OPTIMIZATION OF LINE PATTERN TRANSFER OF INTEGRATED OPTICAL MACH-ZENDER INTERFEROMETER FOR OPTICAL SENSOR

by

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LIST OF ABBREVIATIONS

AFM	Atomic Force Microscope
ANOVA	Analysis Of Variance
CD	Critical Dimension
CMOS	Complementary Metal Silicon Oxide
DFM	Dynamic Force Microscope
DI	Deionized
DOE	Design Of Experiment
DRM	Development Rate Monitor
EUV	Extreme Ultra-Violet Radiation
HPM	High Power Microscope
IC	Integrated Circuit
IO-MZI	Integrated Optical Mach-Zehnder Interferometer
LED	Light Emitting Diode
LOC	Lab-On-Chip
MEMS	Micro-Electro-Mechanical System
NSL	Nanosphere Lithography
PAC	Photoactive Compound
pH	Potential For Hydrogen
PPA	Periodic Particle Array
PR	Photoresist
RIE	Reactive Ion Etching
RPM	Rotation Per Minute
sccm	Standard Cubic Centimeter Per Minute
SPM	Filmetric F20 Spectrophotometer

SPR	Surface plasmon resonance
TFT-LCD	Thin Film Transistor-Liquid Crystal Display
TIR	Total Internal Reflection
UV	Ultra-Violet

LIST OF SYMBOLS

V_{ac}	Alternating Current
CO_2	Carbon Dioxide
cm	Centimeter
S_{rx}	Constant Thickness Removed
S_{rt}	Constant Time For Resulting Thickness
^0C	Degree Celcius
Δ	Delta (Total)
ε_r	Dielectric Constant
S_{rg}	Dissolution Rate At 40% Dose
S_r	Dissolution Rate Ratio
n_{eff}	Effective Refractive Index
e^-	Electron
d_1	Final Thickness
t_2	Final Time
F	Fluorine
HF	Hydrofluoride Acid
H	Hydrogen
H_2	Hydrogen Gas
d_0	Initial Thickness
t_1	Initial Time
L	Interaction Length
J	Joule
λ	Lambda
$<$	Less Than
m	Meter
µm	Micrometer
$>$	More Than
nm	Nanometer
NO_2	Nitrogen Dioxide
N_2	Nitrogen Gas
O_2	Oxygen Gas
%	Percentage
I	Periodicity

φ	Phi (Phase Shift)
π	Pi
±	Plus Or Minus
KOH	Potassium Hydroxide
n	Refractive Index
s	Second
SiF_4	Silane
Si	Silicon
Si_3N_4	Silicon Nitride
SiO_2	Silicon Oxide
NaOH	Sodium Hydroxide
CF_4	Tetra Fluorocarbon
CF_3	Trifluorocarbon

Pengoptimuman Pemindahan Garis Lurus Meter Gangguan Mach-Zehnder Optikal Bersepadu Untuk Penderiabio Optikal

ABSTRAK

Konvensional fotolithografi sering digunakan dalam proses fabrikasi di dalam makmal untuk pemindahan corak garis pandu gelombang optik untuk aplikasi Penderiabio Optikal. Meter Gangguan Mach-Zehnder optikal bersepadu (IO-MZI) telah digunakan secara meluas untuk aplikasi penderiabio optikal. Kajian ini mengaplikasikan asas pengoptimuman proses fotolitografi di dalam makmal, berpandukan pemindahan corak garis pandu gelombang optik pada cip untuk aplikasi penderiabio optik. Oleh itu, adalah penting untuk mendapatkan pemindahan corak garis yang baik dengan kelebaran yang kecil iaitu kira-kira 4μm dan 3cm panjang, yang mana mempunyai kelebihan ketara untuk meningkatkan sensitiviti penderiabio. Walau bagaimanapun, kadar kejayaan pemindahan corak IO-MZI adalah sangat rendah dengan menggunakan proses kepelbagaian pembangunan konvensional. Salah satu faktor utama adalah pencemaran zarah yang disebabkan oleh penggunaan semula cecair pembangunan. Dalam kerja ini, proses pembangunan tunggal yang inovatif telah dicadangkan dengan meggunakan penyediaan yang sama. Konsep kaedah ini bepusat pada pengoptimuman jumlah masa pembangunan berasaskan kadar pembangunan model eksperimen dan matematik. Selain itu, proses pembangunan tunggal yang dicadangkan telah meningkatkan kadar kejayaan pemindahan corak IO-MZI daripada 30% (kaedah pelbagai pembangunan) kepada 90% (proses pembangunan tunggal). Pencirian pembangunan tunggal dalam proses fabrikasi di makmal telah meningkatkan kejayaan fotolitografi bagi pemindahan garis lurus dan pemindahan corak reka bentuk yang lebih kompleks.

