# Development of multi-layer anti-reflection structures for millimeter-wave silicon optics using deep reactive ion etching process


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## Introduction

To show the technical feasibility of a high-frequency and broadband anti-reflection( AR ) coating for silicon optics in millimeter wavelengths, we fabricated a prototype of the 4-layers sub-wavelength structures ( SWS ) by using a combination of a deep reactive ion etching ( DRIE ) and dicing processes.
Also, we fabricated the 3-layer SWS using a multi-layer DRIE technique.

## SWS Fabrication Using Combination of DRIE and Dicing Processes

### Fabrication method

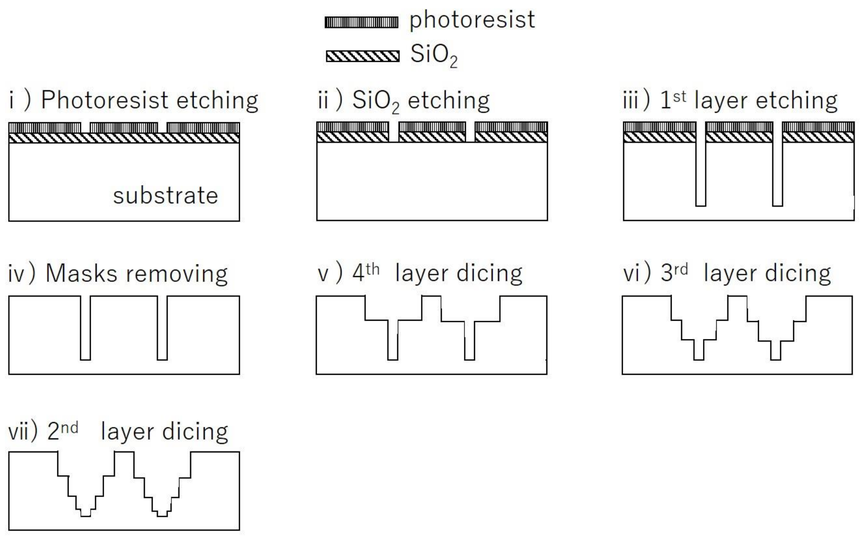


**Fig. 1** Fabrication method for 4-layers SWS with the combined process.

### Prototype fabrication

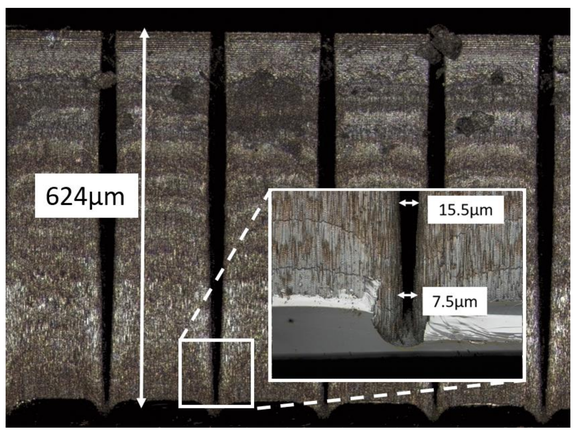


**Fig. 2** Cross-section of the first layer of the 4-layers SWS processed with DRIE.

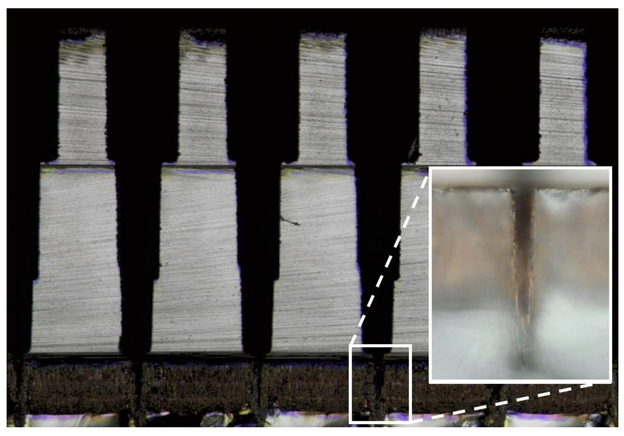

**Fig. 3** Cross-section of the prototype 4-layers SWS with the combined process.

### Simulation

**Table 1** Width and depth of each layer of the 4-layers SWS used in the HFSS simulations.

| | w 1 | w 2 | w 3 | w 4 | d 1 | d 2 | d 3 | d 4 |
|---|---|---|---|---|---|---|---|---|
| Design [$\mu$m] | 13 | 31 | 60 | 100 | 616 | 517 | 389 | 219 |
| Prototype [$\mu$m] | 7 | 41 | 61 | 104 | 592 | 492 | 382 | 202 |

