

# Compact hybrid plasmonic-Si waveguide structures utilizing Albanova E-beam lithography system

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**Abstract:** In this document, I will show our recent fabrication works of compact hybrid plasmonic-Si waveguide structures, which utilized Albanova E-beam lithography system to realize the micro/nanometer scale processes.

## Introduction

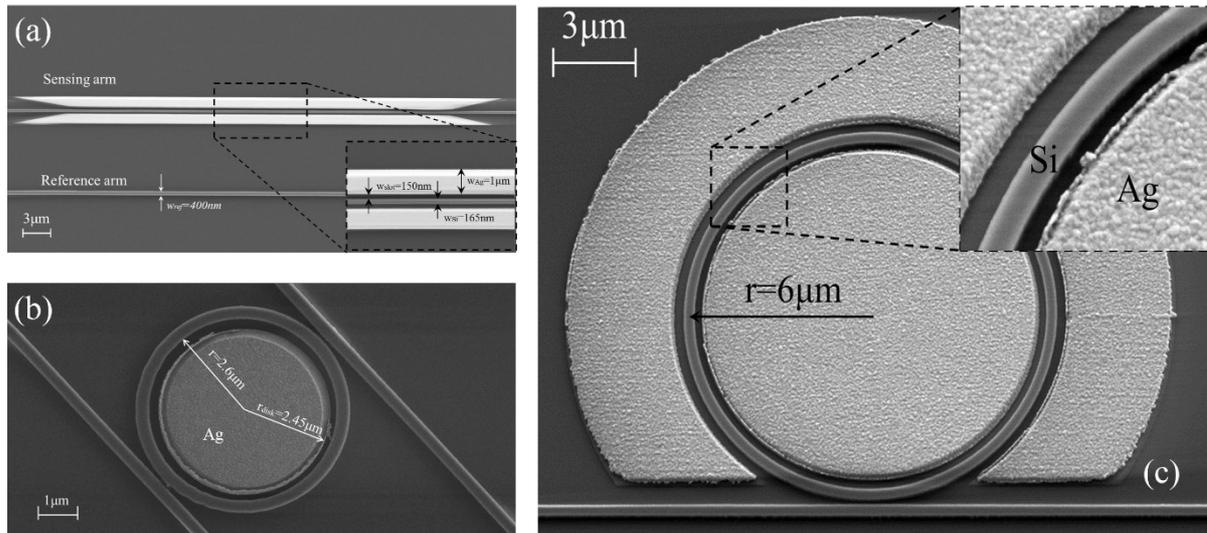
Silicon-on-insulator (SOI) on-chip photonic devices show the advantages of low propagation loss, high refractive index and CMOS compatible fabrication process, therefore they are considered as the most promising technology platform for realizing photonic integrated circuits (PICs) towards optical communication, bio-sensing, optical interconnect and data processing. However, the low Pockels electro-optic (EO) effect and indirect bandgap of Si material limits the development of SOI technology. Additionally, the diffraction limited modal field of a Si waveguide also restricts the size of SOI photonic devices to be further smaller (less than 200nm). To overcome these limitations, semiconductor material (Ge, GaAs, InP), nonlinear crystals (LiNO<sub>3</sub>, LiTaO<sub>3</sub>), organic materials (EO polymers) and plasmonic materials (Au, Ag) have been widely studied to be integrated into SOI photonic devices.

Hybrid plasmonic-Si (HP) waveguide structures, a combination of SOI photonics structure and surface plasmon polariton (SPP), can guide optical waves with sub-wavelength scale with low propagation loss. Besides, HP waveguides also provide a high optical confinement factor in the low-index layer, which can be applied into refractive index sensing devices. However, the fabrication process of HP waveguide structures is much more complicated than SOI photonic devices. It requires high resolution patterning of nano-structures and precise alignments between different layers. In the following sections, I will introduce the fabrication processes of HP waveguide structures utilizing e-beam lithography system in Albanova.

### 1. Slot hybrid plasmonic waveguides and resonate cavities

Slot HP waveguides are structured by precisely locating plasmonic layers (Ag or Au) directly beside the Si ridge, and in this way, narrow slots are formed between Si and Ag. A large optical confinement is realized in the narrow slots between Si ridge and Ag

layers, which provides a large sensitivity for the liquids filled into the slots. The fabricated devices are shown in Fig. 2, which includes Mach-Zehnder interferometer [1] [2], slot hybrid plasmonic ring resonator [3] and double-slot hybrid plasmonic ring resonator [4]. All of those devices have good performances in optical refractive index sensing. Besides, they also have the possibility to realize EO modulation by filling the slot with organic nonlinear polymers. The plasmonic layers can be used as electrodes as well, and the e-field between plasmonic layers is pretty large due to the narrow slot. More details of principles and results can be read from the referenced works.

