Monolithic formation of thin films on the vertical surface of a substrate by a dual-ion-beam sputtering technique

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We have developed a novel method for the selective deposition of thin films on the vertical surface of a planar substrate with a vertical step. This was done with a dual-ion-beam sputtering apparatus that is equipped with two ion-beam sources. Using this technique a multilayer filter was monolithically formed on the vertical surface of a Si substrate on which a photodetector had been fabricated, and clear filtering-photodetecting characteristics were observed. This technique can be applied to the monolithic integration of thin-film devices and waveguide-type optical devices with a vertical end facet.

Key words: Integrated photonics, thin film, ion-beam sputtering, multilayer filter, selective deposition.
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1. Introduction

A rf bias-sputtering technique, with which rf power is supplied simultaneously to the target and the substrate, has been proposed to form a smooth film on a rugged substrate.^{1,2} This technique was applied to the deposition of dielectric films on a substrate with a large vertical step of 20–30- μm height by a group including one of the authors, and the phenomenon that dielectric films can be selectively deposited on the sidewall of the substrate step, as shown in Fig. 1, was discovered.^{3–5} Since this sidewall is perpendicular to the surface of the substrate, the sidewall of the step is referred to as the vertical surface, otherwise known as the vertical surface-selective deposition (VSSD) method.⁵ This method is useful for monolithic integration of thin-film devices such as a multilayer filter and waveguide

devices that have a vertical end facet such as in etched mirror semiconductor lasers. Using this method, a multilayer filter consisting of 17 layers of $\text{TiO}_2/\text{SiO}_2$ was formed on the vertical surface of a (110) Si substrate, on which a photodetector had been fabricated prior to thin-film deposition, and clear filtering-photodetecting characteristics were observed.⁴

Two problems remain with regard to the shape of the deposited film: one is a steep angle at the top corner of the thin film, and the other is the damage to the top corner of the Si substrate as shown in Fig. 1. In this study we aim to solve these problems by introducing the ion-beam sputtering (IBS) apparatus shown in Fig. 2.

2. Principle of Vertical Surface-Selective Deposition by the rf Bias-Sputtering Technique

Let us suppose the deposition and etching of film on a substrate with an inclined slope as shown in the inset of Fig. 3. The target material and Ar^+ ion are considered to impinge on the substrate almost perpendicularly. The angle of the slope is designated as θ . With rf bias sputtering, the deposition and etching rates have different angular dependences as shown by the dashed curves in Fig. 3. The etching rate has its maximum value around $\theta = 40^\circ$ because of the so-called oblique incidence effect, and when $\theta = 90^\circ$ the rate approaches zero. On the other hand, the deposition rate decreases monotonically with an increase of θ , and when $\theta = 90^\circ$ the rate

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Fig. 1. Problems with the VSSD method when rf bias sputtering was used.

should theoretically be zero. However, it is not actually zero because the target material deposited on the horizontal surface is resputtered by the rf bias power and is redeposited on the vertical surface.³

Now let us suppose film deposition on a substrate with a vertical step. In this case there are only two angles on the substrate, i.e., 0° (horizontal surface) and 90° (vertical surface). The ratio of rf powers applied to the target and the substrate can be controlled so that the deposition rate is balanced with the etching rate on the horizontal surface ($\theta = 0^\circ$) and is greater than the etching rate on the vertical surface ($\theta = 90^\circ$) as shown by the dashed curves in Fig. 3. Then a film can be selectively formed on the vertical surface.

However, there have been two problems as shown in Fig. 1. The first is a steep angle (referred to as the peculiar angle θ_p) that is caused by the existence of an angle at which the deposition rate is balanced with the etching rate as well as $\theta = 0^\circ$ as shown in Fig. 3. Once the surface with this angle appears, the cross-sectional shape of the film deposited on the vertical surface is limited to the shape of a trapezoid bounded by horizontal and vertical lines and peculiar angle θ_p . Therefore, the existence of the peculiar angle reduces the available flat area of the film. The second problem, damage to the top corner of the substrate, is caused by the concentration of the electric field on the top corner. Since the surface of the substrate has a uniform electric potential, the electric field is more likely concentrated on a sharp edge such as the top corner of the step. Because the plasma exists near the substrate with rf bias sputtering, the Ar^+ ion impinges on the top corner more frequently than on the other part along this concentrated electric field.

