Patterning of Optical Gratings for Photonic Applications Using a Focused Ion Beam Technology

Natalia Salamon, Technical University of Lodz

Abstract

In this paper the optimization of the production process of optical gratings using a focused ion beam technology is presented. A focused ion beam system (FIB) is a tool in which the ion beam is directed towards the sample, and upon interaction, it generates signals that are used to create the high magnified images of the sample. The main abilities of the FIB, namely milling, imaging, selective etching and material deposition, make it a multifunctional tool for the microelectronics [1]. The work presented in this paper was aimed at fabricating special grating couplers for photonic applications. Because of the fact that the fabrication of these structures with an assistance of the traditional photolithography was impossible due to their non-standard geometry, the FIB technology had been used. The influence of each parameter on the etch depth as well as on the quality of etches was examined. The parameters considered as the most important for evaluation were as follow: the beam current, the dwell time, the overlap, the type of the gas that should be used to enhance etching process and the time of the process. The way of optimization of the production process, measurements and results’ analysis are presented.

1. Introduction

Nowadays the dimensions of the electronic devices are getting smaller almost every day. The customers have higher expectations, which results in necessity of designing more advanced integrated circuits. Due to that tendency the companies are faced with a necessity of finding new techniques for improvement, modification and testing of new equipment. For this reason the electronic industry is continuously improving standard procedures and decreasing time and costs, which is necessary to introduce a competitive product. The properties of the FIB make it an attractive technology to reduce both cost and turnaround time. This paper presents the possibility of using the FIB system for photonic applications.

The miniaturization of optical waveguides below the range of is one of the approaches to reach more optical functions on a single integrated circuit. This can be obtained in semiconductor materials such as silicon or indium phosphide. The attractiveness of FIB etch method in the area of photonics lies in the fact that extremely small structures can be directly fabricated, because of the beam size below 10 nm [1]. Hence the main motivation for using it comes from need of nanostructuring with features much smaller than the wavelength of light without intermediate lithography and subsequent. Several of these photonic applications involve materials or material combinations that are hard to etch using more conventional chemical methods. The FIB is the only one technique that is well suited to flexibly fabricate and modify nanophotonic structures with complex geometries [2].

2. Endfire coupling

In the past, the endfire coupling was the most practical way to couple the light from optical fiber to a silicon waveguide. With miniaturization, however, this process becomes more difficult, due to the larger mode mismatch between the coupled fiber and the waveguide.

As there is shown in Fig. 1, the loss of the light is low at a large coupled waveguide and it becomes bigger when the waveguide dimensions are smaller.

![Fig.1. Losses of the light during coupling the light from optical fiber to silicon waveguide, depending on the waveguide size (results for 4µm, 1,5µm and 0,22µm waveguide.)](image)

For a waveguide with the size of several hundred nanometers, the loss of the light can achieve even 30dB, which is completely unacceptable. Because of that, it was necessary to find another way to couple light to small waveguides.
Silicon photonic integration technologies are focused mainly on adapting microelectronic industry tools to evolve very large scale integration photonic components and circuits. The silicon nanophotonic circuits can exhibit a very high level of functional integration, due to the very small cross sections of the silicon waveguides. However, such circuits (with typical dimensions of 200nm × 500nm) must be interfaced with optical fibers that have much larger dimensions, typically 10µm × 10µm. This large deviation in dimensions is an important problem that must be solved in order to minimize the coupling loss [3]. The diffraction grating coupler is one of the best candidate to perform this mode size conversion with good performances [4].

3. Grating couplers

Fiber grating couplers are diffractive structures coupling an optical fiber and a light waveguide of the nanophotonic circuit. They are placed at the end of a lateral taper and create an exiting mode having the same dimensions as a single mode fiber, making possible a direct butt coupling between the fiber and the waveguide on the chip. Such couplers allow light coupling without the need of dicing the chip previously, which enables wafer-scale testing of nanophotonic circuits [5].

Fig.2 displays the difference in dimensions of fiber and waveguide mode (a) for endfire coupling and the difference between a fiber mode and the field emitted by grating coupler (b). The x axis presents diameters of both modes, whereas y axis shows relative electric field.

3.1 Shallow grating coupler

The conventional grating design (Fig.3) consists of shallowly etched rectangular trenches in a broad silicon waveguide. However, due to the diffraction into the substrate and the mode mismatch, the experimental fiber-to-waveguide coupling efficiency is rather low. To increase the efficiency of upward diffraction the grating slits must be better designed.

3.2 Slanted grating coupler

One of the method to enhance the coupling efficiency is the use of slanted slits, as it is shown in Fig.4.

In Fig.5, the comparison of two graphs that show the outcoupling efficiency as a function of wavelength for the shallow grating coupler(a) and for the slanted gratings (b) is presented.

The plots show that in the first case the efficiency achieves about 60% whereas, for the tilted couplers, it is much higher and can reach even more than 80%. Unfortunately, such gratings are not manufacturable with standard processes of IC fabrication. This is the reason for using the FIB system to optimize the production process of such promising for photonic application structures.

