ORIGINAL ARTICLE

Silicon Optical Waveguides: State of the Art

Imran Khan[1], Md. Ashraful Islam[2], Zahid Hasan Mahmood[3]*

ISSN: 2186-0114
http://www.IJEI.org

ARTICLE HISTORY

Received: 23 August, 2012
Revised: 1 January, 2013
Accepted: 5 January, 2013

Published online:
18 February, 2013

Vol. 2, No. 1, 2013

Abstract

State of the art of most popular passive device-silicon optical waveguide is discussed here. The first wave guiding through the single layer crystal silicon waveguide to the recent silicon based hybrid plasmonic waveguide and reconfigurable photonic crystal waveguide are covered sequentially. The development of the technologies or fabrication methods to fabricate the waveguide and its performance in terms of losses are considered.

Keywords: *Single mode waveguide, Fabrication method, State of the art.*

I. Introduction

An optical waveguide is a light conduit consisting of a slab strip or cylinder of dielectric material embedded in another dielectric material of lower refractive index. The light is transported through the inner medium without radiating into the surrounding medium. Light confinement is carried out by successive total internal reflection on the two interface guide-substrate and guide-superstrate. Optical waveguides can be classified according to their geometry (planar, strip, or fiber waveguides), mode structure (single mode, multimode), refractive index distribution (step or gradient index) and material (glass, polymer, and semiconductor). The discussion here will be on material based-Optical Waveguides. In 1985 new material, single crystal silicon was used to fabricate optical waveguide [1]. In case of the optical waveguides the key concern goes to different kind of losses. At the very beginning the propagation loss was found for a planner waveguide as 1 dB/cm [2]. By inventing new technology the propagation loss decreases gradually from 0.8 to 0.04 dB/cm as reported in [5,11,18,19,22]. The performance of the waveguides also depend on fabrication technology [9,19]. Materials used for waveguides fabrication and related wavelength also affect the performance [12]. Here we mostly considered the silicon based optical waveguides to discuss the state of the art.

II. Development

The focus will be mainly on the fabrication methods and performance of various waveguides. It was reported for the first time in 1985 by Soref and Lorenzo that the waveguiding is possible in silicon. They demonstrated the slab and channel wave guiding at wavelength 1.3 μm in high resistive single crystal layers of silicon [1]. These were the devices which were fabricated using highly doped silicon substrates. Due to this highly doped substrate the refractive index is increased in the upper layer of the silicon. As we know that the light always try to stay in a higher refractive index area so light is confined in it and propagates through the high refractive index layer. Other substrates such as Silicon on Sapphire (SOS) and Silicon on Insulator (SOI) also used for the wave guiding purpose. In the nineties, silicon waveguides were developed using IMplantated OXygen

AUTHORS INFO

Author 1 Imran Khan*
e-mail: ikhan@jstu.edu.bd
Address: Dept. of EEE, Jessore Science & Technology University (JSTU), Jessore-7408, Bangladesh.

Author 2 Md. Ashraful Islam
e-mail: ashraf.diu@gmail.com
Address: Dept. of CSE, JSTU, Jessore-7408, Bangladesh.

Author 3 Zahid Hasan Mahmood
e-mail: zahid@univdhaka.edu
Address: Dept. of APECE, Dhaka University, Bangladesh.

*Corresponding author
e-mail: ikhan@jstu.edu.bd OR
ikr_ece@yahoo.com
Tel:+8801717933007; Fax: N/A

(SIMOX) substrates, and Bond and Etch-back SOI (BESOI) [2].

A. Single Mode Waveguide Realization

In the late seventies Petermann tried to realize the geometrical constraints necessary to enable realization of large cross-sectional single-mode rib waveguides. Later on, Soref normalised the Petermann's equations to determine the necessary cross-sectional dimensions for a single-mode rib waveguide. This was formulated considering the Fig. 1 as [3]:

$$\frac{a}{b} \leq 0.3 + \frac{r}{\sqrt{1-r^2}} \quad \text{(Assuming } 2b\sqrt{n_1^2 - n_2^2} \geq 1\text{)} \tag{1}$$