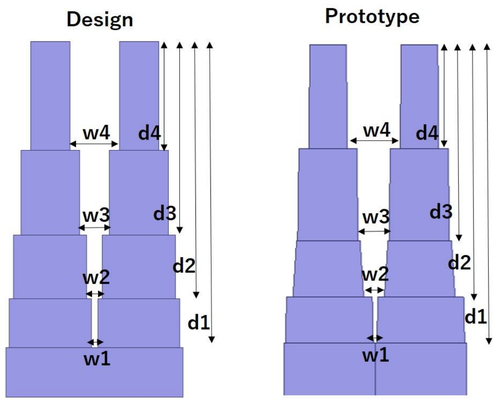


**Fig. 4** 4-layers SWS models used in the HFSS simulations.

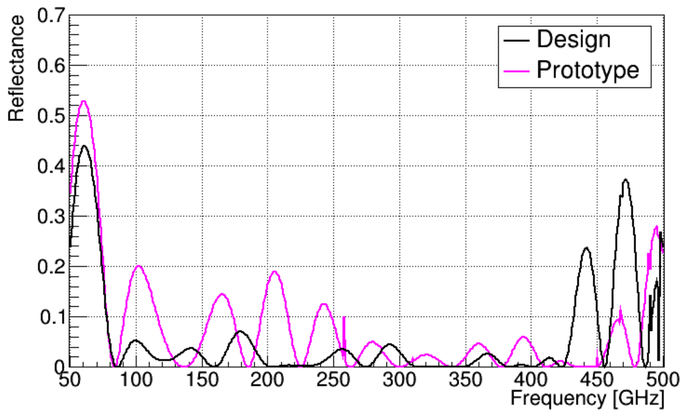


**Fig. 5** Expected reflectances of the 4-layers SWSs at 4 K. The designed and prototype structures show the averaged reflectances of 2.0 % and 3.7 % at 100 - 450 GHz, respectively.

