redundancy, reliability, capacity and cost efficiency, optical mesh and ring networks are now being built with the ability to route wavelength channels along multiple paths to get to their final destination. In order to accomplish this, products such as Optical Add/Drop Multiplexers (OADMs) allow the insertion or separation of one or more wavelengths from the many wavelengths in the fiber. This allows WDM systems to achieve the desired network topology. OADMs can be realized as Mach-Zehnder interferometers with selective filters based on thin film or Bragg grating technology.

Finally, optical switches that allow dynamic rerouting of separate wavelength channels are also necessary to realize fiber optical network with minimal optic-into-electric and electric-into-optic conversions of signals. These components are usually realized in MEMS (micro electro-mechanical systems) technology or thermally switchable waveguide integrated devices. For several years a lot of effort has been devoted to optical fiber technology to master the fabrication of single mode fibers with very low loss in the wavelength range of 1530 to 1570 nm. Nevertheless, long distance
communication links still demand signal amplification. Here an erbium doped fiber amplifier (EDFA) can be used. EDFA has the capability to amplify up to 100 wavelength channels identically every 100 kilometres in order to overcome the transmission loss in the optical fiber. Similar to fiber technology, the material used for the described functional devices should also be optimized for low optical losses. In order to develop these devices several advanced technologies have been invented and a number of cutting edge solutions have been proposed. The challenges involve bringing forward new methods of amplification, higher data transmission speeds, and smaller size, lower cost modules. All this may occur through the transition from hybrid products with discrete fibers, laser modules and functional chips to fully monolithic products that integrate these functions onto a common substrate. There are several material platforms under development for planar optical integration including III-V semiconductors, polymers and silicon. The silicon-based architectures are extremely flexible and support a modular building block design approach.

Silica-based planar lightwave circuits (PLCs) on a silicon platform will play a key role for fabrication of multifunctional devices for WDM network systems. Silica waveguides and waveguide devices will serve as communication paths between different elements on the platform as well as fill wavelength selective functions. Silica-on-silicon technology has shown the ability to keep high performance even for devices with high levels of integration, such as arrayed waveguide gratings. Some of the recently considered solutions for densely integrated PLCs are structures based on silicon/silica photonic crystals (PCs). Unique properties of photonic crystals not only offer drastic miniaturization and high degree integration but can also be utilized for enhancing device performance or adding new functions.

Imprinting of UV generated Bragg gratings in silica waveguides allows for building demultiplexers and add/drop filters and can also be used for external cavity lasers to stabilize output wavelength [1]. UV processing of silica-based integrated devices also includes post-fabrication phase adjustment and wavelength tuning [2], direct UV-writing of waveguides [3], birefringence compensation by UV illumination [4] and UV-assisted poling [5]. WDM communication networks based on multifunctional integrated systems are a major step toward fully optical networking.

Some of the mentioned devices, that in the near future can represent building blocks of these integrated systems, were realized by the author and will be described in the following parts of this work.

Although optical communication is a main driving force responsible for progress in integrated optical devices, technology for integrated optical sensors is following this progress and even developments made for sensing applications were found to be very important mile-steps in the field of communication. This was the case when side-written UV Bragg gratings, were developed by Meltz and Morey in 1989 [6]. During the following years the main effort in Bragg grating development was directed towards strain and temperature sensors and distributed sensor systems. It was also the main interest of the author at that time. The first applications of fiber Bragg gratings
for narrowband filters, gain control in EDFAs and line broadening compensation by chirped Bragg gratings appeared in 1993. In fiberoptic sensors, environmental changes alter the optical properties of a fiber, creating a signal that is sent back along the fiber to be analyzed or recorded. The two basic classes are extrinsic sensors, in which an external device impresses information of the fiber, and intrinsic ones, where the changes are generated directly within the fiber by the action of the environment. The last ones are mainly based on fiber Bragg gratings and will be described later on.

1.2. Objectives and motivation

Silica-on silicon and silicon-based integrated devices are key components for future all-optical communication networks. New challenging trends in the photonic integration are towards PLCs, based on silicon platforms for monolithic integration of passive dielectric components with semiconductor active photonic devices and electronic circuits. Recently demonstrated GaAs films grown on silicon bring up good perspectives for fabrication of III-V devices directly on silicon wafer. Another problem to solve is to make the subsequent deposition of silica passive components non-destructive for these temperature sensitive semiconductor structures. Existing deposition methods are usually high temperature ones or demand post processing annealing at high temperatures to obtain material with acceptable optical quality and low loss for optical communication wavelengths.

The aim of this thesis was to develop new technologies for fabrication of silica- and silicon-based components. In the beginning the work was focused on the development and optimization of the silica-on-silicon channel waveguides fabrication process based on PECVD (Plasma Enhanced Chemical Vapor Deposition) processing for deposition of thin films and ICP (Inductively Coupled Plasma) etching for channel formation. These two processing tools have been acquired and installed at the KTH-laboratory especially for development of silica-on-silicon technology and the author got responsibility for this research activity. The optimization of the technology generated some original solutions for low temperature processing \[\text{papers E - G}\] with completely eliminated absorption peaks due to N-H and Si-H bonds created during the deposition process. Several years of practice with “hands on” processing gave a better understanding of plasma deposition parameters and their influence on the optical quality of fabricated waveguides \[\text{papers K and L}\]. With these results we hope to solve one of the important problems in the research on monolithic integration of silica-based passive components with semiconductor ones.

UV-induced changes of the refractive index in Ge-doped material allow for adding new functionality to these components. In the first stage of the thesis we have developed and optimised methods for writing gratings in fibers for sensor applications. We have also designed and built a distributed sensor system for simultaneous strain and temperature measurements \[\text{papers A - D}\].

The aim of the recent part of this work was to adopt UV technique for development of planar grating assisted components. For that purpose a new
UV- laser laboratory was built up. The author’s knowledge and experience of the subject dated from the infancy of fiber Bragg gratings at early 90’s contributed considerably to this work. Bragg gratings acting as narrow band filters imprinted into the integrated planar components like multimode interference couplers open possibilities for creating novel compact wavelength selective devices such as add-drop multiplexers. The addressed in the thesis material photosensitivity issues and the realized UV-assisted devices are described in papers H, I and M. One of the thesis aims was also to develop low loss amorphous silicon in application to 1D and 2D photonic crystals in Si/SiO$_2$ materials. E-beam lithography and etching procedures have been also developed for realizing of these submicrometer structures. The recent results of this research in application to a new device, PC-based narrow band coupler are reported in paper J.

1.3. Structure of this thesis

The following sections (2 – 7) serve as a background to the work presented in this thesis. Section 2 describes and characterises different silica-on silicon technologies that are used for the fabrication of photonic devices. In section 3 PECVD technology is described in more detail. It also includes an analysis of plasma assisted deposition and the optimization of process parameters described in papers E - G, K and L. Section 4 provides a comprehensive description of the process steps for the fabrication of a simple buried channel waveguide. In section 5 UV-sensitivity of fibers and planar waveguides is described as well as Bragg gratings formation and other applications of refractive index change. This subject is considered in papers A - D, H, I, K - M. Section 6 presents examples of integrated devices fabricated with PECVD technology at KTH in the author’s lab for confirmation of material quality for photonic applications (papers E, F, I and J). The concluding remarks are presented in section 7. With sections 2 - 7 as a background, the research reported in this thesis is summarized in section 8.

1.4. References


2. Different silica-on-silicon technologies

A number of different technologies are used for the fabrication of silica-on-silicon integrated devices including flame hydrolysis, low pressure chemical vapour deposition, sputtering, ion exchange and ion implantation, sol-gel techniques and plasma enhanced chemical vapor deposition. These techniques will be shortly characterized below.

2.1. Flame hydrolysis

Flame hydrolysis (FHD) is mainly a technology for the fabrication of optical fiber preforms. It was adopted for the production of planar devices for optical communication in 1990 [1] and is now commonly used for the deposition of glass on silicon for integrated optical circuits such as star couplers, splitters, Mach-Zehnder interferometers and Arrayed waveguide gratings.

The first step of the process is to deposit two successive glass particle layers as the undercladding (called also buffer) and core on a Si substrate (alternatively one layer above a thermally oxidized silicon wafer) by the flame hydrolysis of SiCl$_4$. This process leads to the deposition of a “soot” of silica (SiO$_2$) that for the core layer can be doped by the inclusion of GeO$_2$, P$_2$O$_5$, and B$_2$O$_3$, all from their respective halide gases. After sintering of the soot at 1200-1350°C, glasses of different refractive indices can be obtained. The desired core ridges for the channel waveguides are then defined by photolithography followed by reactive ion etching. The obtained pattern is finally covered with an overcladding (top) layer in another FHD process. Deposition of sequential layers of silica with differing refractive indices leads to the microfabrication of buried optical waveguide structures.

The deposition is relatively fast (several $\mu$m/min), glass composition can be widely changed by co-deposition of different precursors, although this composition can be changed both physically and chemically during the consolidation process. The optical quality of the obtained film is very good and optical losses are very low.

2.2. Low pressure chemical vapor deposition

Low pressure chemical vapor deposition (LPCVD) is a traditional method for fabrication of silica dielectric layers in silicon microelectronic technology. Deposition is done on both sides of the wafer, which minimises wafer bowing. The Buffer and core layers can be deposited in a single step by changing the precursors after the buffer deposition is finished. The main precursors are silane and oxygen for the buffer layer and additional germane and/or other dopants for core layer. Alternatively, the buffer layer can be obtained by high pressure steam oxidation of the silicone substrate. In this process a large number of wafers can be processed simultaneously, but as the oxidation is limited by diffusion, the process is very slow and the layer thickness increases as the square root of time. A 15 $\mu$m thick layer can take over 50 hours of oxidation.
Deposition temperatures range from 400 to 800°C and post processing annealing in 900 – 1100°C for several hours is necessary to obtain a dense homogenous film. This method is also sensitive for particle contamination [2].

### 2.3. Sputtering

In sputtering deposition glass molecules can be sputtered from a target by means of electron or ion bombardment, as well as rf-power. In one of the earlier papers describing the formation of channel waveguides [3] the authors used RF power applied both to the substrate and to the target. This method (bias sputtering method) allows filling small trenches or gaps between the waveguides otherwise difficult to fill during sputtering. In conventional sputtering the sputtered glass is deposited upon the grooves, but the grooves remain unfilled since overhangs can easily close them up.

The glass composition is limited by the available targets. In order to obtain a core with a high refractive index, pure silica can be used as a target, since the refractive index of sputtered silica is higher than that of bulk material by about 0.5 percent. The refractive-index difference depends on the RF power applied. Typical sputtering rate is quite low, approximately 1 µm/h. Usually the deposited glass is of poor quality leading to high propagation loss of order 1 dB/cm.

### 2.4. Ion exchange

Ion exchange is a very old technique used in glass technology for more than a century. In 1972 it was used for the first time for the fabrication of ion-exchanged waveguides by the exchange of Ti⁺ ions in a silicate glass [4] and then became one of the more important techniques for the manufacturing of waveguides during the next 20 years. The physical phenomena responsible for the exchange process are diffusion and convection. The refractive index change is caused by three major physical changes: ionic polarizability, molar volume, and stresses created by the exchange of ions with different radii. The substrate is usually an optical glass containing alkaline oxides. The glass substrate is immersed in a dopant salt bath at elevated temperature, typically over 400°C. In most cases sodium ions in the substrate glass are exchanged for one of the cations: Cs⁺, Rb⁺, Li⁺, K⁺, Ag⁺ or Ti⁺. Also Cs⁺ and K⁺ exchange have been used for waveguide fabrication. Driven by the concentration gradient, dopant ions diffuse into the substrate. To preserve charge neutrality, glass metal cations diffuse out. The result is a glass composition locally modified to produce waveguides. The waveguide can be buried by applying an electric field. The ion-exchange process can be spatially controlled using a patterned mask with apertures. The fabrication is quite slow; several hours are needed for the exchange process to be ready. The waveguide profile is not well defined and it is difficult to model the process in order to obtain the demanded cross section. Propagation losses are not so high (0.5 – 0.6 dB/cm), but the refractive index change is limited to about 0.01 and so bending losses become an issue.