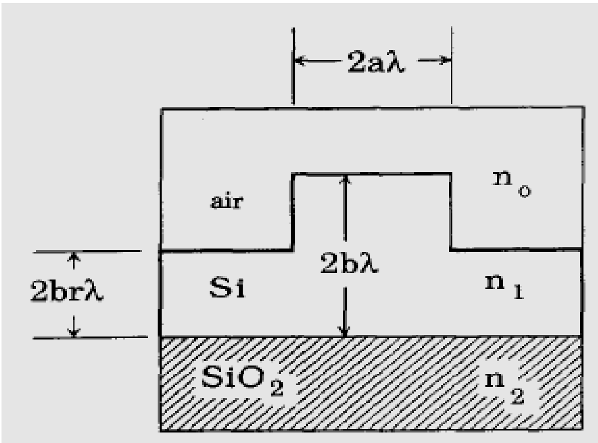

Fig. 1. Dimensions for a single mode Rib waveguide for (1) [3].

In 2004 it was proved that (1) was not completely correct to realize a single mode waveguide [4]. The formula is correct with some modifications. In the following year a single mode curved rib-waveguide was realized with the same formula as mentioned below with a modification that the formula is applicable when h/H≥0.5 (Fig. 2)

$$\frac{W}{H} \leq 0.3 + \frac{\frac{h}{H}}{\sqrt{1-(\frac{h}{H})^2}} \tag{2}$$

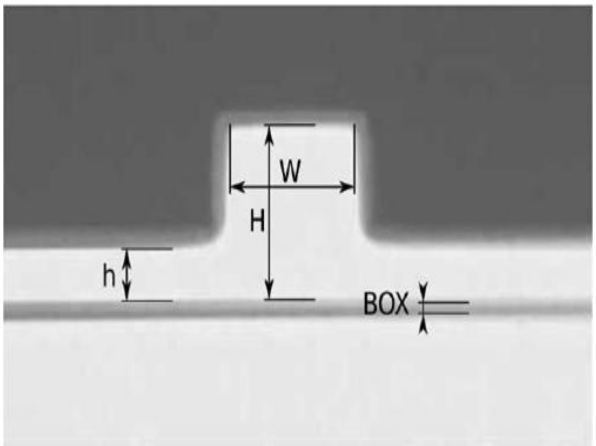

Fig. 2. Microscopic photograph showing a cross section of the realized rib-waveguide structure with dimensions [5].

We know that one of the reasons for the loss in the waveguide is due to the facet roughness which is caused by the etching process usually for dry etching. This roughness produces scattering of light which is one of the main reasons for loss in waveguide. If a facet is smooth then the scattering losses will be negligible. So using this idea in [5] they used the anti-reflection coating at the end facet of the waveguide to make it smooth by atomic layer deposition. They measured the propagation loss as 0.13 ± 0.02dB/cm at telecom wavelength for curved waveguide. To get smooth facet the etching depth is an important parameter to get a single mode waveguide.

TABLE I. Mode characteristics depending on etching depth [6].

r=3.17 (μm)						
Width, w (μm)	**Etch Depth, e (μm)**					
	0.34	0.68	1	1.28	1.68	2.01
1.69	TE_{00}, TM_{00}	TE_{00}, TM_{00}	TE_{00}, TM_{00}	TE_{00}, TM_{00}	TE_{00}, TM_{00}	MM
2.79	TE_{00}, TM_{00}	TE_{00}, TM_{00}	TE_{00}, TM_{00}	MM	MM	MM
3.62	TE_{00}, TM_{00}	TE_{00}, TM_{00}	MM	MM	MM	MM
4.5	TE_{00}, TM_{00}	MM	MM	MM	MM	MM
5.47	TE_{00}, TM_{00}	MM	MM	MM	MM	MM
6.37	TE_{00}, TM_{00}	MM	MM	MM	MM	MM

r-silicon over layer thickness, w-rib waveguide width, e-etch depth, MM-multimode

From TABLE I we can see that to get a single mode waveguide we have to consider an optimized design for width and etching depth. Otherwise the waveguide becomes multimode. Another way to find out the mode in a waveguide is the normalized frequency or V-number, which is used to characterized the mode characteristics of a waveguide (usually for optical fiber). V-number is independent of waveguide geometry. If V≤ 2.405 then only one mode will exist in the waveguide i.e. single mode, otherwise it will be multimode waveguide. For example let us consider Fig. 3.