4. Optimization of grating couplers production process

In order to produce high-quality grating couplers the best parameters had to be found. All the investigations were made using a Dual Beam system which is a type of the FIB combining both, the FIB and the SEM (Scanning Electron Microscopy) in
a single system, which expands the capabilities of the FIB by the possibility of performing electron beam assisted inspection and deposition, which is less harmful than using the ion beam. The ion column is typically used for selective removal of the material by ion beam milling, whereas the electron column allows to nondestructive, high resolution imaging and analysis [6]. The advantage of using electrons instead of ions for imaging is that surface features are better preserved because much less sputtering occurs from the impinging electrons.

The parameters considered as the most important for evaluation were as follow: the beam current defined as the amount of ions emitted as the ion beam per time unit; the dwell time corresponding to the time of the ion beam lasting at a certain position; the overlap that defines the percentage of the beam overlap between neighboring points; the type of gas that should be used to enhance etching process and the time of the process.

The shallow gratings were produced with or without the gas enhancement by using the ion beam with three different values of current, 1pA, 4pA and 11pA, five values of the dwell time, 0,1µs, 2,5µs, 5µs, 7,5µs, 10µs, five values of the beam overlap, 0%, 25%, 50%, 75% and 99% and for different times of the total procedure. The depth of slits was measured to determine the influence of each parameter on the etch depth. The quality of the etches was checked as well. After finishing that part of the work, the best parameters of the shallow gratings were chosen. The second part of measurements was aimed at producing good overall quality slanted slits.

In order to make the correct analysis of obtained results, it is necessary to understand the scanning method used by a Dual Beam. The method used to distribute the ion beam on the surface of the sample is called the raster time one. In that technique, the single frame is a sequence of the operations necessary to scan all the area once and to go back to the start position, as it is depicted in Fig.6.

The frame time describes the time that is necessary to scan a single frame of the FIB box. It depends on the number of pixels and the dwell time that is the time of the ion beam lasting at a certain pixel. The vertical refresh time is the delay time between the end of the one frame and the beginning of another one. During the vertical refresh, the beam remains blanked. The beam overlap defines the percentage of the beam overlap between neighboring points, in which the beam is milling. Fig.7 depicts the positions of each beam spots during the milling process with different values of the overlap.

5. Results

5.1 Beam current influence on the etching process

In order to check its influence on the etching process, slits for three different values of the beam current were created at constant values of the dwell time and the overlap. The dwell time was fixed to 10µs and the overlap to 50% whereas the etching time was different for each slit in order to find a function showing the etch depth dependence on the time of the process.

Fig.8 depicts a function showing the etch depth dependence on the time of the process for three different values of the beam current: 1pA, 4pA and 11pA. The results shown in Fig.8 prove that a higher beam current results in a higher etch rate. The same depth of the slit can be obtained much faster for the higher current than for lower.

5.2 Dwell time influence on the etching process

Many measurements were done in order to check how the etching process depends on the dwell time. The fabrication of the structures was carried out in the etching process without gas enhancement for the beam overlap 75%, the beam current 4pA and five different values of the dwell time 0,1µs; 2,5µs; 5µs; 7,5µs; 10µs, respectively. In Fig.9, the etch depth as
a function of time for parameters placed is depicted.

Fig. 9. The etch depth as a function of time for etching process without gas, 4pA beam current, 75% overlap and different values of the dwell time (0, 1µs, 2,5µs, 5µs, 7,5µs, 10µs).

Fig. 10 shows the etch depth as a function of time for etching process enhanced by a gas (iodine). Although the values of the dwell time, the overlap and the beam current were exactly the same as in the process without the gas enhancement (Fig.9), the big difference in slits’ depth occurs.

Fig. 10. The etch depth as a function of time for etching process with gas, 4pA beam current, 75% overlap and different values of the dwell time (0, 1µs, 2,5µs, 5µs, 7,5µs, 10µs).

In both cases, one can notice that for the large dwell time, the depth of etch is low. Such results could be obtained due to drilling in the same point for a long time. It produces a lot of sputtered material that cannot be removed effectively and remained in the vicinity covering the places for the next drilling processes. This way, when the ion beam starts to drill in these places, most of the time, it is drilling in the sputtered material. Fig. 10 shows that the gas application helps in the transport of the sputtered material allowing the larger dwell time, but the general tendency remains the same, the lower dwell times gives better effects in the drilling process.

5.3 Overlap influence on the etching process

In order to find the etching process dependence on the overlap percentage, the slits were created using different overlap values and constant values of the dwell time and the beam current. The function showing the etch depth dependence on the time of the process is presented in Fig.11.

Fig.11. The etch depth as a function of time for etching process without a gas, 1pA beam current and different values of overlap (0%, 25%, 50%, 75%, 99%).

The influence of the overlap on the etching process is not fully clear. One can notice that general, the etch rate is larger for the larger overlap, although in the case of overlap values equal to 0% and 99% some differences occur. Since the measurement results were random to a large extent, unfortunately, one cannot be sure the reasons of the observed discrepancies.