2.5. Ion implantation

Formation of low loss channel waveguides using Ge ion implantation was demonstrated in 1995 [5]. The substrate for ion implantation is usually fused silica or a deposited thick silica layer of about 20 µm thickness. Channel waveguides are formed by irradiation of the sample through a patterned mask with Ge, P or Si ions at an energy of 3 – 5 MeV and at a dose of $10^{12} - 10^{17}$ ions/cm$^2$. During implantation the substrate temperature is about -200°C to maximize the increase of the refractive index, which can raise 1 – 2 %. The as implanted waveguides exhibit losses of about 1 dB/cm, which can be considerably diminished to 0.1 – 0.2 dB/cm after a 1 hour annealing at 500°C. As in the case of ion exchange it is difficult to obtain the demanded cross section profile.

2.6. Sol-gel techniques

The main fabrication steps of the sol-gel technique are a hydrolysis in which a precursor is reacted with water and then a condensation step, which turns the initial chemical solution into a sol, that after solvent evaporation become a viscous liquid and finally a gel that is transformed into a glass by suitable manipulations. In the first step the substrate is covered by a sol-gel film by means of dip coating, spin coating, electrophoresis or thermophoresis. Up to 30 layers, 200 nm each are deposited in sequence to obtain a necessary thickness. After the deposition of each individual gel film, it is necessary to densify it before the next deposition in order to avoid cracking and to obtain a dense glassy material. A high temperature of about 900°C for 5 min is used in each step to homogenize the material and diminish scattering losses. The method was developed in 1993 [6] and the obtained losses were about 1 dB/cm. The main problem was the tendency of even thin silica films to crack when deposited on Si substrate. Later on some modifications have been introduced giving a certain degree of loss reduction as well as more stable layers. Generally the technique is quite slow and the number of dopants is limited which limits a large index change.

2.7. Plasma enhanced chemical vapor deposition

Plasma enhanced CVD has largely replaced LPCVD for SiO$_2$ and other film depositions because it provides higher deposition rates and step coverage, is less prone to particle contamination and has a number of other advantages that make it one of the most important technologies for the deposition of amorphous thin films. Initiation of chemical processes with the help of electric discharge producing ions and radical species was known for a long time. In 1963 Atl et al. [7] showed that the plasma- enhanced CVD process could be used for
microelectronic applications. The method was primarily used for diffusion masks and passivation. More common applications of this process for microelectronic fabrication started with the introduction of commercial processing equipment in 1974. In recent years, new material demands and lower-processing-temperature requirements in ULSI circuits, solar energy cells, flat-panel displays, and optoelectronic integrated systems have made plasma-enhanced deposition processes increasingly important. One of the major advantages of plasma deposition processing for optical integration besides it’s high deposition rate is it’s flexibility for depositing films with desirable properties. Films with unique composition and given physical and chemical properties can be obtained by adjusting deposition parameters such as temperature, rf power, pressure, precursors gas mixture and their ratio. Although the deposition is at relatively low temperatures, to achieve low loss material high temperature annealing is commonly applied. Mechanically and chemically stable thick films can be deposited and easily formed into channel waveguides and waveguide components by plasma etching. The deposition rates can be in the range of 0.15 – 0.3 µm/min and the optical quality of the obtained films is usually very good giving optical losses of 0.1 dB/cm and below.

2.8. References


3. PECVD technology for Si/SiO\(_2\) photonic integrated devices

For optoelectronic application and silica-on-silicon waveguide formation the deposition rate and optical quality of the deposited films are of critical importance. Typical thicknesses of the deposited films are much larger than in microelectronics. For channel waveguides three layers of a total thickness of 30 \(\mu\)m are usually deposited. The films should be homogeneous, with uniform thickness and refractive index over the deposition area and have very good transmission for the optical communication wavelengths 1.3 – 1.6 \(\mu\)m. It should be also possible to add dopants to change the refractive index and/or some other parameters such as UV photosensitivity, melting temperature, introducing active ions and other species.

3.1. PECVD deposition mechanisms

Instead of using thermal energy to generate the species that subsequently react and deposit on substrate surfaces, as in the case of LPCVD, the plasma energy supplied by an external rf source in the form of an electric or magnetic field accelerates the electrons and ions in the reaction chamber for the generation of these reacting species. As the plasma reactions are very complex and dependent on many parameters and variables, the whole plasma process is still not fully understood. The fabrication is often established on an empirical basis and then further optimisation of the process can be based on models developed due to analysis and understanding of the empirical data. A set of reactions has been found that helps to understand the process of chemical dissociation of molecules and surface reactions leading to the building of stable layers [1]. There are different gas phase precursors containing silicon and oxygen that are in different PECVD systems used to deposit SiO\(_2\). The silicon precursors can be SiH\(_4\), SiCl\(_4\), SiF\(_4\), and the organometallic TEOS, which diminishes cusping and fills the gaps better because of the higher surface mobility of the reactants. The oxygen precursors are O\(_2\), N\(_2\)O, CO\(_2\), and other oxygen containing gases. Depending on the chosen precursors the gas delivery system can be different because many of the hydrides react with oxygen at room temperature and must be delivered separately to the gas chamber to avoid spontaneous reactions and massive particle formation. Most common PECVD reactors are based on SiH\(_4\) and N\(_2\)O chemistry that allows a common mix gas inlet to the chamber and the best uniformity of the deposited layers.

The basic reaction for the formation of the silica in this case can be written as follows:

\[
\text{SiH}_4 \text{ (gas)} + 4\text{N}_2\text{O} \text{ (gas)} \Rightarrow \text{SiO}_2 \text{ (solid)} + 2\text{H}_2\text{O} \text{ (gas)} + 4\text{N}_2 \text{ (gas)}
\]

and is based on the oxidation of silane by molecular (or atomic) oxygen produced by electron collision dissociation of N\(_2\)O (paper K). The process starts with the primary initial electron-impact reactions between electron and reactant gases to form ions and radical reactive species. Ions
and electrons are accelerated and collide with other particles generating more and more excited species. During the transport of these species towards the substrate many elastic and inelastic collisions occur, which contribute to the generation of new ions and radicals. In the next phase absorption and surface reactions of the reactive species take place [2]. Species with higher mobility can migrate on the surface to the positions of lower energy. Less mobile ones stay at the position, they arrived contributing to the deposited material defects. The reactive species and reaction products can be incorporated into the deposited films or re-emitted from surface back to the gas phase. Ion bombardment plays a significant role in this process [3]. Surface reactions critically affect film properties such as density, stress, defects and impurity incorporation. Ion bombardment can modify these characteristics as well as contribute to gap-filling and surface planarization.

### 3.2. Overview of different PECVD techniques.

This classification depends on the type of power supply and the method of power source coupling to the reaction chamber. The coupling can use electrodes within the chamber or outside of it and can be capacitive, inductive or antenna type. Traditional parallel-plate plasma reactors are well established. In this configuration an rf power in the range of kW is used at radio frequencies, typically low frequency at 380 KHz and/or high frequency at 13.56 MHz. High-density-plasma (HDP) reactors are designed so that the plasma electrons are excited in a direction parallel to the reactor boundaries. In an inductively coupled plasma (ICP) reactor, the plasma is driven by a magnetic potential set up by a coil wound outside the dielectric walls. Electron cyclotron resonance (ECR) and helicon sources can also be used in HDP reactors to couple electromagnetic fields into the plasma. In ECR PECVD [4] the plasma is created by superposing a static magnetic field and a microwave radiation of 2.45 GHz in a chamber with the precursor gases. When the cyclotronic frequency of the electrons is equal to 2.45 GHz, the resonance condition is satisfied and the electrons absorb more efficiently energy from the microwave source. Consequently, the plasma is much denser than when rf-plasma is used. The method is used to obtain very dense hydrogen free layers, but deposition rates are in the order of some nm/min. When using a helicon source [5] the microwave oscillations are coupled inductively to the plasma with the help of a near field antenna to generate the travelling helicon wave. HDP CVD processing usually includes simultaneous deposition and etching due to argon sputtering. The ratio of the deposition and sputtering rates (D/S) determines the gap-fill capability of the process. If the ratio is too small, corners of the features to be filled can be sputtered off (this is normally referred to as “corner clipping”). If the ratio is too large, voids or weak seams can form. The three principal mechanisms are ion-assisted plasma deposition, argon sputtering, and redeposition of the sputtered material.
3.3. PECVD technology at KTH

3.3.1. Description of the system

The PECVD system used at KTH is a conventional parallel plate reactor (see figure 3.1.) with SiH$_4$ and N$_2$O as the main precursors for the deposition of undoped and doped silica layers. Doping is used to control the refractive index difference between the core and the cladding of fabricated waveguides. The gas mixture is introduced into the chamber through a showerhead to obtain good uniformity in the deposited material. Two different RF frequencies, LF at 380 KHz and/or HF at 13.56 MHz can be applied by capacitive coupling to the top or bottom electrode. A standard 4” (100) silicon wafer is placed on the bottom electrode, which can be temperature stabilized in the range from 200°C up to 350°C.

![PECVD parallel plate plasma reactor with capacitive coupling of rf power.](image)

The waveguide fabrication starts with the deposition of a 12 µm thick silica buffer layer using a SiH$_4$ : N$_2$O (≈1:100) gas mixture, pressure of 300 - 400 mT and LF power up to 1000 W applied to the top electrode. In these conditions the deposition rate is typically in the range of 1600 - 1800 Å per minute, and is very much dependent on the silane flow rate. The subsequent deposition of the core layer of 6 – 8 µm is done by adding GeH$_4$ and/or other dopant precursors into the gas mixture. Doping materials can be incorporated into the core or buffer and cladding layers in order to control the optical and physical properties of the material. Germanium not only increases the refractive index of the core, but also makes the waveguide UV sensitive for devices with UV induced refractive index change. Boron increases the photosensitivity, additionally, but it decreases the refractive index. Phosphorus and boron decrease the melting temperature of the glass and are used when the reflow [6] process is necessary. Thermal reflow (annealing at temperatures close to the melting point of the material) is sometimes used for improving waveguide quality by diminishing defects in the material, smoothing waveguide boundaries after etching, and modifying core cross-sectional shape.
3.3.2. Optimization of the silica deposition process

In the PECVD process, the precursors used and the deposition parameters strongly influence the optical properties and quality of the deposited films giving a large flexibility in the fabrication of integrated devices. Unfortunately, the as deposited PECVD films usually exhibit two strong absorption bands in the optical communication window at a wavelength range of 1.3 – 1.6 µm. The band at 1.38 µm is associated with the well known (from optical fibers) O-H bonds. The other band near 1.5 µm is associated with N-H and Si-H bonds having vibrational absorption bands at 1.48 µm and 1.51 µm respectively. The deposition method and the precursors containing nitrogen, hydrogen and oxygen were considered to be responsible for these absorption peaks and the commonly used method to improve the optical quality of deposited films was post deposition annealing at around 1000 °C [7-9]. In high-plasma-density systems like ICP, ECR, Helicon and hollow cathode deposition system N-H absorption is usually eliminated by using of oxygen instead nitrous oxide [9].