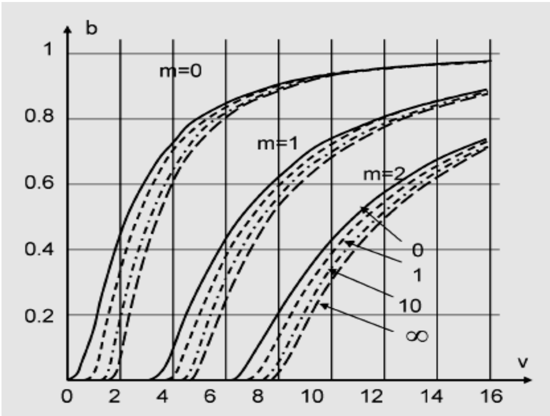

Fig. 3. Relative effective index 'b' vs. V-number 'v' for a three layer slab waveguide with asymmetry parameter [7].

In Fig. 3 above 'm' is the TE modes and asymmetry parameter a=0, 1, 10, ∞. We can see that when V≤ 2.405 then only the fundamental mode exist. i.e. it works as a single mode waveguide. When V≥2.405 then it will be multi-mode waveguide.

B. Technology

In 1988 Silica-based embedded single-mode channel waveguide was introduced with a low propagation loss. The loss was evaluated as 0.1 dB/cm. This embedded single-mode channel waveguides were fabricated by a combination of Flame Hydrolysis Deposition (FHD) and Reactive Ion Etching (RIE) [8]. In 1990 silica glass planar waveguide technology based on a combination of flame hydrolysis deposition, photolithographic and reactive ion etching processes were developed to ensure high performance and cost effective waveguide circuits [9]. The TABLE II below is taken from [9] to have an idea about the performance of the silica waveguide at that time.

TABLE II. Performance of silica waveguide [9].

Waveguide	**Core size**	**Index Diff.**	**Loss**	**Fiber-coupling loss**	
(Type)	(um)	Δ (%)	(dB/cm)	Measured	Calculated
Single-mode buried	8x8	0.25	<0.1	<0.05 dB/point*	0.01 dB/point*
Single-mode ridge	8x8	0.25	0.3	0.2 dB/point*	-
Multimode ridge	40x40	1.0	0.2	1.8 dB/(input+output)**	1.7 dB/(input+output)**

*Single-mode fiber: core = 8.9 um Δ=0.27%

**Multi-mode fiber (GI): core = 50um Δ= 1% Uniform mode excitation

It was always desired to form the optical and electrical or electronic components on the same substrate so that the IC fabrication becomes easy and economic. As a result of this idea in 1991 the formation of optical waveguides on metalized Al_2O_3 substrates by using FHD method was reported. The purpose of this invention was to form optical waveguide on metalized substrates. So that optical waveguides and integrated optical circuits can be formed on a common substrate with IC chips to enable the integration of optical integrated circuit and electronic integrated circuits on the same component [10]. In 1996, 0.1 dB/cm waveguide loss was reported at a wavelength of 1.3 μm for SOI rib waveguides fabricated by wet chemical etching method. According to the widely used formula, the single-mode waveguides have a large cross section which introduces field mismatch losses. The loss was reported as approximately 0.17 dB/facet for both polarizations [11]. This loss can be compared with the loss obtained from the waveguide fabricated by the dry etching with atomic layer deposition. The losses from these two cases are approximately same. But in case of wet etching method we do not need the atomic layer deposition step. If we consider the loss in the waveguide the wet etching method was more economic than the dry etching method. In 2008, a new technology to fabricate waveguide by using the Femto-Second Laser Pulses was introduced [12]. By using this laser pulses we can write the waveguide or waveguide based devices on the substrate by moving the laser beam as shown in Fig. 4. So there is no need of complex fabrication steps anymore.

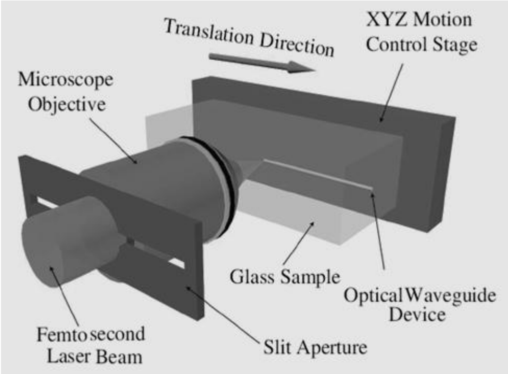

Fig. 4. Writing setup used to fabricate optical waveguide devices [12].