5.4 Gas influence on the etching process

There were two possibilities to enhance the etching process with a gas in the Dual Beam system. One can use the more reactive xenon difluoride (XeF₂) or the less reactive iodine. The results obtained with the etching process using XeF₂ are presented in Fig.12. The extremely high damages of the surrounding structures shown in Fig.12 prove that the etching enhanced by such a reactive gas as xenon difluoride is impossible to control for our small etch depths. If the waveguide, in which the gratings are produced, is damaged by introducing even small roughness, it will become very lossy. For that reason, to enhance etching process the iodine had been chosen.

Fig.12. The damage to the surface caused by XeF₂.

In Fig.13, the etch depth dependences on the time for etching process with and without gas are plotted. The gas influence on the etching process is clear. The application of gas, which helps to remove the sputtered material, makes the etch rate much higher, but using too reactive gas, such as XeF₂, causes too much damage of the etching surface,
which completely unacceptable during a fabrication of very small structures.

![Fig.13. The etch depth as a function of time for the etching process with and without a gas enhancement.](image)

### 5.5 Quality of etch

The quality of etch is equally as important as the possibility of the etch depth control. In order to examine the quality, the side wall angle of etch was measured. The difference between the angle that should be obtain and the angle that was actually fabricated is plotted as a function of the etch depth in Fig.14.

![Fig.14. The difference between the angle that should be obtain and the angle that was actually fabricated as a function of the etch depth.](image)

When there is a low or almost zero difference in the etch angle, the quality of etch is good. In such a case, the side walls of the slit are parallel as it is shown in Fig.15. This case is represented in Fig.14 by the green line indicating that all the measured slits had parallel side walls.

![Fig.15. Good quality slits.](image)

The blue line corresponds to bad quality with high differences in the etch angles or high deviations occurs, when one can observe a V-shape slit, as it is shown in Fig.16.

![Fig.16. Bad quality slits.](image)

The etch is also unacceptable when there are roughness on the surface of the created slit. This kind of defect is depicted in Fig.17.

![Fig.17. Bad quality slits; roughness makes the waveguide very lossy.](image)

When all the measurements for shallow grating couplers were made, the parameters giving the best quality of etches were chosen. The manufacturing of good tilted grating couplers was the next part of the work. In order to produce them, the parameters that gave the best effects for normal slits had been used and the influence of the different time of the process on the quality of tilted slits had been checked. Fig.18 covers two pictures of manufactured tilted gratings with three periods, one of good quality (a) and one destroyed (b). The parameters chosen to etch both the gratings were the same. The dwell time value was 7,5μs and of the beam overlap was 75%. The time of the process that lasted 6min30 for good quality gratings and 7min30 for destroyed ones was the only difference between both the processes. Obtained results proved that not only well chosen parameters influence on the quality of etches but also the beam time that cannot be too long. This is an important result because it means that it is not possible to obtain a desirable etch depth just by using higher beam time.

![Fig.18. Tilted gratings with three periods, one with good quality (a) and one destroyed (b).](image)
6. Conclusions

In this work the investigations of the production process of grating couplers for photonic applications are presented. From the presented experimental results and analysis of the influence of different parameters on etching process some conclusions can be drawn. At first, it has been found that the larger beam current results in the higher etch rate and for the higher current the same slit depth can be reached much faster than for the lower one. The best results were obtained for the beam current equal to 4pA. The slits etched by the beam current 11pA were too deep and the process was difficult to control. The influence of the dwell time on etching process is different, so with its higher value the etch rate is lower although the effective dose is higher due to a larger fraction of the scan time within one frame. The reduction of etch rate with longer drilling in the same point location produces a lot of sputtered material in the vicinity of the location, which cannot be removed effectively. Therefore, the ion beam is drilling a considerable amount of sputtered material. For the lower dwell time, the process seems more effective e.g. less sensitive to the remainder of previous scan frames. Below the dwell time 0,1µs, however, the measurement results were completely random, which could be caused by the limits of the machine. The influence of overlap on the etching process was not so clear. One could observe that for the higher overlap the etch rate was higher but most of the results were random especially for the beam overlap equal to 99% and 0%. The gas usage makes the etch rate much larger in comparison to the process without the gas enhancement, because it helps to remove the sputtered material away. With the gas enhancement, the better quality of etched surfaces can be reached. The experiments revealed that the choice of proper gas and is very important. etching with a more reactive one (XeF₂) caused so much damage to the sample that it made the waveguide very lossy and the etching process impossible to control for small etching. The measurements shown that too long etching process worsened the quality of etches. It means that not only well chosen parameters influence on the quality of etches but also the beam time, so that it is not possible to obtain a desirable etch depth just by using higher beam time. The best results were achieved for the beam overlap 50 and 75% and the dwell time 5µs and 7,5µs, in the etching process enhanced by iodine.

Bibliography


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Authors:

MSc. Natalia Salamon
Technical University of Lodz
ul. Wolczanska 211/215
90-924 Lodz
tel. (42) 631 26 81
fax (42) 636 80 24
email: natt.salamon@gmail.com