Improvement of this standard technology has been made (paper E) followed by a more systematic study of the deposition conditions (paper F), which resulted in the development of low temperature fabrication of the silica-on-silicon material with completely eliminated absorption peaks at 1.5 µm with no need of annealing (paper G). The most important guidelines for this optimized process are as follows (papers K and L):

- Use of low pressure (300-400 mTorr), high dilution of silane in nitrous oxide (ratio \( \approx 1:100 \)) and high total flow (2000 sccm)
- Use of low frequency (380 KHz) of the RF source
- Use of high RF power levels (800-1000 W).

Following these criteria we have fabricated straight buried channel waveguides to test the optical quality of our thick films. The final result, shown in figure 3.2, confirms that a flat loss spectrum can be obtained in the

![Figure 3.2. Transmission and loss spectra for as deposited channel waveguides. a): before introduced improvements and b): improved processing. Lower curves: waveguide transmission spectrum; middle curves: fiber-to-fiber reference transmission; upper curves: waveguide insertion loss. Loss values of a non-annealed 2 cm long waveguide including propagation and coupling losses are given on the right vertical scale. The loss spectrum b) does not show any absorption peaks related to N-H or Si-H bonds at 1.48 µm or 1.51 µm.](image-url)
wavelength range from 1.48 \textmu m to 1.55 \textmu m, without any localized absorption due to presence of Si-H or N-H bonds. This has been achieved without any high temperature consolidation step. Figure 3.3 shows a comparison between cross sections of straight waveguides fabricated with standard and improved processing parameters, taken from an optical microscope with back illumination. The air gaps (seams) appearing during the deposition of the overcladding due to the shadowing effect, that usually are removed by thermal reflow (1000\degree C), could be avoided by high energy ion bombardment and resputtering (paper K).

![Figure 3.3. The evolution of the waveguide quality from standard to improved processing (paper K).](image)

In the first period of the work during the running-in of the PECVD tool a lot of effort was devoted to reduce film particulates, improve film uniformity, and eliminate “shower-head pattern” that in some uncontrollable way appeared on the wafer. The experience gathered during those hundreds of hours of work on the “clean room floor” resulted later in fast troubleshooting and elimination of malfunctions of the system and bad quality of the processing results.  For fabrication of the devices with very close situated waveguides as in the case of 3 dB couplers, the gap filling process is an important issue. In this case the amount of deposition on the sidewalls and bottom of the gap is less than on the top of the feature leading to closing of the gaps and leaving air pockets within the gap as seen in figure 3.4.a. In order to avoid this effect the PECVD deposition is used in conjunction with an argon sputter etch in a multistep PECVD high energy processing similarly to the processing in high density plasma reactors (see §3.2). In figure 3.4.b the result of high ion bombardment and sputter etch is seen. The air pocket has been successfully removed, but too high of a sputter/deposition (S/D) ratio can lead to corner clipping of the waveguide core. The (S/D) ratio should be optimised. This same process can be also used for the planarization of the top surface, when the (S/D) ratio is appropriately chosen, as seen in figure 3.4.c and d.

The development of the fully low temperature processing of silica waveguides and components on silicon platforms opens new possibilities for the fabrication of novel monolithic integrated structures with temperature sensitive active devices and electronic circuits.
3.3.3. Deposition of amorphous silicon

Fabrication of photonic crystal structures and devices based on SiO$_2$/Si technology can be provided with Plasma Enhanced Chemical Vapor Deposition (PECVD) and subsequent Reactive Ion Etching (RIE) as the main processing steps.

Amorphous silicon deposited in low temperatures by sputtering or evaporation, has poor optical qualities, due to the high density of localized states in the mobility bandgap, originated from either strained or dangling bonds in the silicon network. In PECVD deposition, when using silane as the gaseous precursor the incorporation of hydrogen atoms in the film saturates the silicon dangling bonds and waveguide losses as low as 0.7 dB/cm have been obtained at 1.3 µm and at 1.55 µm with this method [10]. However, the incorporation of a significant amount of hydrogen makes the material less stable due to porosity and creates the similar to silica absorption at 1.51 µm.

With respect to these two aspects, the parameters of the deposition process and of the subsequent thermal treatments must be carefully optimized as too high annealing temperature causes material crystallization and increases losses again due to scattering.

In the preliminary studies the samples were annealed in a nitrogen atmosphere and subsequently monitored with FTIR spectrometry (to study the...
hydrogen effusion), X-ray diffractometry (to detect the onset of crystallization), and by measuring the refractive index (to estimate the density increase). The preliminary results showed that after a 3h annealing at 550°C the absorption peak related to the Si-H stretching vibration bond at 1.51 µm became undetectable in 0.5 µm thick films and no crystallisation was revealed by the X-ray measurement. Optical losses of the fabricated waveguides were about 2 dB/cm.

3.4. References

4. Description of the fabrication process

In this chapter the fabrication process of a simple buried channel waveguide is described.

Fabrication starts with the deposition of two thick layers of SiO$_2$ and Ge-doped SiO$_2$ for undercladding (buffer) and core, respectively. The exact thickness of the layers is controlled by programming the time of the deposition process. After each 6µm deposition the process is stopped and the “etch back” of the chamber is provided to remove the deposited material from the electrodes and chamber walls. Nevertheless the deposition rate can be slightly different depending on the chamber condition. That means the amount of remaining films covering the chamber walls from previous depositions counted from the last mechanical cleaning of the chamber. Therefore testing of the deposition rate is usually carried out prior to the deposition. A 1µm thick test film is deposited with the same parameters as for the main process. Then the thickness is measured with help of the interferometric microscope or the prism coupler system that allows very accurate measurements of thickness and refractive index of deposited films. This same system is used for exact tuning of the GeH$_4$ flow during the deposition of the core layer to obtain the required refractive index difference between the core and the cladding of the device.

The processing flow looks as follows:

1. Programming of the PECVD sequential processing:
   - SiO$_2$ deposition: gases flow (N$_2$O and SiH$_4$), rf power, chamber pressure, chamber temperature and time (see Table I),
   - oxygen plasma etch back;
   - SiO$_2$ second deposition,
   - oxygen plasma etch back,
   - Ge/SiO$_2$ deposition: gases flow, rf power, chamber pressure, chamber temperature, time.

2. Test deposition, thickness measurement, deposition rate calculation:
   - test deposition is done on a dummy wafer,
   - thickness measurements (for deposition rate calculations) are done using interferometric microscope.

3. Sequential deposition of 12 µm buffer and 6 µm core layers.

4. Backside deposition (10-12 µm) to diminish wafer bow due to temperature introduced strain.

5. Metallization – 1µm thick metal (Si) layer deposition for mask.

6. Spin coating of photoresist, baking
   - $1^{st}$ bake 120-150$^\circ$C for 15-30min,
   - HMDS furnace 20 min,
   - Spin of the photoresist SJR 5440 (~6µm), 400 RMP, 15 sec followed by RMP 2000, 30 sec,
   - Soft baked ~105$^\circ$C for 1min,
   - Final bake 85-90$^\circ$C for 30 min.

7. Preparing of the mask (cleaning with Acetone) and lithographic tool (control and adjustment of the illumination intensity, mounting of mask).

8. Exposure of the mask pattern onto the wafer. Exposure conditions: power density 20-35 mW/cm$^2$, time of exposure 25-35 sec.
8. Development of the photoresist followed by control of the pattern under the microscope and baking:
  - developing conditions: developer 2401, diluted with water 1:5, developing time 2-5min,
  - pre-wash in bubler for 5min and then centrifugal.
9. Etching of the metal mask and repeated control of the pattern. Before etching, baking of the samples at 110°C for 30min.
10. Removing of the remaining photoresist in oxygen plasma, cleaning:
  - time of the oxygen plasma run is to be found experimentally each time,
  - clean in 7-up mix (H_2SO_4:H_2O_2 with proportion 1:5) for 15-20min,
  - pre-wash in bubler for 5min and then centrifugal.
11. Programming of the ICP (inductively coupled plasma) etching tool (Ar, CH_4 and C_4F_8 gas flow, coil rf power, platen rf power, chamber pressure, chamber temperature and time (see Table II).
12. ICP etching of the 6 µm core layer followed by etching depth control with a stylus profilometer.
13. Metal wet chemical clean followed by several steps of wafer cleaning.
14. Sequential deposition of 12 µm top cladding layer of SiO_2.
15. Wafer cleaving and characterization. A test part of the wafer containing straight waveguides is mounted on the xyz table and but-coupled to the in- and out fibers connected to the light source and optical spectrum analyzer (OSA), respectively. HeNe laser is used for aligning. The broadband spectrum with help of a white light source is taken to check the absorption at 1.4 and 1.5 µm and waveguide loss at dedicated wavelength is measured with help of a tunable laser and OSA. A strip of wafer with short, some millimeter long waveguides is used to visualize the cores profile in a cross section using optical microscope with back illumination.

Table I. Process parameters used for deposition of the SiO_2 films.

<table>
<thead>
<tr>
<th>Substrate Temperature</th>
<th>200 - 350 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF Power @ 380 KHz</td>
<td>200 - 1000 W</td>
</tr>
<tr>
<td>Pressure</td>
<td>300 - 900 mT</td>
</tr>
<tr>
<td>Process gases</td>
<td>SiH_4, N_2O, GeH_4</td>
</tr>
<tr>
<td>Deposition rate</td>
<td>1000 - 6000 Å/min</td>
</tr>
<tr>
<td>N_2O flow</td>
<td>1000-2000 sccm</td>
</tr>
<tr>
<td>SiH_4 flow</td>
<td>10-40 sccm</td>
</tr>
<tr>
<td>GeH_4 flow</td>
<td>1-3 sccm</td>
</tr>
<tr>
<td>SiH_4 : N_2O ratio</td>
<td>1:15 – 1:100</td>
</tr>
</tbody>
</table>
Table II. *Standard ICP etching process parameters for SiO₂ films.*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF Power @ 13.56 MHz (Platen/Coil)</td>
<td>200 / 800-1000 W</td>
</tr>
<tr>
<td>Pressure</td>
<td>&lt; 6 mT</td>
</tr>
<tr>
<td>Gases</td>
<td>C₄F₈, CH₄, Ar</td>
</tr>
<tr>
<td>Etch rate</td>
<td>&gt; 2300 Å/min (with Ar &gt; 1700 Å/min)</td>
</tr>
<tr>
<td>Selectivity to the silicon mask</td>
<td>10:1</td>
</tr>
</tbody>
</table>

With the described processing sequence, the waveguide core has final dimensions of 6 x 6 µm to 8 x 8 µm with a quasi-rectangular cross section and a relative refractive index difference between the core and the cladding of 0.7 to 0.3 %.
5. UV induced Bragg gratings and photosensitivity

5.1. Background

Bragg gratings with periodic modulation of the refractive index along the light guiding media were discovered in 1978 by Hill and co-workers in germanosilica optical fibers using illumination by an Ar-ion laser at 488 nm [1]. Photosensitivity of this material – the ability of changing refractive index due to the influence of light - was associated with the presence of GeO$_2$. The absorption band located near 240 nm is known as the effect of oxygen deficiency in the GeO$_2$ - SiO$_2$ matrix [2].

In Hill’s experiment the absorption of the 488 nm light occurred due to a two photon absorption process and a Bragg grating was created due to interference of two counter propagating beams. This induced a periodic index change in the core of the fiber. This method was not very versatile because of limited wavelength tunability as the grating period was only dependent on the laser wavelength.

The use of UV-light at 244 nm was much more effective and the method proposed 1989 by Meltz et al. [3] based on transverse holographic projection allowed to write gratings with any period by changing the angle between interfering beams:

$$\theta = \frac{\lambda_w}{2\sin \phi},$$

(1)

where $\lambda_w$ is the writing light wavelength, $2\phi$ is the angle between writing beams and $\Lambda$ is the written grating period. Such gratings can be used as wavelength selective filters or mirrors imprinted directly in the fiber core. The reflected wavelength from such a grating is given by a Bragg condition:

$$\lambda_B = 2n\Lambda,$$

(2)

where $n$ is the effective refractive index of the core.