Optimization of Line Pattern Transfer of Integrated Optical Mach-Zehnder Interferometer for Optical Biosensor

ABSTRACT

Conventional photolithography usually used in in-house fabrication process to transfer the design of line pattern. This research lays the foundation for the optimization of photolithography process for line pattern transfer of complex optical circuitry. Integrated Optical Mach-Zehnder Interferometer (IO-MZI) has been widely used for biosensor applications. In order to have a significant advantage in improving the sensitivity of the biosensor, it is crucial to get a good, consistent and conformal line pattern transfer with a fine width; in our case is approximately 4μm and 3cm length. However, the success rate of IO-MZI pattern transfer had been low using the conventional multi-development process. One of the main factors is the particle contamination due to the usage of reused developer bath. In this work, an innovative single development process had been proposed with the utilization of the same conventional set-up. The concept of this method centers around the optimization of the total development time based on the experimental and mathematical model of the development rate. By doing so, the development process can be completed with only one immersion of the substrate in the developer bath. Due to this reason, the aim of this project is to improve the success rate and repeatability of photolithography process without compromising the resolution and vertical profile, which is necessary for the optical waveguide fabrication. Besides, the manipulation of development rate by varying exposure time in this work also revealed the possibility of manipulation of line-width based on the exposure time. In short, the proposed single development process had increased the success rate of IO-MZI pattern transfer from 30% (multi-development method) to 90% (single-development method). The characterization of in-house single development fabrication process has improved the current photolithography setup for line pattern transfer and complex design pattern transfer.

CHAPTER 1

INTRODUCTION

1.1 Overview of sensor

As the demand for improving the quality of human health blooms, the role of optical sensor has been steadily increasing in term of communication data transfer, detecting and analyzing body movement, temperature or fluids and turning chemical or mechanical signal into an electrical signal. In addition, the sensor is available to be integrated into a self-contained device that is able to provide accurate information or semi-quantitative analysis, quantitative biology by identifying the elements that come into contact directly with the transduction element (Momsia, 2013). Optical sensors use principles of light to quantify object characteristics. Optical sensors have a variety of uses and therefore they are made according to their requirement at different places. There are large numbers of optical sensors available to meet the demands in industrial and any other sector. The application of these sensors ranges from computers to motion detectors (Fan et al., 2008; Wang et al., 2012; Yildirim, Long, & Gu, 2014; Filho, Lima, & Neff, 2014; Kashem & Suzuki, 2015).

Research and development in the optical sensor field is motivated by the expectation that optical sensors have significant advantages compared to conventional sensor types in terms of their properties. The advantages of optical over non-optical sensors are greater sensitivity, electrical passiveness, freedom from electromagnetic interference, wide dynamic range, and multiplexing capabilities. Optical sensor usually has two points. One is the transmitting point where light is emitted and the other end is the receiving end. Generally there are three types of optical sensor which is through beam (Shchepakina & Korotkova, 2010; Papadopoulos et al., 2012), reflective (Xia et al., 2010; Kou et al., 2010; Dubra & Sulai, 2011) and retro reflective (Jin & Holzman, 2010; Lengsfeld & Shoureshi, 2011; Mihailov, 2012).

Integrated optical Mach-Zehnder interferometer (IO-MZI) is one of the types of optical sensor. Among the various types of optical sensors, IO-MZI devices have been gained much attention for chemical or biological sensing applications due to high sensibility, mechanical stability and the integration in silicon based devices (Fan et al., 2008; Densmore et al., 2009; Duval, et al., 2013). Lots of researches about optical waveguide have been reported in last decade. Integrated optical Mach-Zehnder interferometer (IO-MZI) structure is always a component among them. These devices usually used as data transfer for optical telecommunication purposes. These devices also can offer high extinction ratio of 30dB, low insertion loss of 0.9dB, and large operating range with 100nm . Moreover, optical waveguide are compact and compatible with optical integrated circuit.