To solve these problems, we introduced a dual-ion-beam sputtering apparatus.

Fig. 2. Schematic configuration of the IBS apparatus.

Fig. 3. General deposition and etching characteristics versus slope angle of the substrate. The dashed curves correspond to the Ar^+ ion and target particles that impinge on the substrate perpendicularly, as indicated by the open arrows in the inset. The solid curves correspond to the Ar^+ ion that is incident in the direction from upper right to lower left and target particles that are incident in the direction from upper left to lower right, as indicated by the meshed arrows in the inset.

3. Principle of Vertical Surface-Selective Deposition by the Ion-Beam Sputtering Technique

The IBS apparatus used in this study has two ion sources (a Kaufman-type, 30-mm ϕ ion gun made by Commonwealth Scientific Corp.) as shown in Fig. 2. One of the ion sources is irradiated to the target and the sputtered particles are deposited on the substrate. The other is irradiated directly to the substrate. To prevent the accumulation of positive electric charge on the target and substrate, we neutralized these ion beams by using thermal electron radiation just after the beams are emitted from the sources.

With the IBS apparatus, the direction of each ion beam can be varied independently and arbitrarily. This means that the characteristic curves of deposition and etching rates shown in Fig. 3 can be shifted in the lateral direction by changing the incident directions of the beams of target particles and Ar^+ ions. When we shift the Ar^+ ion to the clockwise direction and the target particles to the counterclockwise direction as shown by the meshed arrows in the inset of Fig. 3, the characteristic etching rate curve shifts to the right and that of the deposition rate shifts to the left as shown by the solid curves in Fig. 3. Therefore, by changing the irradiation angle, we can selectively deposit a thin film on a vertical surface and can reduce the peculiar angle. In addition, the top corner of the substrate is protected from damage because the electric potential of the substrate is kept at zero and there is no plasma near the substrate.

4. Fabrication of Multilayer Filters

The vertical surface was formed by an anisotropic wet etching of a (110) Si substrate using an APW etchant (ethylenediamine:pyrocatechol: water = 10/

Table 1. Operating Conditions of the IBS Apparatus

Conditions	Ion Source for Etching	Ion Source for Deposition
Beam current	5 mA	20 mA
Beam voltage	500 V	750 V
Background pressure	$1.33\text{--}2.67 \times 10^{-4}$ Pa	$1.33\text{--}2.67 \times 10^{-4}$ Pa
Operating pressure	4.00×10^{-2} Pa	4.00×10^{-2} Pa
Incident angle on substrate	40 deg	90 deg
Distance between ion source and center of substrate	120 mm	
Distance between ion source and center of target		90 mm
Distance between center of target and center of substrate		90 mm

17:2/17:5/17 mole fraction, 100 °C). The height of the vertical step was approximately 30 μm .

The operating setup of the IBS apparatus that was used in this experiment is shown in Table 1. Prior to selective deposition on a vertical surface, we deposited SiO_2 film on a Si substrate and observed the distribution of film thickness on the horizontal surface. Since the deposition and etching profiles on the horizontal surface are not similar to each other, a balanced region appears i.e., the etching rate is balanced with the deposition rate. This region appears as a band. The substrate with a vertical surface was located in the balanced region. The vertical surface faced the ion beam for etching.

Fig. 4. Optical microscope photographs of a cross section of SiO_2 films deposited by (a) rf bias sputtering (Ref. 3) and (b) dual-ion-beam sputtering (this paper).

Fig. 5. Measured results of deposition rates of SiO_2 and Si on a vertical surface for which the conditions are listed in Table 1.

With regard to the balanced region, SiO_2 film was formed selectively on the vertical surface. An optical microscope photograph of a cross section of the deposited film is shown in Fig. 4(b). Compared with the previous result shown in Fig. 4(a),³ which was deposited by the rf bias-sputtering technique, it can be seen that the top corner of the step of the substrate was perfectly protected from damage and the peculiar angle θ_p at the top corner of the film decreased from 75° to 55°. The deposition rates for SiO_2 and Si on the vertical surface were measured by changing the deposition time. The deposition rates were evaluated to be 0.10 $\mu\text{m}/\text{h}$ for SiO_2 and 0.46 $\mu\text{m}/\text{h}$ for Si, as shown in Fig. 5.