It was reported recently in 2009 that the recent modern technology can be used to fabricate waveguide using surface plasmons. Silicon and Metal was used to do so as shown in the Fig.5.

It was reported that the propagation distance which is more, than the conventional pure dielectric waveguide can be achieved through this hybrid plasmonic waveguide. Moreover the light confinement for the proposed hybrid plasmonic waveguide is higher than the conventional waveguides [13]. In 2010 the above theoretical approach is implemented experimentally and found almost the same performance as theoretical [14].

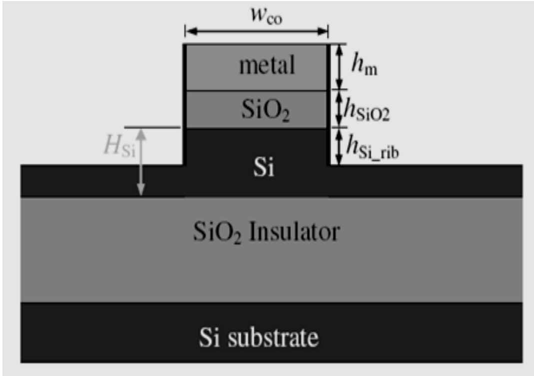

Fig. 5. Silicon based hybrid plasmonic waveguide [13].

C. *Performance*

The performance of a waveguide depends on the losses. The losses in the waveguide depend on the materials, wavelength and fabrication method used. We can have an idea from TABLE III, how the materials and fabrication method affect the loss in the waveguide [15].

TABLE III. Materials, Wavelengths, Growth Method and Corresponding Loss [12].

Material	**Growth Method**	**Wavelength (μm)**	**Structure**	**α (dB/cm)**
On GaAs				
GaAs-AlGaAs	OMCVD	1.15	DH, SM	0.65
GaAs-AlGaAs	MBE	1.15	SH,SM	1.9
GaAs-AlGaAs	MBE	1.52	DH,SM	0.4
GaAs n-/n+	VPE	1.06	LE,SM	1.5
GaAs n-/n+	LPE	1.3	SH,SM	2
On InP				
InGaAsP-InP	OMCVD	1.52	DH,SM	0.18
InGaP-InP	OMCVD	1.32	DH,MM	1.25
InGaAsP-InP	CBE	1.67	ARROW	0.9
InGaAlAs-InP	MBE	1.55	SH,MM	2.2
InGaAsP-AnP	LPE	1.3	BH,SM	6
Lattice-mismatched				
GaAs-AlGaAs on Si	OMCVD	1.3	SH,SM	0.95
GaAs-AlGaAs on InP	OMCVD	1.52	SH,SM	0.9

OMCVD-Organo Metalic Chemical Vapor Deposition, MBE-Molecular Beam Epitaxy, LPE-Liquid Phase Epitaxy, CBE-Chemical Beam Epitaxy, VPE-Vapor Phase Epitaxy, SH (DH)-Single (Double) Heterostructure, BH-buried Heterostructure, IID-Impurity Induced Disordered, SM (MM)-Single (Multi) mode

It can be observed from TABLE III that at 1.15 μm wavelength for the GaAs-AlGaAs material on GaAs the loss varies due to the growth method variation. The propagation losses 0.65 dB/cm and 1.9 dB/cm are measured for the growth methods OMCVD and MBE respectively. So the losses are varying here due to the growth method. It is also clear from the TABLE III, that when we change the material or the wavelength then the losses are also changing. By using oxidized porous silicon waveguide loss can be further reduced. The waveguide characteristics can be improved by optimizing the technological processes such as removing the swirl defects, controlling the porosity and by using the silica mask. The waveguides based on oxidized porous silicon are less lossy than others because it reduces the planar losses by swirl-defect neutralization. It was found that maximum loss value in the visible range is not higher than 0.8dB/cm [16]. Another source of loss in the waveguide is the dispersion. The loss due to dispersion in the waveguide is highly dependent on the structure of the waveguide. In 2008 it was shown for a slot waveguide the dispersion effect varies due to the slot and slab size variation [17]. So a tradeoff between waveguide size and dispersion is required.

From the discussion it is clear that the performance of the waveguide depends on the loss. One of the losses comes from the inner wall roughness of the waveguide. The total loss in a waveguide can be expressed as [6]-

$$L_t = L_a + L_{ss} + L_{vs} + L_c \qquad (3)$$

Where-

L_t = Total loss

L_a = Absorption loss

L_{ss} = Interface induced scattering

L_{vs} = Volumetric refractive index inhomogenity scattering

L_c = Coupling of guided modes to substrate modes

The loss due to roughness can be reduced by using the different fabrication method such as SOI Anisotropic Etching and SOI Oxidation Smoothing [19]. It is shown in Fig. 6.