Despite different type of waveguide materials, these sensors share a common feature which is the large devices area of approximately 3cm to 4cm in length (Prieto, et al., 2003; Sepúlveda et al., 2006; Hong et al., 2006) with waveguide width of only the 4µm to 5µm. Long length dimension is required to improve the sensitivity while the narrow width is needed to maintain mono-mode behaviour of the waveguide. Besides, small line-width variation is necessary to reduce the variation of line width that can lead to mode conversion loss. This particular feature of IO-MZI sensor had resulted in a challenge in the fabrication process of the pattern transfer, particularly the photolithography process.

There is an array of photolithography technology available nowadays. The first type of photolithography process is the conventional photolithography process that undergoes a common string of processes such as spin coating of PR, soft bake, exposure, post-exposure bake, development process, and hard bake. The second type of photolithography process is the soft lithography (Xia & Whitesides, 1998). Soft lithography applies non-photolithographic strategy by self-assembled structures and replicating designs using molds for carrying out micro-fabrication or even nanofabrication (Xia & Whitesides, 1998). This photolithography process is more convenient, low cost and efficient compared to the conventional photolithography process (Xia & Whitesides, 1998). The third type of photolithography process would be the nanosphere lithography (NSL) process (Hulteen & Van Duyne, 1995). NSL is used to produce a periodic particle array (PPA) surface having nanometer scale features (Hulteen & Van Duyne, 1995). A variety of PPA surface could be prepared by using identical single layer or double layer masks made by self-assembly of polymer nanospheres with a diameter of 264 nm (Hulteen & Van Duyne, 1995).

The fourth example of photolithography process would be electron beam lithography process. Electron beam lithography emphasizes on fabricating device at the nanometer scale (Tseng et al., 2003). Due to the very short wavelength of the electron beam and reasonably energy density characteristics, electron beam lithography surpasses the conventional photolithography to produce device pattern at nanometer scale (Tseng et al., 2003). The electron beam lithography generally applies the step-and-scan writing strategy instead of step-and-repeat scheme normally used in photolithography system (Tseng et al., 2003).

The key innovative improvement from the conventional photolithography, which used the multi-development process, to single development process is to transfer the line pattern successfully without overdeveloping the pattern. The optimized single development process based on manipulation of development rate holds great promise for the advanced polymer deposition, allowing different patterns (continued and discrete) to form on a variety of substrates. This technique is used in this research for transfer waveguide pattern in fabrication process and thus providing a highly simplified fabrication process.

1.2 Problem Statement

Figure 1.1 shows the multi development process which is commonly used in the in-house cleanroom laboratory mainly because it is simple to use and the developer bath can be re-used to reduce waste of developer. This multi-development method had been a success for pattern transfer with design of big feature size (w > 0.5mm). However, it suffers more disadvantages when complex and fine design is involved such as IO-MZI in this case (Madou, 2011; Lau, Khor, & Shahimin, 2014). The factors include the possible mishandling of wafer that causes the non-uniform development rate across the substrate and particle contamination in the re-used developer bath.

Mishandling of wafer is mainly caused by the use of tweezers to hold the wafer in a horizontal position which is not suitable for the procedure of immersion. Using the tweezers to retrieve the wafer for silicon dice from a developer bath is very difficult and almost impossible to achieve within seconds. Thus, the mishandling of wafer using tweezers gives rise to two major problems in multi development process. First, the multi immersion step required by multi development process increase significantly the risk of wafer mishandling which all too often causing rework which in turn wasteful in time and resources. Besides, being not able to retrieve the wafer immediately also increases the risk of over-development and thus failure in pattern transfer.