The filter’s spectral full-width half-maximum is given by:

$$\Delta\lambda = \lambda_B s \sqrt{\left(\frac{\Delta n}{2n}\right)^2 + \left(\frac{1}{N}\right)^2},$$

(3)

and peak reflectivity:

$$R = \tanh^2 \left(\frac{\pi \Delta n L}{\lambda - \eta}\right),$$

(4)

where $\Delta n$ is the index modulation, $N$ is the number of fringes, $s$ is a factor that changes between 0.5 and 1 for weak to strong gratings, $\eta$ is the mode overlap (typically equal 0.8 – 0.9) and $L$ is length of the grating.

Using these four equations and having the possibility to adjust the refractive index modulation, angle between interfering beams and length of the grating...
one can fabricate an optical filter or wavelength selective mirror adjusted to any desired wavelength of optical signal and necessary filter rejection. To then obtain a specific spectral profile of the filter (especially to suppress sidelobes) one also needs to calculate the grating apodization function, an appropriate distribution of the index change along the grating.

The experiment of Meltz and co-workers was a starting point for a dynamically grown research area of fiber Bragg gratings and later, waveguide gratings and related components. In the beginning the main application of fiber Bragg gratings was oriented towards sensors and sensor systems. Later on, at the beginning of 1993 telecom application took over the main direction of development. Many aspects of UV-induced gratings have been considered during the last decade including different grating writing methods, understanding of photosensitivity mechanisms, methods for increasing the photosensitivity in different materials as well as design of different grating types, apodizations and finally different applications.

5.2. Fiber Bragg gratings for sensor applications

As mentioned earlier, the development of side-written Bragg gratings (Meltz et al., 1989) was done with the intention to implement them in quasi-distributed measurements of temperature and strain. The proposed application was not described in detail in their paper [3], but the idea was either to monitor the shift in the Bragg wavelength of the sensing regions (each sensor adjusted to a distinct wavelength) or by forming independent Fabry-Perot cavities, each consisting of a pair of gratings. In the first case the shift of wavelength was due to the change of refractive index (see eq. 1) with temperature or induced strain whereas in the second one a shift of the Fabry-Perot fringes was observed. At that time the author was employed at the Institute of Optical Research (today ACREO), responsible for the project group dealing with distributed sensor systems for application to “smart structures”. Already in 1992 the author with co-workers proposed one of the first complex solutions for the absolute and independent measurement of strain and temperature in a distributed sensor system based on time division multiplexing of in-line coupled Fabry-Perot interferometers with fiber Bragg gratings used as weak reflectors (paper A). Next year the group was the first in Sweden and one of the ten first in the world to start to fabricate UV-imprinted Bragg gratings, from the beginning with phase mask, later on with the interferometric method (papers B and C). In 1994 the proposed earlier distributed sensor system was built and tested (paper D). One of the interesting outputs from this research was the observation that during the illumination the growing grating was simultaneously moving towards the longer wavelengths, which indicated that the mean refractive index in the core in the grating area increased. This shift was used for estimation of how large of a change in refractive index could be obtained by illumination of different core materials and with different light sources.
Today, in many civil structures like bridges, tunnels and dams, embedded fiber optic sensor systems based on similar solutions are used for monitoring deformations and displacements of concrete and steel constructions [4]. In the Emosson Dam situated in the Swiss Alps (figure 5.1) two sensors, 39m long and 29 m long were installed side by side with traditional extensometers. The measurement of sensors were regularly (monthly) performed over two years and compared with measurements carried out with neighbour extensometers showing high accuracy of displacement measurements of the dam.

Another example is a new Årsta railway Bridge in Stockholm. The bridge will span Stockholm’s Årstaviken bay, with a length of 833 meters. 46 sensors will be embedded starting January 2003. The aim of the monitoring is the comparison of the measurement results with theoretical hypotheses, control of the bridge behaviour during construction, testing period and life span, to verify the uncertainties of bridge design and to increase know-how for future projects which will integrate monitoring in bridge design.

5.3. Photosensitivity of fibers and planar waveguides

Before starting the discussion on photosensitivity of germanosilica glass components it is necessary to explain the classification of UV imprinted gratings into three main groups:
- type I gratings, the most common and historically the first type of gratings fabricated by side illumination [3], characterized by a close to symmetrical reflection curve and a positive change of the refractive index, during exposition grows monolithically until reaches saturation, temperature stable up to 300-400°C.
- type II gratings, written usually by one or few strong laser pulses [5], “damage” gratings, written as periodic mechanical relief in the material, often

![Figure 5.1. View of the Emosson shell dam in the Swiss Alps](image-url)
at the interface, high losses at the short wavelength side of the grating profile, written even in Ge free material, temperature stable up to 800°C. - type IIa gratings, written by slightly higher pulse energies as type I gratings, the growing process consists of two steps, the first similar to type I gratings, then this grating decreases followed by growing of the negative grating (decrease of the refractive index with UV illumination)[6], temperature stable up to 500°C.

Initially, photosensitivity was attributed to the presence of GeO₂ in the glass matrix. Although later investigations showed that even in germanium free fibers the photosensitivity was observed. The following discussion will be limited to germanium-doped material, as it remains the most important one for the fabrication of fiber and waveguide devices. The magnitude of the refractive index change depends on the irradiation conditions (including laser wavelength, light intensity, accumulated energy dose and quality of interference pattern), irradiated material composition (mainly Ge content and possibly co-dopants) and preparation of the material prior to UV-irradiation. There exist a large number of different laser sources used in the UV-imprinting of Bragg gratings. Most commonly used are excimer ArF laser with pulsed irradiation at 193 nm, excimer KrF laser with 248 nm pulses and CW frequency doubled Ar ion laser generating light at 244 nm. Each of them has different characteristics and affect the material in a different way. Excimer lasers, for example, have a much shorter coherence length in comparison to frequency doubled argon laser and so are not suitable for interferometric arrangement that usually gives the best fringe contrast and possibility for simple wavelength tuning. On the other hand they are much stronger and can serve for introducing structural changes in materials. For preparation of the material to increase its photosensitivity, technologies such as hydrogen loading [7], flame brushing [8] and UV presensitization [9] have been proposed.

UV induced refractive index changes in germanosilicates are still not fully understood. Three main mechanisms that have been suggested by different research groups to explain the phenomena responsible for refractive index change in germanosilicate fiber cores due to UV illumination are: color-center model, stress-relief or structural relaxation model and densification or compaction model. The following short explanation will serve as a background for the further discussion on the photosensitivity of planar devices. More information about these phenomena in fibers can be found in the revue article of B. Poumellec et. al. [10] as well as in ref. 6, 11 and 12.

5.3.1. Color center model

In the color center model photosensitivity is associated with absorption band at around 242 nm, arising from germanium-related oxygen-deficient centers. The band was observed to bleach when illuminated with 242 nm light with simultaneous increasing of the absorption at shorter wavelengths at around 195 nm (absorption band of a GeE’ color center) [13, 14]. A UV absorption spectra before and after 242 nm illumination of Ge doped single mode fiber with 8 mol% germania, given in [13] is shown in figure 5.2.
It was found that through the Kramers-Kroning relation this absorption change and creation of the Ge$E'$ centers are responsible for the refractive index increase [15, 16]. This was confirmed later on by observation that the fluence dependence of the photoinduced Ge$E'$ center, its thermal annealing behaviour, and its reaction with H$_2$ are similar to that of the index modulation generated in both, H$_2$-loaded and unloaded germanosilicate fibers [15]. Simultaneously it was found that the much higher photosensitivity of H$_2$-loaded Ge-SiO$_2$ fibers is attributed to the much higher formation efficiency of Ge$E'$ centers. This statement is very important in understanding the reasons why the deposited core material fabricated by the author is much more photosensitive than a standard PECVD material although not sensitized by hydrogen loading or other method. We attribute this to the expected high content of Ge$E'$ centers in an as-deposited material due to a large amount of hydrogen incorporated in our material during deposition.

5.3.2. Structural relaxation model

The stress-relief or structural relaxation model was introduced in 1991 as an alternative to the color center model for explaining the mechanism responsible for the refractive index change [17, 18]. In this explanation the refractive index change arises from a relaxation of the thermoelastic stress in the core of the fiber. The cores of germanosilicate fibers are usually under tension due to the difference in coefficients of thermal expansion between the core and the cladding, with the stress developed as the fiber is cooled during drawing. Accordingly, tension reduces the refractive index through the stress-optic effect. The result of stress relief in the case of fiber will be the increase of the refractive index. This result is observed experimentally. Due to UV-irradiation the photo-refractive index change will be a consequence of the relaxation of
the stressed glass network initiated by breakage of “wrong bonds” in the form of Ge-Si or Ge-Ge. This relaxation effect will be quite different for planar structures in silica-on-silicon PECVD technology. In the case of as deposited silica and Ge-doped silica films on a silicon substrate, the total stress is compressive for a 1 µm thick film and up to 20 mol% of GeO₂ in SiO₂ as shown in figure 5.3 [19]. The extrinsic or interfacial stress between the thin film and the silicon substrate is generated during cooling of the sample due to differences between thermal coefficients. Consequently this stress is larger in the case of a pure silica thin film than for Ge-doped silica as the difference to the thermal expansion coefficient of silicon is larger for the former case. The intrinsic stress generated in the thin film itself is also compressive and higher in the case of pure silica in comparison to Ge-doped silica.

![Figure 5.3](image)

**Figure 5.3.** As-deposited intrinsic and extrinsic stress components in germanosilicate glasses (1 µm thick films on silicon substrate) [19].

The structural relaxation effect in the case of thin films on a silicon substrate will be dilution and consequently a decrease of the refractive index through the stress-optic effect for both pure silica and germanosilica films (for low Ge content).

### 5.3.3. Densification (compaction) model

The fact that ultraviolet irradiation induces compaction in the amorphous silica was known even before the investigations of photosensitivity initiated by development of UV-induced Bragg gratings [20]. According to [21] and an extensive review of data collected from a large number of investigations [11] photosensitivity in silica fiber can lead to an index change of up to $10^{-3}$ using conventional imprinting methods (up to $10^{-2}$ in case of hydrogen loading). In [22] Poumellec et al. proposed a photoelastic
densification model experimentally investigated in fibers and performs. Using different microscopic methods it was later shown that photoelastic densification plays an important role in the refractive index change during grating formation and can explain at least 40% of the photosensitivity in nonhydrogen loaded germanosilicate.

5.3.4. Complex photosensitivity of planar waveguides

The photosensitivity of planar waveguides usually consists of contributions from the three described processes and the net result is determined by their relative importance that depends on a number of factors.

For conventional PECVD technology and one, as-deposited germanosilica layer on the silicon substrate, the refractive index change and thickness change as a function of energy fluence under irradiation with a 193 nm excimer laser are shown in figure 5.4 a) and b), respectively (paper M). Due to large compressive stress at the germanosilica – silicon interface, UV-induced relaxation starts immediately when the irradiation is applied. From a certain fluence level bond breaking in the glass matrix and generation of color centers become more and more efficient in contributing to an increase of the refractive index. With further increase of the fluence this process tends to saturate and the further relaxation of the interfacial and intrinsic stress turn over the refractive index towards lower values accompanying with further dilation of the material. For pure silica at higher fluences the dilation decays most likely due to consolidation of silica material as in the case of thermal annealing. This effect is not observed for Ge-doped silica for the fluence levels as in fig. 5.4. Ge-doped silica may require higher fluences for consolidation process, probably due to lower mobility of germania in the glass structure.