TABLE IV. State of the art: WG performance

Year	**WG Type**	**Loss**	**Thickness/ Width/Length /Bend**	**Technology**	**Ref. [#]**
1989	Planar Silicon WG	1 dB/cm (prop.)	0.2 µm (thick)	SOI, With Burried Oxide (SiO2-Si-SiO2-Si-SiO2-Si)	02
1991	Silicon Rib WG	0.5 dB/cm (prop.)	7 µm (rib width)	SIMOX (Si-SiO2-Si)	18
1996	SOI Rib WG	0.1 dB/cm (prop.)	8 µm (width)	BESOI (SiO2-Si-SiO2-Si)	11
2001	Strip Silicon WG	0.8 dB/cm (prop.)	0.5 µm (width)	SOI, Photolithography, RIE (Si-SiO2-Si)	19
2005	Curved Silicon WG	0.13±0.02 dB/cm (prop.)	114 cm (length)	SOI, DEP (Si-SiO2-Si)	05
2005	Single Crystal Silicon WG	1.9 dB/cm (prop.)	630 nm (width)	SOI, Photolithography, WCO (Si-SiO2-Si)	20
2008	Silicon WG	6.7 dB/cm (prop.)	3.5 µm (core width)	Proton Beam Writing (250KeV)	21
2010	Hybrid Silicon Waveguide	Higher Light Confinement (Nanoscale)		LOCOS	14
2011	Planar WG	0.045±0.04 dB/m (prop.)	2.15 to 15 µm (core width)	LPCVD	22
2011	Planar WG	3 to 9 dB/m	2 to 0.5 mm (bend radius)	TriPlex LPCVD	23

2012	PhC WG	Reconfigurable WG	Selective Liquid Infiltration	24

WG- Waveguide, Prop- Propagation, SOI-Silicon on Insulator, SIMOX- Separation by IMplantated Oxygen, BESOI- Bonded and Etched-Back Silicon-On-Insulator, RIE- Reactive Ion Etching, DEP- Dry Etching Process, WCO- Wet Chemical Oxidation, LOCOS-Local Oxidation of Silicon, LPCVD-Low Pressure Chemical Vapor Deposition, PhC-Photonic Crystal.