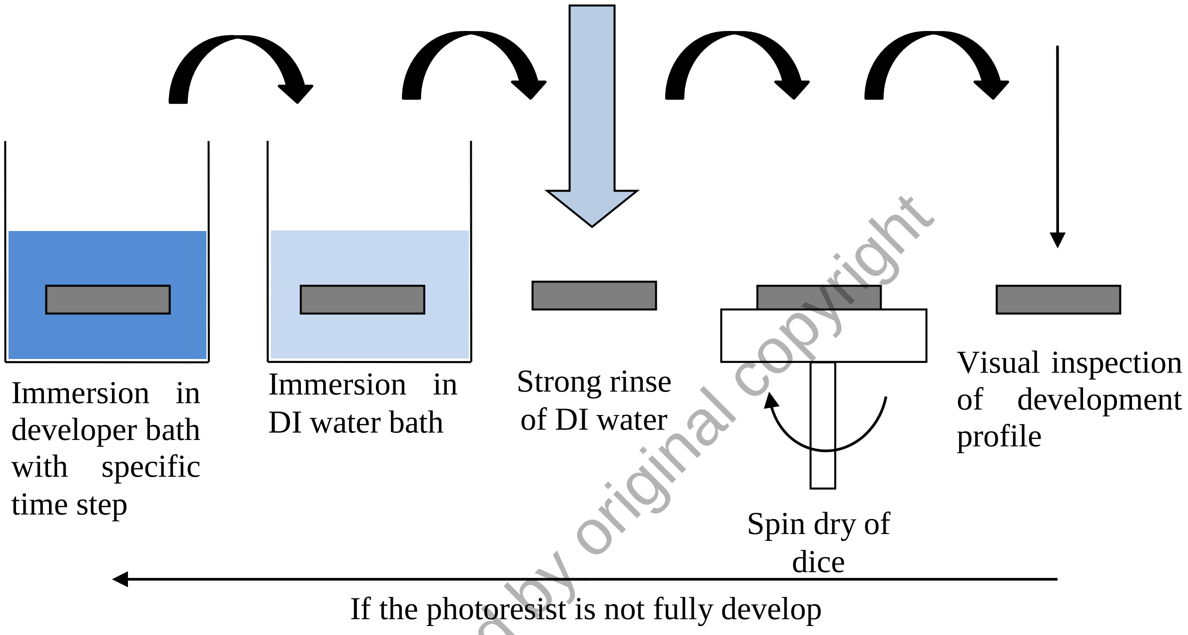

Figure 1.1: Process flow of the conventional multi development process.

Another important issue of using multi development process in fine pattern transfer is the particle contamination. Particle contamination is always a major issue in micro fabrication and most of the efforts had been given in getting rid of this problem through either the improvement in ventilation system or the equipment standard operating procedure to reduce the generation of particle. The multi development process however require the reuse of developer as vast volume of developer is needed to support the multi immersion step of silicon dice or wafer as well as to optimize the usage of developer. As developer is reused, the removed photoresist from the substrate remains in the developer when the subsequent development process is performed. Due to this reason, there is a high risk whereby this photoresist particle might contaminate the substrate and thus the fine and complex pattern to be transferred.

Besides, due to the fine line width of IO-MZI, visual inspection using bare eye which is usually done to reduce process time is almost impossible in this case. As a result, visual inspection can only be done by using high power microscope. In order to do so, the silicon dice or wafer must first be cleaned and spun dry properly and this again adding extra processing time. The most important drawback of using multi development process in fine line pattern transfer is the high risk of over development process (Rathsack et al., 1999; (Borah et al., 2011). This is because development time needed is totally unknown usually and the completion of development process is fully relied on visual inspection. Addition to this, the performance of developer also degrades over time and the amount of photoresist removed.

Due to this reason, an innovative single development process had been introduced in this work for the aim to improve the success rate of IO-MZI pattern transfer. The main idea of single development process is to reduce the multi-development process into only one process so that the all mentioned disadvantages caused by multi-development step can be eliminated and this idea is similar to the advanced puddle development process commonly used in the industries. In order to do so, total development time must be accurately estimated based on the actual development rate which is the challenging part of this work.

In addition to this, this research will optimized the single development process in photolithography. It is an innovative idea to further increase the success rate is to manipulate the development rate based on the manipulation of process parameter including baking temperature, exposure time and developer concentration. By using this innovative single development process, pattern transfer of IO-MZI as well as other complicated optical devices can be achieved with high success rate.