As it is seen from figure 5.4, the overall refractive index change for Ge-doped silica layer on a silicon substrate is negative. In practice quite different results are obtained when writing UV Bragg grating in the core of the channel waveguide. In this case however the core material is relatively well isolated from the interface with silicon due to a 12 \( \mu \)m thick buffer layer. Consequently the structural relaxation due to compressive stress from the silicon wafer acts
as a remote overall negative index change and competes with the positive index change, due to formation and/or bleaching of germanium related colour centers. This last mentioned effect, as a local one, is mainly responsible for the modulation of refractive index and positive grating formation, whereas the stress relaxation effect, as a remote one, is contributing to the overall index change in opposite directions. In this situation it can happen that writing of a positive grating (increase of refractive index due to color center contribution) can be accompanied by an overall decrease of index (caused by relaxation effects) resulting in formation of type IIa grating. In this case, however, the grating does not need to grow in two steps, as was described in section 5.3, by decreasing and growing again.

5.4. Fabrication of UV-induced Bragg gratings

Three main laser-writing techniques are in use to produce photoinduced Bragg gratings and all of them were developed for fiber gratings: interferometric, phase mask and point-by-point techniques.

5.4.1. Interferometric techniques

The interferometric (or holographic) technique for the fabrication of fiber Bragg gratings is employed by splitting the writing UV-laser beam into two separate beams and subsequently recombining them at the fiber or planar waveguide, where an interference pattern is produced. This interferogram is written transversely onto the waveguide and, because of the photosensitivity of the waveguide core, results in a lateral variation of the index of refraction along the core. This technique can be divided into two experimental arrangements: amplitude-splitting and wavefront-splitting interferometry.

Amplitude splitting divides the source beam into two distinct beams, most commonly achieved via a beamsplitter. This technique was used for the first side-written gratings by Meltz et al. 1989. Upon interacting with beamsplitters, the laser light undergoes a series of lateral transpositions, which affect the spatial coherence of the laser light at the interference region (phase distortions). Such change to the coherence of the light affects the purity, or definition, of the interferogram and, correspondingly, the quality of the Bragg grating. The transpositions are a consequence of a greater number of reflections of one beam over the other. This problem can be compensated for by the introduction of a second mirror or by using of a Sagnac type of interferometer [23]. The interferometrical arrangement is subject to various forms of mechanical disturbance (including vibrations, temperature gradients, air convection), which affect the accuracy and definition of the writing of the Bragg grating. In the case of the Sagnac interferometer this effect is diminished as light in both arms of the interferometer is going exactly this same way (in opposite directions) and so they undergo the same form of distortion minimizing the phase difference at the interferogram plane.

The main advantage of an ‘amplitude’ interferometer is, according to eq. 1, that the grating period can easily be adjusted by changing the angle between
the interfering beams. The other possibility is wavelength tuning. This control is especially important for fabrication of WDM devices, where different wavelength channels are to be separated.

Wavefront splitting is typically accomplished by means of a geometrical dividing of a laser beam by a prism. Interference by this technique is a consequence of the reconstitution of secondary waves. The grating length is limited to at most half the beam width, which is quite disadvantageous. Usually it is possible to change the grating Bragg wavelength for the prism interferometer, but it is limited by the geometry and scale of the apparatus. In contrast to the amplitude splitting technique, the prism interferometers are less exposed to a risk in reduction of interference contrast due to sensitivity in mechanical and atmospheric vibrations. On the other hand such a interferometer is usually unbalanced because of different arm lengths or number of reflections.

In general, interferometrical methods need higher spatial and temporal coherence of the writing laser beam in comparison to other methods.

### 5.4.2. Phase mask techniques

The phase-mask technique (see figure 5.5) was invented by Hill *et al.* in 1993 [24] making a considerable improvement to the ease with which fiber Bragg gratings could be created. Essentially, the phase-mask is the transmission diffraction grating that recreates a spatial modulation onto the fiber or waveguide via illumination of UV light. Such phase-masks can be made by holographic or lithographic methods and in such a way that the zero-order diffracted beam results in only a few percent of the total power of the pulse and most of light (about 70%) in the +1 and −1 orders. When the phase mask is situated directly on the fiber or waveguide, these two diffracted order beams interfere to produce a periodic pattern that photoimprints a corresponding

![Figure 5.5](image)

**Figure 5.5.** Schematic of photolithographic apparatus for photoimprinting a refractive index Bragg grating in a photosensitive optical fiber waveguide [24].
pattern in the waveguide’s core material. It is important to mention that the period of the written grating is half of the period of the phase mask and is independent of the wavelength of UV light used for illumination, although the design of the phase mask to get most of the light in the +1 and −1 orders and the least in the zero-order is wavelength dependent. Temporal coherence variations due to mechanical and other vibrations previously discussed do not play as great a role in the phase-mask technique as they do in the interferometric technique and the manufacturing process can be greatly simplified. The laser source can have quite a short spatial coherence, when the phase mask is placed in close proximity or in contact with the fiber or waveguide. A drawback of this technique is that a separate phase mask is required for each different Bragg wavelength as it is not possible to tune by changing the angle between interfering beams (the angle between diffraction orders is constant) or imprinting wavelength.

5.4.3. Point-by-point technique

In the point-by-point technique reported in 1993 by Malo et al. [25] each grating plane is written into the fiber or waveguide separately by a focused single laser pulse. After each exposure the waveguide is moved though a distance \( \Lambda \) parallel to the core axis. This displacement represents the grating periodicity and sub-micron accuracy is essential to this technique. Such displacement is usually controlled interferometrically and makes the method quite advanced. The advantage is that during the exposition grating parameters can be changed to obtain a specific filter function such as chirp or apodization. A drawback is that the technique is suitable for writing only short gratings and long period gratings due to the number of planes needed. Moreover, thermal stresses due to local, tightly focused irradiation cause irregular periodicities along the core.

5.5. UV laser processing of planar devices at KTH

The laser-processing laboratory has been equipped with two laser systems for the study of UV sensitivity of germanosilica and development of components with UV-induced refractive index modifications.

5.5.1. Interferometrical method

The interferometrical method for writing Bragg gratings in fibers and waveguides is used in the first laser system described below. The system consists of a continuous wave (CW) UV laser, a Sagnac interferometer and a monitoring unit as shown in figure 5.6. A frequency doubled argon ion laser Coherent Innova 90 Fred provides a high quality laser beam at 244 nm. The output power at this wavelength is 100 mW and the beam diameter is 0.6–0.8 mm. A beam expander consisting of two cylindrical lenses expands the laser beam 15 times in one direction giving a collimated laser beam in form of a vertical line at the output. Such a formed beam is reflected from a motorized mirror and then split mainly to the −1 and +1 diffraction orders at the phase mask. Zero- and higher-order diffracted
beams have quite low efficiency and fall out of the system. The phase mask is used here as a beam splitter in the Sagnac interferometer.

![Figure 5.6. Setup for writing and evaluation of waveguide gratings with interferometrical method; LED – broadband light source, PMF – polarization maintaining fibre, SMF – single mode fiber, PBS – polarisation beam splitter, OSA – optical spectrum analyser, A – programmable attenuator, CYL – cylindrical lens, MM – motorized mirror, PM – phase mask, M1, M2 – interferometer mirrors.](image)

The waveguide is placed slightly above the phase mask. One of the two diffracted UV-beams is reflected off mirrors M1 and M2 while the other diffracted beam goes in the reverse direction. The two beams are recombined on the waveguide by introducing a tilt of the mirrors M1 and M2 with respect to the picture plane. Another cylindrical lens can be situated prior to the waveguide to focus the laser beam in the direction perpendicular to the picture plane. In this case the illuminated waveguide area is 10 µm x 12 mm.

By moving the motorized mirror MM along the phase mask, the interference pattern is formed along the waveguide allowing writing gratings with maximum length equal to the length of the phase mask. The angle between the diffracted and the phase mask beams is determined by the phase mask period and the angle between the interfering beams at the waveguide plane depends on the three parameters: diffraction angle and tilt of mirrors M1 and M2. When the system is symmetric, the waveguide is situated at the same plane as the phase mask and the imprinting angle is equal the diffraction angle, so the imprinted grating wavelength will be:

$$
\lambda_{B0} = n \Lambda_m
$$

where $n$ is again the effective index of the fundamental guided mode and $\Lambda_m$ is the phase mask period. To write gratings for different Bragg wavelength the tilt of the mirrors is changed. For $\lambda_B < \lambda_{B0}$, the waveguide is brought closer to the mirrors to position it in the interference pattern. In the same way, for $\lambda_B > \lambda_{B0}$, the waveguide is moved away from the mirrors.

The spectral response of the grating is measured during the writing of the grating using a broadband light source and an optical spectrum analyzer.

The spectral response of the grating is a Fourier transform of the envelope of the index modulation $\Delta n$ along the grating. In the simplest case, when a finite-length grating has a uniform modulation of refractive index, $\Delta n = \text{const}$, as seen
in figure 5.7.a, the main peak or Bragg resonance in the spectral response is accompanied by a series of sidelobes at adjacent wavelengths (sinc function). In WDM applications in which high rejection of adjacent channels is required it is important to lower the reflectivity of the sidelobes, or to apodize the reflection spectrum of the grating.

A known method of suppressing the side lobes is to apodize the index profile such that towards the edges of the grating the index modulation approaches zero (Gaussian apodization) as seen in figure 5.7.b. The direct use of a laser beam with a natural Gaussian profile of intensity leads to the Gaussian apodized Bragg grating. The gratings of this index profile show a significant suppression of side lobes, but on the short wavelength side it remains a residual peak. Figure 5.8 a) and b) shows the simulated profile with Gaussian apodization and the spectral response of the grating fabricated in the laboratory, respectively. Both profiles show the same behaviour that can be explained by a non-uniform average index profile along the grating.

Sections with a lower refractive index on both sides of the grating contribute to reflection of light with a shorter wavelength than the center part of the grating. Additionally these two reflections form a Fabry-Perot cavity that gives an additional peak at the shorter wavelengths.

To suppress the side lobs caused by the described effect it is necessary to raise the average index of the grating to be constant along the grating length. An apodization using this index profile, the raised Gaussian apodization is shown in figure 5.7.c and the simulated transmission spectrum of such a grating in figure 5.9. To implement this apodization as well as other even

\[
\text{Figure 5.7. a): finite-length grating with uniform modulation of refractive index; b): self Gaussian apodization and c): raised Gaussian apodization of the laser intensity modulation for writing Bragg gratings. Line in the middle shows an average index profile. The period of the grating has been exaggerated for illustrative purposes.}
\]
more complicated apodization functions, programmable double exposure is necessary. Using a programmable tunable attenuator A and motorized mirror MM (shown in figure 5.6) one can expose an arbitrarily chosen intensity profile along the grating to get an appropriate $\Delta n$ profile. Prior to this exposition a “negative” blanket exposure should be done, which gives an opposite profile of the mean refractive index change. Then, when overlapped with the modulated one a uniform average index profile along the grating is obtained. It is important to note that when using a beam splitter instead of a phase mask the mirror movement would smear out the interference fringes preventing any refractive index modulation.

**5.5.2. Phase mask method**

The phase mask method is used in the second laser system described below. A Lambda-Physik COMPex 110 excimer laser is used for light generation at two different wavelengths: 193 nm with an ArF gas mixture and 248 nm when using a KrF gas mixture. In order to increase the coherence length and improve the beam quality, unstable resonators are used for each of the wavelengths, which considerably decreased the maximum output power, but it still remains well above the damage threshold of the exposed germanosilica.
films. The maximum pulse energy for 193 nm and 248 nm with unstable resonators is 120 mJ and 220 mJ respectively and the max. pulse repetition rate is 100 Hz. The experimental setup for waveguide grating writing is shown in figure 5.10.