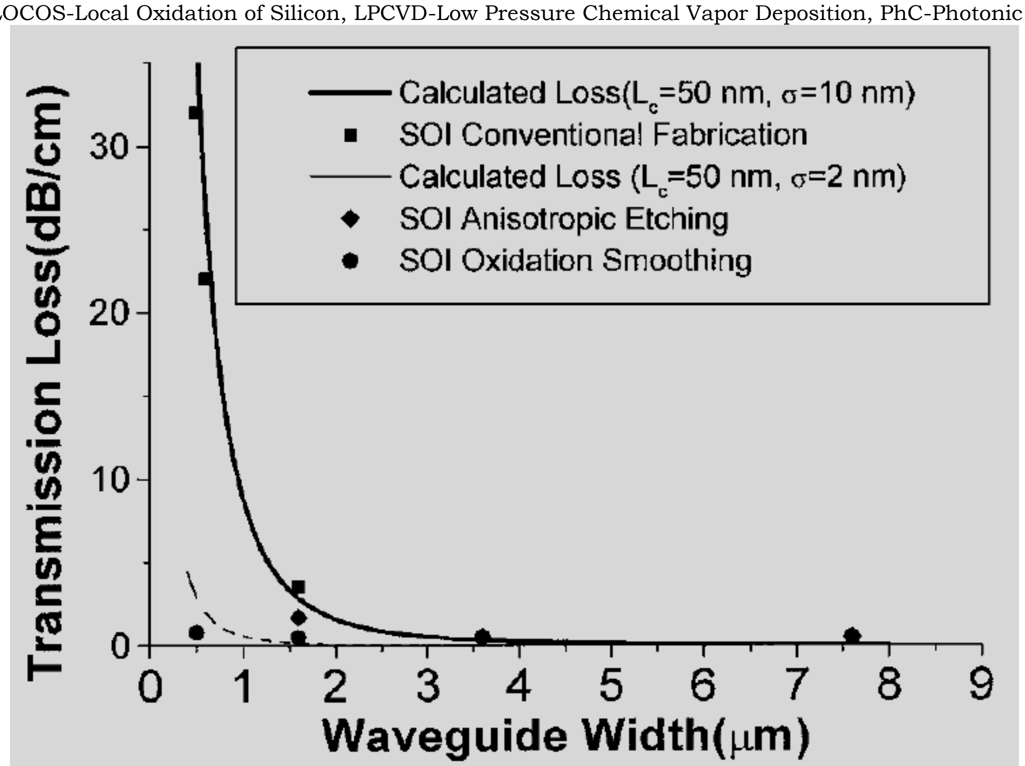

Fig. 6. Roughness loss reduction using SOI Anisotropic Etching and SOI Oxidation Smoothing, where σ:L_c is sidewall: roughness values [19]

Recently it is reported that the propagation loss as well as the loss at bend can be reduced using the LPCVD and TriPlex LPCVD technology [22-23]. They got 0.045±0.04 dB/m propagation loss having core width 2.15 to 15 µm and they got 3 to 9 dB/m bend loss having the bend radius as 2 to 0.5 mm. Moreover a new kind of photonic waveguide is introduced in [24], this waveguide's properties are flexible. That means we can reconfigure the waveguide as per our need. As mentioned before the waveguide loss also depends on the fabrication technology and it is reported in [25] that bonded thermal oxide approach (one of the fabrication technologies) has lower propagation loss.

III. CONCLUSIONS

The development of the first silicon waveguide and the recent silicon based hybrid 17 lasmonic waveguides and reconfigurable photonic crystal waveguides are discussed. The losses in the waveguides generally depend on three key factors- 1) materials for fabrication, 2) fabrication method and 3) the wavelength dependence. The loss also depends on the dimensions of the waveguide. Still now the development is going on to reduce the propagation, bend and total loss in the waveguide as well as to get the best performance in nanometer sized waveguide. So to get a good performance from a waveguide a tradeoff is required among the fabrication method, material selection and cost.

REFERENCES

[1] R.A. Soref and J.P.Lorenzo "Single-Crystal Silicon: A New Material for 1.3 and 1.6 µm Integrated-Optical Components", *Electronics Letter*, Vol. 21 No. 21, 10th October 1985, pp.953-954.

[2] G.T.Reed, W.R.Headley and C.E.Jason Png, "Silicon Photonics-The Early Years," *Proc. Of SPIE*, vol. 5730.

[3] R.A. Soref, J. Schmidtchen and K. Petermann "Large Single-Mode Rib Waveguide in GeSi-Si and Si-on-SiO2", IEEE Journal of Quantum Electronics, Vol. 27 No. 8, August 1991, pp.1971-1974.

[4] J.Lousteau, D.Furniss, A.B.Seddon, T.M.Benson, A.Vukovic and P.Sewell, "The Single-Mode Condition for Silicon-on-Insulator Optical Rib Waveguide with Large Cross Section", *Journal of Lightwave Technology*, Vol. 22, No. 8, August 2004, pp.1923-1929.

[5] K.Solehmainen, T.Aalto, J.Dekker, M.Kapulainen, M.Harjanne, K.Kukli, P.Heimala, K.Kolari and M.Leskela, "Dry-Etched Silicon-on-Insulator Waveguides with Low Propagation and Fiber-Coupling Losses", *Journal of Lightwave Technology*, Vol. 23, No. 11, November 2005, pp.3875-3880.

[6] A.G.Rickman, G.T.Reed & F.Namavar, "Silicon-on-Insulator Optical Rib Waveguide Loss and Mode Characteristics", *Journal of Lightwave Technology*, Vol. 12, No. 10, Oct, 1994

[7] R.Baets and G.Roelkens, Photonics Course Syllabus, 2009-2010, Ghent University, pp.7-9 & 10.

[8] N.Takato, K.Jinguji, M.Yasu, H.Toba and M.Kawachi, "Silica-Based Single-Mode Waveguides on Silicon and their Application to Guided-Wave Optical Interferometers", *Journal of Lightwave Technology*, Vol. 6, No. 6, June 1988, pp.1003-1010.