## SWS Fabrication Using Multi-layer DRIE

### Fabrication method

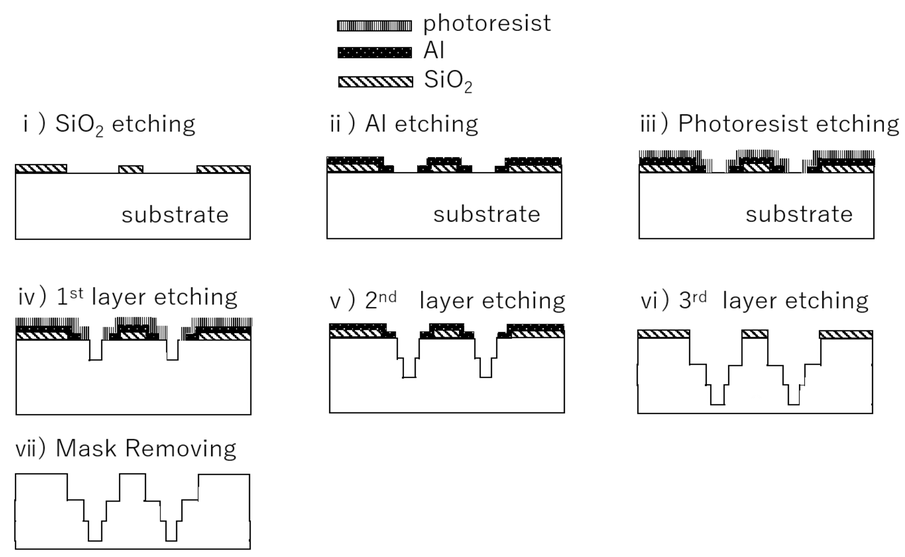


**Fig. 6** Fabrication method for 3-layers SWS with the multi-layer DRIE.

### Prototype fabrication

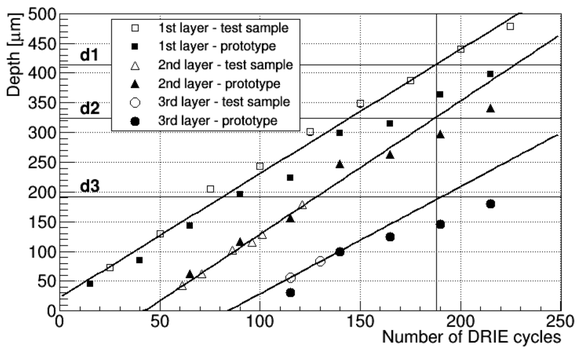


**Fig. 6** Relation between the etched depth and the number of DRIE cycles for each layer.

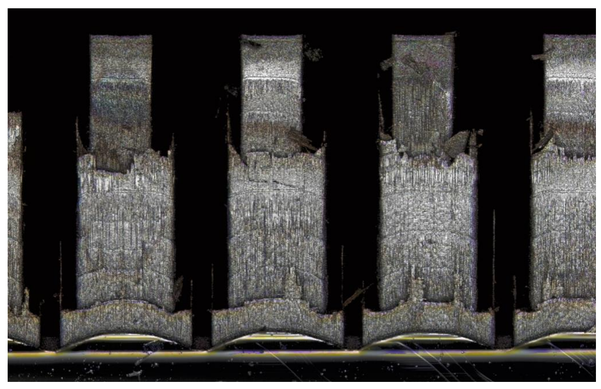

**Fig. 7** Cross-section of the protptype 3-layers SWS with the multi-layer DRIE.

### Simulation

**Table 2** Width and depth of each layer of the 3-layers SWS used in the HFSS simulations.

| | w 1 | w 2 | w 3 | d 1 | d 2 | d 3 |
|---|---|---|---|---|---|---|
| Design [$\mu$m] | 15 | 60 | 100 | 414 | 324 | 192 |
| Protptype [$\mu$m] | 25 | 63 | 104 | 398 | 341 | 180 |

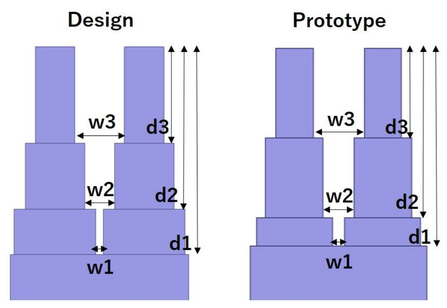


**Fig. 9** 3-layers SWS models used in the HFSS simulations.

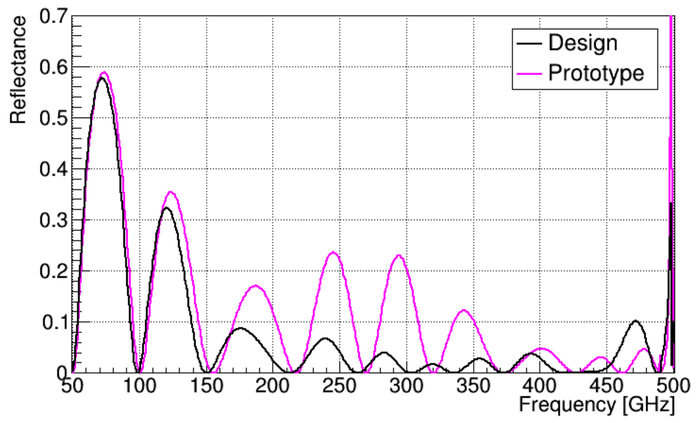


**Fig. 10** Expected reflectances of the 3-layers SWSs at 4 K. The designed and prototype structures show the averaged reflectances of 1.6 % and 5.2 % at 150 - 450 GHz, respectively.

## Conclusions

We fabricated the prototype 4-layers SWS with the combined process and 3-layer SWS with the multi-layer DRIE technique.
The 3- layer and 4-layer prototypes show the expected averaged reflectances of 5.2 % at 150 - 450 GHz and 3.7 % at 100 - 450 GHz, while the designed structures show 1.6 % and 2.0 %, respectively.


## Acknowledgements

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