![Figure 5.10. Setup for writing and evaluation of waveguide gratings; LDS – tunable laser diode source, PM – phase mask, ROT – optical circulator, PBS – polarisation beam splitter, WDCA – Wavelength Domain Component Analyzer, CYL – cylindrical lens, MIC – microscope, PMF – polarization](image)

The Bragg gratings are photoinduced using a 30 mm long phase mask with a period of around 1\(\mu\)m and suppressed zeroth- and higher diffraction orders of transmitted light at 193 nm or 248 nm. The exposure is carried out with a laser beam of about 5 x 15 mm size, which is filtered and focused with a cylindrical lens to a 100 \(\mu\)m x 5 mm focal line. The cleaved piece of wafer with the fabricated channel waveguides and phase mask laying directly on it, is held by a vacuum chuck which is attached to a computer-programmable x-y scan table having a resolution and repeatability of 0.1 \(\mu\)m and an absolute accuracy of 0.25 \(\mu\)m. Short gratings down to 5 mm are exposed without using the scan table whereas longer gratings are fabricated by scanning the laser beam along the device.

The gratings are written with different pulse energies up to 8 mJ/ pulse at 100 Hz during about 5 min. The spectral response of the gratings is measured using an Agilent 86082 Wavelength Domain Component Analyzer. The tunable laser source is connected to the tested device via optical circulator and polarization maintaining fibers. This allows the observation of the signal reflected back to the input port of the device and the isolation of it from the source. The output signal is connected to the analyzer with a single mode fiber. The Wavelength Domain Component Analyzer has a resolution of 1 pm and a dynamic range of 90 dB (together with a special tunable laser source). This dynamic range is much lower in case the polarization selective devices are used to investigate polarization birefringence and is limited by the quality of these devices.

With this system the strongest to date gratings written in germanosilicate channel waveguide without hydrogen loading have been obtained (paper I).
Figure 5.11 shows the transmission spectrum of a Bragg grating imprinted in a straight channel waveguide with a standard germanium content of 12-mol%, a core-cladding refractive index difference of 0.7% and a $6 \times 6 \ \mu \text{m}$ channel. The grating was recorded with a pulse energy of 2.3 mJ, total energy fluence on the substrate of 4.8 kJ/cm$^2$ and movement of 20 mm. The total grating length was 25 mm with the apodization profile at the grating edges originating from the Gaussian intensity profile of the laser beam. The grating was registered with TE polarized light and shows an extinction ratio of 47 dB. The grating shift during the exposure was about 1 nm, which corresponds to refractive index change of $2 \times 10^{-3}$. The grating filter exhibits a 3 dB bandwidth of 0.2 nm.

5.5.3. Other UV-induced refractive index modifications

UV-induced refractive index modifications also includes post-fabrication phase adjustment and wavelength tuning, direct UV-writing of waveguides, birefringence compensation by UV illumination and UV-assisted poling.

Post-fabrication phase adjustment can be used, for example, to balance the Mach-Zehnder interferometer fabricated in planar technology with a thermal element in one of the arms. To perform switching functions the phase difference at the output should be 0 for “off” and $\pi$ for “on” states. To adjust 0 phase difference for an unpowered switch, a short part of one of the arms of the interferometer is blanket UV illuminated to increase the optical path length of this arm. The output from the device is monitored during the illumination and the process is stopped when the perfect matching is reached. In one of our experiments it was possible to introduce a several $\pi$ phase shift by illuminating a 5 mm long element of a planar Mach-Zehnder interferometer arm by 193 nm light from the excimer laser.

Wavelength tuning of wavelength selective devices can be achieved in a similar way. A Bragg grating-based component can be fine tuned to the center...
of the desired wavelength channel by a blanket exposition of the grating. The increase of the mean refractive index at the grating area tunes the device towards the longer wavelengths.

**Direct UV-writing of channel waveguides** can be performed in a specially prepared 3-layer slab waveguide with a Ge-doped UV-sensitive core layer. For fabrication of waveguide components the system described in section 5.5.2 can be used. The laser beam must be spatially filtered and focused into the core with a short focal length lens to obtain a beam diameter of 5-6 µm. The desired structure can be programmed into the computer controlling the high precision x-y scan table. The structure is imprinted directly into the core of the slab waveguide by point-to-point writing with pulse laser illumination.

**Birefringence compensation by UV illumination** can be performed for waveguide components fabricated by PECVD technology as it usually exhibit some birefringence between TE and TM polarizations, mostly due to the stress birefringence (paper H). By writing a weak grating in the waveguide element, the compensation process can be monitored. After grating writing a 193 nm blanket exposure can be used to relax the stress birefringence, which is provided until the gratings for the two polarization directions overlap. In figure 5.12 it occurs for the total fluence of about 50 J/cm².

In this way UV illumination allows localized birefringence compensation of certain components that should be polarization independent.

**Figure 5.12.** Evolution of Bragg wavelength for both TE (open squares) and TM (filled squares) polarization eigenstates of the PECVD grating with 193nm post-processing (paper H).

**UV-assisted poling** is a separate part of UV-treatment of germanosilica materials performed in order to create the second-order nonlinearity and the linear electro-optic effect, which can be used for practical applications such as
modulators and switches. Some examples of this application will be described in section 6.4.

5.6. References

6. Fabrication of integrated components with PECVD technology at KTH.

The studies on the optimization of PECVD technology and material structure investigations have been followed by fabrication of a number of state-of-the-art devices for application in optical communication systems. These devices were not in each case original new constructions developed by the author, but rather fabricated for confirmation of material quality and technological ability for production of these state-of-the-art devices.

6.1. Multimode interference devices

Multimode interference (MMI) devices, couplers and splitters are based on the self-imaging effect [1, 2]. The design of these devices can be done with help of software tools [3 – 5] available on the market.

In the example shown in figure 6.1 light is injected from the left into a multimode interference section and the output varies with the length of this section. The modal method employed by the software means that once the eigenmodes are known for each section of the device, the output field is recalculated instantaneously. The optimal coupling length can be obtained by doing a length scan of the middle section.

For testing the feasibility of these devices using our technology, a mask with a series of different MMI couplers/splitters (1 x 2, 2 x 2, 3 x 3, 1 x 4, and 4 x 4 channels) have been designed and several wafers with these devices have been fabricated and evaluated (papers E and F). Figure 6.2 presents an example of the fabricated 1x4 MMI coupler. The total length of the designed 1 x 4 splitter is only 1.6 mm, which is much less than the equivalent traditional splitter that needs several centimeters for the in-series coupled “Y” junctions. The obtained splitting asymmetry was +/- 1.5% and the losses per channel...
about 3 dB (including in- and out-coupling loss) on top of the 6 dB per channel for splitting as seen in table 6.1.

<table>
<thead>
<tr>
<th>Device number</th>
<th>Loss [dB] (incl. in- and out-coupling loss)</th>
<th>Split asymmetry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>straight 1-1 1-2 1-3 1-4</td>
<td></td>
</tr>
<tr>
<td>M14:5</td>
<td>1.78 9.06 9.01 8.84 8.79</td>
<td>+/- 1.5%</td>
</tr>
</tbody>
</table>

Table 6.1. Loss data [dB] for $\lambda = 1530$ nm (not annealed sample)

These devices, due to their compactness, flexibility and low insertion loss, are attractive candidates for photonic integrated subsystems with a moderate number of channels and high level of compactness.

6.2. Arrayed waveguide gratings

Arrayed waveguide gratings are key components for Dense wavelength-division multiplexing (DWDM) optical communication systems. AWGs can be used as multiplexers or demultiplexers with high flexibility with respect to the number of channels and the wavelength spacing. They are superior in mass production, compactness and reliability.
A number of AWG devices in silica-on-silicon technology have been fabricated and evaluated in our laboratory. Figure 6.3 shows a schematic layout and a series of fabricated AWGs on a 4" Si wafer.
The device consists of two slab waveguide star couplers, connected by a dispersive waveguide array. Light propagating in the input waveguide will be coupled into the array via the first star coupler. Due to the constant path length difference between adjacent waveguides, after passing through the array the signals that reach the output slab waveguides are spread by diffraction, but due to the mutual interference between the signals from each

The parameters are:
$W = 80 \, \mu m$, $L = 1635 \, \mu m$,
$a_1 = 40 \, \mu m$, $d = 6 \, \mu m$,
$l_1 = 800 \, \mu m$, $d_1 = 8 \, \mu m$,
$b_1 = 8.8 \, \mu m$, $b_2 = 29.6 \, \mu m$,
$b_3 = 50.4 \, \mu m$, $b_4 = 71.2 \, \mu m$. 
waveguide, all the wave fronts are diffracted, at a specified wavelength, in a uniform direction. Accordingly, the signals of differing wavelength are focused at different positions on the output side of the output slab waveguides. The correct positioning of the output waveguides allows the spatial separation of the different wavelengths.

The fabricated 32-channel AWG has been evaluated with a broadband light source and optical spectrum analyzer. The device shows very good performances in channel isolation, spacing, signal-to-noise ratio and overall good characteristics (see figure 6.4). This confirms good quality and homogeneity of the deposited material with respect to thickness, impurities and refractive index as well as good control over the process parameters.

**Figure 6.3.** Schematic layout and a series of AWGs on a 4” Si wafer fabricated with PECVD technology at KTH. Red-light illumination is used to show the light path through the AWG device.

The fabricated 32-channel AWG has been evaluated with a broadband light source and optical spectrum analyzer. The device shows very good performances in channel isolation, spacing, signal-to-noise ratio and overall good characteristics (see figure 6.4). This confirms good quality and homogeneity of the deposited material with respect to thickness, impurities and refractive index as well as good control over the process parameters.

**Figure 6.4.** The graph illustrates the demultiplexing properties of a Gaussian-profile-type arrayed waveguide grating with 32 output channels and 100 GHz (0.8 nm) channel spacing.
6.3. Grating assisted Optical add-drop multiplexer based on 2x2 MMI coupler

Optical add-drop multiplexers are also very important components for wavelength-division multiplexing WDM communication systems to select and route different channels, to extract certain wavelength channels from a transmission line (drop function) and/or to add new channels at the same wavelengths or at new wavelengths to the transmission line (add function). These add and drop functions are required on each node of a WDM-system. Various OADM configurations have been investigated, including fiber or polymer gratings with circulators, a Mach–Zehnder interferometer with gratings, cascaded unbalanced Mach–Zehnder structures, and arrayed waveguides. The crosstalk suppression is an important issue for most of applications. Therefore, a new type of add-drop multiplexer has been developed with improved crosstalk performance.

The design is based on the MMI 2 x 2 coupler with the Bragg grating imprinted in the multimode section of the MMI structure [6]. In the first step the device with drop function has been realized (paper I). Figure 6.5 shows the schematic layout of the realized Bragg grating-assisted MMI (MMI-BG) structure.

As it is seen on the layout, the MMI coupler is designed in such a way that all the wavelength channels injected into Port 1 are coupled out through Port 4. The imprinted Bragg grating acts as a selective filter reflecting the resonance wavelength to Port 2, which is the drop channel Port. The length of the imprinted Bragg grating is 5 mm and the total size of the device is 10 mm x 70 µm. Figure 6.6 shows the simulated and realized transmission and drop channel spectra of the fabricated device.

The presented device is the first fabrication of a compact Add/Drop multiplexer based on MMI-Bg. 30 dB suppression of the dropped channel in the transmission spectrum and 3 dB excess loss of the dropped channel with respect to the transmitted channels was obtained. In the reflected spectrum the TM polarization was not filtered out, that’s why two grating peaks can be seen. Despite this fact the background rejection at ±1 nm from Bragg wavelength is below 30 dB. Further experiments are needed for optimizing the birefringence compensation.