To investigate the quality of the film deposited by this method, we formed a multilayer filter on the vertical surface of substrate and measured the filtering characteristic. A simple band-cut filter consisting of four layers of SiO_2 -Si was adopted for this preliminary demonstration. The film thicknesses were designed to be 0.925 μm for SiO_2 and 0.395 μm for Si, which correspond to seven quarters of the cavity wavelength at a source wavelength of 0.83 μm . Prior to the formation of a multilayer filter, a pn junction as a photodetector was formed on the vertical surface by diffusing phosphorus into a p-type Si substrate. A cross-sectional scanning electron microscope view of the filter is shown in Fig. 6, from which we can observe that the thicknesses of these

Fig. 6. Scanning electron microscope photograph of four SiO_2 -Si films formed on a vertical surface with a photodetector.

Fig. 7. Experimental setup that was used to measure the filtering-photodetecting characteristics.

films were measured to be $1.1 \mu\text{m}$ for SiO_2 and $0.27 \mu\text{m}$ for Si.

5. Measurement of Multilayer Filters

The measurement setup of the filtering-photodetecting characteristics is shown in Fig. 7. Nine laser diodes, lasing at wavelengths ranging from 0.76 to $0.89 \mu\text{m}$, were used as light sources. The laser light was coupled to a single-mode fiber with a connector and the coupled power was monitored at the connector located at the middle point of the fiber. The output end of this fiber was etched to $20\text{-}\mu\text{m}$ diameter and was butt-coupled to the multilayer filter.

Clear filtering-photodetecting characteristics were observed as shown by the filled circles in Fig. 8. These measured values are normalized by the wavelength dependence of detector sensitivity that was measured independently. We calculated the theoretical filtering characteristic from actual thicknesses that were measured as shown in Fig. 6. The refractive-index value of Si film ($n_{\text{Si}} = 3.67$) and the measured refractive index of SiO_2 film ($n_{\text{SiO}_2} = 1.57$ at $0.633\text{-}\mu\text{m}$ wavelength) as deposited on the horizontal surface were obtained from Ref. 6. The calcu-

Fig. 8. Theoretical (solid curve) and measured (filled circles) filtering-photodetecting characteristics of a multilayer filter/photodetector integrated device. The absorption coefficient of the Si layer $k(\lambda)$ was taken into account using the published data.⁶

lated values, shown by the solid curve in Fig. 8, agreed well with the measured values. Therefore, we can confirm that the refractive indices of deposited films are almost the same as those of films deposited on the horizontal surface, which were used in our design and analysis. This conclusion is supported by the fact that the wet etching rates of films deposited on a vertical surface are almost the same as those of films deposited on a horizontal surface.

The refractive index of SiO_2 film deposited on the vertical surface was measured directly using another sample. To increase the height of the vertical surface, we glued a 2-mm -wide, 10-mm -long Si bar perpendicular to another Si substrate and deposited a SiO_2 film selectively on the vertical surface of the Si bar using the VSSD method. After deposition, the Si bar was removed from the substrate and the refractive index of the SiO_2 film was measured using an ellipsometer at $0.633\text{-}\mu\text{m}$ wavelength for which the result was 1.548 . This value is 1.4% lower than the 1.57 refractive index of SiO_2 film deposited on the horizontal surface and is 6% higher than that of bulk SiO_2 . The discrepancy in these values from that of bulk SiO_2 was caused by a lack of oxygen, because we did not introduce O_2 gas during deposition.

6. Summary

We have developed a novel method for the selective deposition of thin films on the vertical surface of a substrate by using a dual-ion-beam sputtering technique. Compared with a rf bias-sputtering technique, we can confirm that the top corner step of the substrate was not damaged and the flat area of the deposited film was increased. In addition, we have demonstrated an integrated device that consists of multilayer filters and a photodetector using this technique and have confirmed that the refractive indices of films on a vertical surface were almost the same as those of films on a horizontal surface. This technique can be applied to the monolithic integration of multilayer filters on the vertical surface of a waveguide end facet.

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