[9] Tadashi Miyashita, "Planner Waveguide Devices on Silicon", *0569-5503/90/0000-0055, IEEE.*

[10] Cheng-ko J.Sun, S.Sakaguchi and Tadashi Miyashita, "Circular Channel Waveguides and Lenses formed from Rectangular Channel Waveguides*", United States Patent*, Patent Number. 5,059,475, October 22, 1991.

[11] U.Fischer,T.Zinke,J.R.Kropp, F.Arndt and K.Petermann, "0.1 dB/cm Waveguide Losses in Single-Mode SOI Rib Waveguides", *IEEE Photonics Technology Letters*, Vol. 8, No. 5, May 1996, pp. 647-648.

[12] M.Ams, G.D.Marshall, P.Dekker and M.J. Withford, "Photonic Waveguide Devices Directly Written into Dielectric Materials Using Femtosecond Laser Pulses", PIERS ONLINE, Vol. 4, No. 1, 2008, pp.146-150.

[13] D.Dai and S.He, "A Silicon-based hybrid 18lasmonic waveguide with a metal cap for a nano-scale light confinement", *Optical Express*, Vol. 17, No. 19, 14 September 2009, pp.16646-16653.

[14] I.Goykhman, B. Desiatov and U.Levy, "Experimental demonstration of locally oxidized hybrid silicon-plasmonic waveguide", *Applied Physics Letter* 97, 141106, 2010, American Institute of Physics.

[15] Robert J.Deri and Eli Kapon, "Low-Loss III-V Semiconductor Optical Waveguides*", IEEE Journal of Quantum Electronics*, Vol. 27, No. 3, March 1991, pp.626-640.

[16] M.Balucani, V. Bondarenko, A.Klusko and A.Ferrari, "Recent progress in integrated waveguides based on oxidized porous silicon", Optical Materials 27, 2005, pp.776-780, www.sciencedirect.com.

[17] Z. Zheng, M.Iqbal and J.Liu, "Dispersion characteristics of SOI-based slot optical waveguides", *Optics Communications* 281, 2008, pp.5151-5155, www.elsevier.com/locate/optcom.

[18] J. Schmidtchen, A. Splett, B. Schiippert and K. Petermann, "Low Loss Integrated-Optical RIB-Waveguides in SOI", IEEE, 1991.

[19] K.K. Lee, D.R. Lim, L.C. Kimerling, J.Shin & F.Cerrina, **"**Fabrication of ultralow-loss Si/SiO2 waveguides by roughness reduction", *Optics Letters,* Vol. 26, No. 2, December 1, 2001.

[20] D.K. Sparacin, S.J. Spector, & L.C. Kimerling, "Silicon Waveguide Sidewall Smoothing by Wet Chemical Oxidation", *Journal of Lightwave Technology*, Vol. 23, No. 8, August 2005.

[21] Ee Jin Teo, A. A.Bettiol, M.B. H. Breese, P. Yang, G.Z. Mashanovich, W. R. Headley, G. T. Reed, D.J. Blackwood, "Three-dimensional control of optical waveguide fabrication in silicon", *Optics Express*, Vol. 16, No. 2, 21 January 2008.

[22] Jared F. Bauters, Martijn J. R. Heck, Demis D. John, Jonathon S. Barton, Christiaan M. Bruinink, Arne Leinse, Ren G. Heideman, Daniel J. Blumenthal, and John E. Bowers, "Planar waveguides with less than 0.1 dB/m propagation loss fabricated with wafer bonding", *Optical Society of America*, 2011.

[23] Jared F. Bauters, Martijn J. R. Heck, Demis D. John, Jonathon S. Barton, Christiaan M. Bruinink, Arne Leinse, Ren G. Heideman, Daniel J. Blumenthal, and John E. Bowers, "Ultra-low-loss high-aspect-ratio Si3N4 waveguides", *Optical Society of America*, 2011.

[24] A. Casas Bedoya, P. Domachuk, C. Grillet, C. Monat, E.C. Magi, E. Li, and B.J. Eggleton, "Reconfigurable photonic crystal waveguides created by selective liquid infiltration", *Optics Express*, Vol. 20, No. 10, 2012.

[25] Jared F. Bauters, Martijn J. R. Heck, Demis D. john, Jonathon S. Barton, Daniel J. Blumenthal, john E. Bowers, Christiaan M. Bruinink, Arne Leinse, and rene G. Heideman, "A Comparison of Approaches for Ultra-low-Loss Waveguides", OFC, 2012.