Figure 6.5. The Schematic layout of the basic MMI-Bg structure [6].
6.4. Mach-Zehnder switch based on silica poling

Silica is naturally an amorphous material and due to the inversion symmetry exhibits very low second order nonlinear optical susceptibility. Since the first observation of induced second harmonic generation in optical fibers [7] considerable interest has been shown in development materials and techniques to increase the second order nonlinearity and/or the linear electro-optic effect in silica fibers and waveguides. This would considerably extend the possible applications of silica based devices including switching and modulation functions.

Thermal poling has been identified as a method giving more stable nonlinear layers than other poling techniques. Although the mechanism is still not fully understood, it is shown that in thermally poled silica the second order nonlinearity is located in a very thin (some micrometers) layer below the anode and can be explained by either a frozen-in electric field inducing a second order nonlinear susceptibility via third order susceptibility or orientation of dipoles making the material polar that exhibits a net dipole momentum.

For our thermal poling experiments we have used Mach-Zehnder interferometer (MZI)-based switch structures fabricated as channel or ridge waveguides with Ge-doped silica cores and 4 cm long electrodes deposited on the top of both arms of the interferometer. The (MZI) structures were poled at 300°C for about 2.25 hours with an applied voltage of +2 kV. Fig. 6.7 shows the output power of the poled MZI as a function of applied voltage. The sinusoidal relationship between the output power and the applied voltage indicates that the optical phase shift was caused by the linear electrooptic effect. Phase change needed for switching of the device is obtained by applying about 5 kV. The effective linear electro-optic coefficient estimated from the MZI optical response is about 0.05pm/V and the achieved extinction is better than 17 dB. These results are comparable to those presented by other authors working with similar materials [8]. Considerable increase of the poling-induced electro-optic effect is necessary to use such devices for practical applications in optical communication systems.
6.5. Photonic Crystal-based coupler

As described in the technology part of this thesis, the possibility of PECVD deposition of amorphous silicon with relatively low material losses of about 2 dB/cm together with our high quality PECVD silica deposition offer a simple and versatile technology for 1D and 2D photonic crystal devices. Due to high refractive index contrast between Si and SiO$_2$ it is possible to fabricate photonic crystal waveguides with much lower losses than similar devices fabricated in III-V materials.

As an example of 1D photonic crystal devices, a narrow band coupler based on a one-dimensional Bragg reflection waveguide has been realized (paper J). A cross-section of the channel coupler and normalized transmission for channel coupler, when input and output ports are in conventional waveguide are presented in figure 6.8.

The fabrication started with deposition of alternating layers of silica and amorphous silicon films on a 4” <100> oriented silicon substrate. After depositing the bottom Bragg reflector consisting of 5 150 nm-layers of silicon and 5 250 nm-layers of oxide the silicon core layer of 280 nm thickness was deposited followed by another 7 alternating layers of the top Bragg reflector and the conventional core layer. The core layer of the conventional waveguide was obtained by doping silica with approximately 4 at% germanium in order to give a 0.65% relative difference in refractive index with respect to the silica top cladding. Channel waveguides, 6 µm wide, were fabricated by reactive ion etching using an inductively coupled plasma reactor. A 16 µm thick silica cladding was then deposited, without performing any subsequent high temperature consolidation step.

![Figure 6.7. The output power of the poled Mach-Zehnder interferometer as a function of applied voltage](image)
The sample was characterized using a wide tunable laser 1480-1590 nm and an optical spectrum analyzer. For 2D photonic crystal devices e-beam lithography and etching have been specially optimized. For e-beam lithography the optimum exposure doses have been determined for each part of the pattern area. Adjusting the exposure dose compensates proximity effects related to scattered electrons. Only shallow etching has been performed for Si - SiO$_2$ material structure. As shown in figure 6.9 good profile quality has been obtained as well as smooth etching through different materials in one step using the same fluorine-based chemistry.

Figure 6.8. Cross-section of channel coupler containing 1D Bragg reflection waveguide and normalized transmission for channel coupler, when input and output ports are in conventional waveguide (paper 10).

Figure 6.9. Etching through silicon and silica using fluorine-based chemistry
6.6. References

3. C2V Olympios: design, simulation and mask layout platform for integrated optics, 7500 AH Enschede, The Netherlands, (software@c2v.nl).
4. Optiwave BPM_CAD, waveguide optics modelling software system, K2E 7X1 Ottawa, ON, Canada, info@optiwave.com.
5. R-Soft BeamPROP waveguide design software, Optima Research, Cambridge CB2 4XQ, UK, info@optima-research.com.
7. Summary and conclusions

The thesis presents work on PECVD and UV processing technologies in application to planar components for optical communications, and to fiber optics sensors.

The most important result is the development of low temperature Plasma Enhanced Chemical Vapor Deposition (PECVD) processing that allows fabrication of high quality low loss Ge-doped silica channel waveguides. For the first time it became possible to fabricate these components while keeping the temperature below 250°C during the entire fabrication process with completely eliminated absorption peaks at 1.5 µm that appear due to N-H and Si-H bonds. This opens new possibilities for monolithic integration with other, temperature sensitive devices, such as semiconductor lasers and detectors, or polymer-based structures on the common silicon platform.

A number of test waveguides and test components have been fabricated. The propagation loss of the straight waveguide has been determined to be 0.1 – 0.2 dB/cm, which is comparable with state-of-the-art losses obtained for silica glass by PECVD deposition with several hours of post processing annealing in temperatures above 1000 °C. Several multimode interference couplers/splitters have been realized with very good split symmetry (+/- 1.5% for 1 x 4 splitter). An arrayed waveguide grating-based multi/demultiplexer fabricated in this technology has 32 channels with 100 GHz channel spacing and excellent wavelength distribution profile.

Another part of the thesis was devoted to UV processed materials and devices. This started with the first in Sweden UV written fiber Bragg gratings for distributed sensor applications. A sensor system for simultaneous measurement of strain and temperature, which can handle over 100 point sensors with repetition rate of 10 MHZ has been proposed and realized. Based on this experience the lab for UV-processing with 193 nm and 244 nm laser sources in application to SiO₂/Si planar devices has been built up. Investigations of the UV photosensitivity of the deposited undoped and germanium doped silica have been done. In accordance with previously reported observations both positive and negative changes of refractive index have been obtained. The sign of those changes has been attributed to the interplay of color center mechanism, interfacial stress relaxation and densification due to photoelastic effect. The observed net changes are essentially different from those reported for optical fiber, which is attributed to the dominant role of the interfacial stress in one layer SiO₂ on Si planar structures. Different saturation behaviours with an irradiation dose were observed for undoped and Ge-doped silica, which can be explained by lower mobility of Ge in the glass structure. This investigation provides deep insight into the mechanism behind UV-induced changes in silica-silicon materials, not well explained before.

Experiments with writing gratings, post-fabrication phase adjustment and birefringence compensation have been performed. This research has resulted in fabrication of the strongest to date grating written in a germanosilicate channel waveguide without hydrogen loading. A record transmission...
suppression of 47dB in a Bragg grating photoinduced in a straight buried channel waveguide has been obtained.

With the developed PECVD and UV processing technologies an original solution for a network component has also been presented. A compact Add/Drop multiplexer based on a Bragg grating assisted MMI 2 x 2 coupler has been fabricated and 30dB suppression of the dropped channel in the transmission spectrum has been obtained.

In the last part of the thesis work has been done on optimization of the material losses (amorphous silicon) and etching procedures for high aspect ratio structures. This has been applied for the fabrication of 1D and 2D photonic crystals in Si/SiO₂ materials. A narrowband filter based on directional coupler utilizing strong dispersion in 1D PC has been fabricated. A 0.8 nm bandwidth was obtained in a 2.2 mm long device.

Future work should evolve towards further improvement of the silica-on-silicon waveguide parameters including losses, gap filling and better control of the deposited material during fabrication. The improvement of the PECVD equipment in the form of real-time diagnostics for the process control would be valuable. Waveguides polarization birefringence should be characterized and methods for its reduction should be closer investigated.

Implementation of the low temperature technology to fabricate monolithic integrated devices is one of the most important continuations of this work. Further studies need to be performed on the methods for increasing photosensitivity of germanium doped planar waveguides. Design tools for fabrication of gratings with more complex apodization functions should be developed especially for systems operating at a very high bit rate.

Implementation of photonic crystal components into future communication networks is one of the most widely addressed issues in the photonic research community. Those components are very promising and provide an ultimate solution for miniature, large scale of integration multifunctional components.
8. Description of original work

The objective of this section is to present a short description of the appended publications forming this thesis. A short description of the author’s contributions to each of the paper is also given.

The first four papers (A - D) describe earlier work devoted on fiber Bragg gratings and their application to distributed sensor systems. Papers E, F, G, K and L consider the PECVD plasma deposition of silica and doped silica films. Papers H, I and J are about different integrated devices and their properties and paper M takes into consideration UV induced changes.

Paper A

Quasi-distributed Fiber-optic Sensor for Simultaneous Absolute Measurement of Strain and Temperature

L. Wosinski, J-P. Bétend-Bon, M. Breidne, B. Sahlgren and R. Stubbe


In this paper a concept for a quasi-distributed fiber-optic sensor for simultaneous absolute measurement of strain and temperature is proposed. The authors present a novel solution of the sensor system based on time division multiplexing (TDM) of in-line coupled Fabry-Perot interferometers with fiber Bragg gratings used as week reflectors. A special dual core fiber was proposed to distinguish between strain and temperature and a dual-wavelength technique was used to perform absolute measurements over an extended dynamic range. TDM means here that the signal from each sensor is allocated to a particular time slot. Using standard telecom components the spatial resolution of the distributed system was of order of 5 cm.

The presented analysis shown that the proposed system can handle a large number of sensors (100 or more) with repetition rate of more than 10 MHz.

Contributions by the author of the present thesis: Background studies of distributed systems and fiber Bragg gratings, proposing the main idea, writing of the paper.

Paper B

Distributed sensing with grating reflectors in optical fibers

L. Wosinski, R. Stubbe and M. Breidne

Invited lecture on European Optical Society First Annual Meeting EOSAM-93, Zaragoza, Spain, July 6-9, 73 (1993).
The aim of this invited paper was to summarize the present status of research and development on fiber Bragg gratings and their applications. After a short historical introduction the paper summarizes the knowledge to date about the photosensitivity in optical fibers. Then the technologies for writing gratings at that time are described together with the best results achieved. In this part the technology used by the author’s group is also described. At that time a new method of writing gratings based on the phase mask was developed and a similar method was also used at the beginning at the author’s lab. Later on a much more sophisticated system was built based on sequential grating writing with an interferometrical method, that evolved to one of the most advanced systems in the world.

Contributions by the author of the present thesis: Collecting of the referenced material, concept of the paper, and writing.

Paper C

Fiber gratings for distributed sensors

L. Wosinski, B. Sahlgren, M. Breidne, R. Stubbe and J-P. Bétend-Bon

In this paper the first gratings written in the author’s lab as well as their application to a proposed earlier quasi-distributed fiber-optic sensor system are presented. The first gratings were fabricated with a system consisting of a tunable excimer pumped dye laser (operating at the wavelengths 480 – 500 nm) and frequency doubling crystal (BBO) providing UV beam at 240 – 250 nm with output power up to 100 mW. Using a “home-made” diffraction reflection grating with 3600 lines/mm and the geometry, where interference pattern between 0 and –1 orders could interfere inside the fiber core, a grating with 60 % efficiency and 0.4 nm spectral width was obtained. The same laser source used with an interferometrical system allowed writing similar grating with 95% efficiency and considerably suppressed side lobs. With an optical spectrum analyzer, that was able to collect traces of several scans, an evolution of the grating during writing process in real time could been observed. It was possible to see that during the growing process the grating moved slightly towards longer wavelengths, which was caused by an average increase in the refractive index of the illuminated part of the fiber.

Contributions by the author of the present thesis: Participating in the experimental work, concept of the paper, and writing.
Paper D

Experimental system considerations for distributed sensing with grating Fabry-Perot interferometers

L. Wosinski, M. Breidne, R. Stubbe, B. Sahlgren and J-P. Betend-Bon

Realization of the earlier proposed quasi-distributed fiber-optic sensor for simultaneous absolute measurement of strain and temperature is described in this paper. A “differential” two-core fiber was used for separate measurement of strain and temperature. Preliminary different fiber cores have been tested to find a pair of cores with large difference in thermal coefficients. It was found that a high germanium doped boron codoped fiber core and usual telecom fiber core, both designed by Ericsson differ from each other by about 23% in thermal coefficients. The alternative possibility that was tested was a solution where both cores were made of the same germanium-boron UV-sensitive material, but one of the cores was surrounded by a ring of another material introducing the internal strain. In both cases simultaneous change of strain and temperature in the point, where Fabry-Perot sensors were situated, detected independently by sensors with cores, that exhibit different temperature and strain dependences gave two linearly independent equations from which temperature and strain could be obtained.

Contributions by the author of the present thesis: Participating in the experimental work, concept of the paper, and writing.

Paper E

Improvement of PECVD technology for low loss silica-on-silicon integrated optics

L. Wosinski, J.K. Sahu, H. Fernando, and T. Augustsson

Experimental results of the first improvements of the standard PECVD technology as well as first components fabricated with the described modifications are presented. It was shown, that by appropriate adjustment of the deposition parameters the absorption at 1.5 µm due to N-H and Si-H bonds could be eliminated. The conditions for deposition of pure stoichiometric SiO₂ were analysed. By increasing of rf power, the O:N ratio in the deposited films increases. The concentration of oxygen atoms in the precursor gas mixture must exceed the silicon atom concentration in the SiH₄ by at least a factor of 100, so that the O atoms are available to play a dual role as reactants for precursor formation in phase reactions with SiH₄ consuming completely the silane and in surface reactions for the removal of
hydrogen and cross linking of the oxide structure. Processing pressure depends on the chamber geometry and should be chosen to optimize the mean free path for collisions forming SiO$_2$ molecules.

**Contributions by the author of the present thesis:** Background studies of the plasma processing, proposing of the main idea, leading and participating in the experimental work, concept of the paper, and writing.

**Paper F**

**Reduction of absorption loss in silica-on-silicon channel waveguides fabricated by low temperature PECVD process**

J.K. Sahu, L. Wosinski, and H. Fernando  

In this paper some details of the deposition process for high quality films are analyzed. Pure SiO$_2$ films as well as Ge doped films have been deposited. It was seen that the refractive index increases linearly with the germane flow rate in the total gas mixture. This allowed to accurate control of the refractive index in Ge-doped core with respect to the buffer and cladding layers, both for unannealed and annealed samples. Although the absolute values of the refractive index changes after annealing, it was observed that for a particular germane flow rate the refractive index difference between pure and doped silica remained the same both before and after annealing. Total insertion losses (including propagation and coupling losses) were found to be less than 1.2 dB obtained for a 20 mm long channel waveguide. Several devices, mostly based on multimode interference (MMI) technique realised using this technology are presented.

**Contributions by the author of the present thesis:** Leading of the experimental work, participating in experimental planning and experiments, in discussions and in writing of the paper.

**Paper G**

**PECVD technology for low temperature fabrication of silica-on-silicon based channel waveguides and devices**

L. Wosinski, J.K. Sahu, M. Dainese and H. Fernando  

A comprehensive analyse of the deposited film composition and material properties dependent on the deposition conditions are presented. Film
composition and thus its physical and optical properties strongly depend on the specific deposition conditions such as rf power, reactive gas ratio, total pressure and temperature. During the fabrication process the deposition parameters were varied and the effects on the film quality and optical properties of the fabricated waveguides have been measured and analyzed. The hydrogen and nitrogen incorporation in the form of Si-H and N-H bonds, which contribute to absorption, increasing of refractive index as well as material porosity, are the main reasons for high losses of the PECVD deposited material.

It was confirmed that the combination of high power and N\textsubscript{2}O to SiH\textsubscript{4} ratio of 100 – 200 results in the deposition of the best quality films, still maintaining high deposition rate about 1800 Å/min. The refractive index of the as-deposited silica films is close to that of thermal oxide and the porosity of deposited material is very low. Increasing of chamber pressure decreases considerably the deposition rate whereas temperature has less significant effect on the film quality for high-energy process.

*Contributions by the author of the present thesis*: Leading of the experimental work, participating in experimental planning and experiments and in discussions. Concept of the paper, and writing.

**Paper H**

**Birefringence control in plasma-enhanced chemical vapor deposition planar waveguides by ultraviolet irradiation**


In this paper a birefringence control of the PECVD deposited planar waveguides by ultraviolet irradiation is analyzed. Complete birefringence compensation is demonstrated with the help of a excimer laser 193-nm blanket postexposure.

It was measured by writing weak gratings (~2–10 dB), that the initial sample birefringence splitting (TE – TM birefringence) was 5 x 10\textsuperscript{-4}, mostly as a result of stress birefringence. After grating writing, a 193-nm blanket exposure was used to tune the birefringence until the two polarization eigenstates of the grating overlapped.

*Contributions by the author of the present thesis*: Participating in the preparation of the samples, in discussions and in writing of the paper.

**Paper I**

**Grating-assisted add-drop multiplexer realized in silica-on-silicon technology**

Lech Wosinski, Matteo Dainese, Harendra Fernando, Torsten Augustsson
Design and fabrication of a compact Add/Drop multiplexer based on a high bandwidth, 2x2 multimode interference device is presented. A Bragg grating written in the multi-mode region is used as a selective reflector. The obtained characteristics prove the proposed Add/Drop principle, showing, in correspondence of the dropped channel, a 30dB dip at the transmitted output and a reflection peak at the drop output.

High photosensitivity of PECVD deposited Ge-doped glasses (not thermally annealed), even without hydrogen loading, lead to a record transmission suppression of 47dB in a Bragg grating photoinduced in a straight buried channel waveguide.

*Contributions by the author of the present thesis*: Background studies of the UV photosensitivity, proposing the main idea of writing gratings, leading and participating in the experimental work, concept of the paper, and writing.

**Paper J**

**Narrow Band Coupler Based on One-Dimensional Bragg Reflection Waveguide**

M. Dainese, M. Swillo, L. Thylen, M. Qiu, L. Wosinski, B. Jaskorzynska and V. Shushunova


A narrow band coupler based on one-dimensional Bragg reflection waveguide (BRW) is presented in this paper. The structure consisted of a weakly guiding conventional Ge-doped silica waveguide (n=1.4558 for the silica cladding, n=1.465 for the core) on top of which a BRW (1D photonic crystal) was stacked. The top multilayer Bragg reflector contained 5 periods, each period being a SiO2/hydrogenated amorphous silicon (a-Si:H) stack, whereas the bottom reflector contained only 3 periods to allow larger field overlap between the two waveguides. The core layer was made of a-Si:H. The refractive indices for SiO2 and a-Si:H were 1.4558 and 3.55 respectively. The strong difference between the dispersion of a Bragg reflection waveguide and a channel waveguide was used to create a narrow band coupler. The principle of operation was confirmed with experimental results showing 0.8 nm bandwidth for cross coupling for a 2.2 mm long structure.

*Contributions by the author of the present thesis* Some input to the realization idea of the device, leading of the experimental work, technical expertise of the PECVD tool, participating in discussions.
Paper K

Material Consideration for Integrated Optics in Silica-on-Silicon Technology

Lech Wosinski, Matteo Dainese and Harendra Fernando

The aim of this invited paper was to summarize the present status of our research and development on the PECVD silica-on-silicon technology. Using a commercial parallel plate reactor, it was shown that plasma enhanced CVD technology for silica based planar lightwave circuits can produce a material with very good optical properties, in the spectral windows routinely used in fiber optic communications, while maintaining a high deposition rate (>1700 Å/min) and without any high temperature annealing step. The results confirm that, besides the gas precursors flow ratio, RF power is a key parameter in optimising the deposition process. Keeping the deposition rate high, low (380 KHz) frequency power supplies and low pressure regime without inert gas dilution are preferable to exploit it’s effect completely. In the high power process regime, the properties of the deposited films display low sensitivity on substrate temperature, in the range from 200°C up to 350°C, and on the total gas flow level, provided that the ratio between nitrous oxide and silane gas flow is high.

Contributions by the author of the present thesis: Partly collecting of the referenced material, concept of the paper, and co-writing.

Paper L

Influence of Ge content and Process Parameters on the Optical Quality of Low Temperature Deposited Silica Waveguides

M. Dainese, L. Wosinski, H. Fernando,

In this paper the feasibility of a fabrication process for high quality silica optical waveguides, with Ge doping of the core, which is carried out strictly at low temperature (300°C) is investigated. The thickness of the core and cladding layers used in this study was 3 to 6 µm and 13 µm respectively, therefore an important requirement was a medium/high deposition rate (here up to around 2000 Å/min), to maintain a reasonable throughput. Then, a high control on the value of the refractive index of the films and its uniformity over the substrate was necessary to cope with the normal design specifications which, depending on the application, required a relative difference of refractive index between core and cladding (Δn/ncore) between 0.3% and 1.5%. The accuracy in the refractive index value must be better than 3.e-4, to achieve Δn/n with accuracy better than 0.04%. In case of germanium doping
(up to 6.5at%), the high reactivity and low surface mobility of germane radicals make the deposition more sensitive to the platen temperature and produces films with higher porosity and co-ordination disorder, compared to pure silica. It was demonstrated that increasing the flow ratio is not enough anymore to obtain correct stoichiometry and RF power becomes a critical variable with respect to this. The final result was a material with low optical losses with no absorption due to higher order harmonics of either Si-H or N-H bond vibrations. Measurements on fabricated optical waveguides have shown that for relative refractive index differences between core and cladding up to 0.75% (~4at%), the optical losses are acceptable for the fabrication of high performance devices.

Contributions by the author of the present thesis: Technical expertise of the PECVD tool, participating in experimental work and in discussions, reviewing of the manuscript.

Paper M

Characterization of UV-Induced Changes In Planar Waveguides

H Fernando, J. Canning, L. Wosinski, B. Jaskorzynska and M. Dainese

Characterization of UV-Induced Changes in Planar Waveguides is presented in this paper. By using a relatively simple spectrophotometric data analysis the photo-induced negative index changes and accompanied unconstrained film dilation in single layer samples, prepared using PECVD technique, was estimated. When studying samples that have glassy layers that absorb the UV light (such as germanosilicate) the local change due to compaction can give rise to changes with spatial dimensions that do not exceed the irradiated region in the glass. In contrast, interfacial relaxation is remote and gives rise to structural relaxation on a spatial scale that can easily exceed that of the irradiation. In this study it was possible to confirm and explain previous reports of the qualitative dependence of the irradiation area with the observed index change in waveguide gratings. The importance of stress in promoting negative index change is shown to be crucial. Previous work in type IIa fibre gratings showed the importance of local stresses located in the immediate vicinity of the waveguide in which a grating is to be written in determining the “threshold” value at which type IIa changes begin. In this work it was also confirmed that despite being remote and anisotropic, i.e. away from the waveguide in which gratings may be written, the large expansion coefficients of typical substrates can give rise to type IIa behavior at much lower intensities and fluences than has been observed in fiber form.

Contributions by the author of the present thesis: Technical expertise of the PECVD tool, participating in the experimental work and in discussions, reviewing of the manuscript.
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