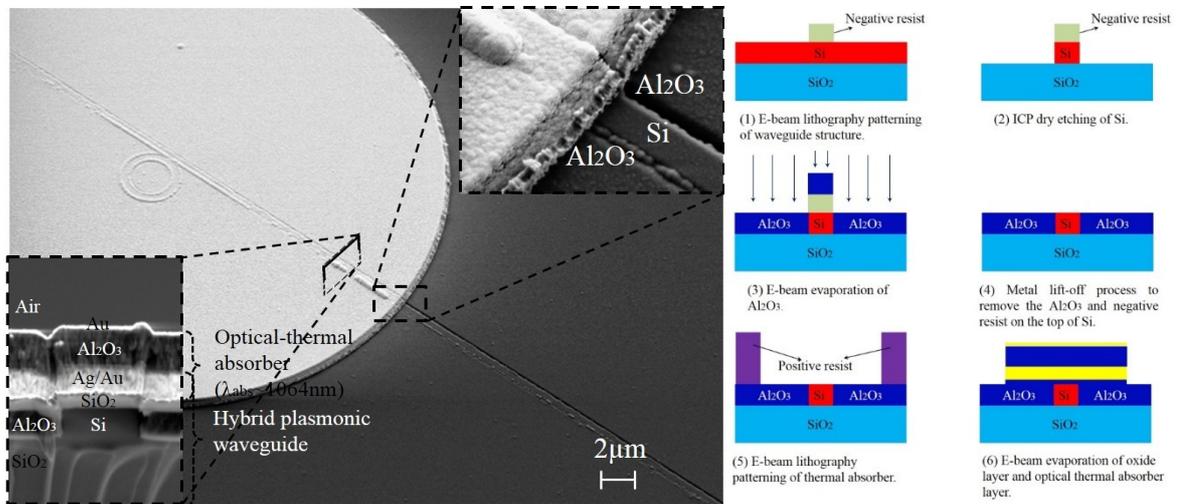


**Figure 1:** (a) Double-slot hybrid plasmonic Mach-Zehnder interferometer. (b) Slot hybrid plasmonic ring resonator, and (c) double-slot hybrid plasmonic ring resonator.

The fabrication process starts from commercial Silicon-on-insulator (SOI) wafer with 250nm crystalline Si on top of 3 $\mu$ m thick SiO<sub>2</sub> buffer layer. After patterning the Si structure with e-beam lithography (EBL), Inductively Coupled Plasma (ICP) dry etching with 10% over etch is performed, which is processed by C<sub>4</sub>F<sub>8</sub>-SF<sub>6</sub> gas mixture under low temperature (~10 °C). Then, after removal of e-beam resist, the second E-beam exposure and etching process are performed to fabricate the highly efficient non-uniform grating couplers. The etching depth is around 80nm. Finally, the pattern of silver pads is introduced by the third E-beam exposure. After patterning, 20nm Ti and 230nm Ag layers are evaporated by metal evaporation tool, where the Ti layer is used to increase the adhesive strength between silver and substrate material (SiO<sub>2</sub>). Then, metal lift-off process is used to open the silver pads. One should notice that the precise alignment in the third time EBL patterning is the key process. Since the e-gun movement error, three-point alignment error and unexpected vibration, the alignment needs to be complete within only one writing field. In this case, the exposure of each device needs to be accomplished individually.

## 2. Vertical hybrid plasmonic devices

Different with slots HP waveguide, vertical HP waveguide is fabricated layer by layer. As in Fig. 2, an all-optical switching HP donut resonator [5] is shown. The fabrication starts from a commercially available SOI wafer with 250nm crystalline Si on top and 3 $\mu\text{m}$  SiO<sub>2</sub> buffer was used. The first e-beam lithography (EBL) with negative resist was performed for patterning the structure of Si ridge. After that, inductively coupled plasma (ICP) dry etching was the next step. The etching depth was about 230nm, and the remaining 20nm Si material (not shown in Fig. 3) was used as a thermal conductivity layer due to the low thermal conductivity of the substrate material (SiO<sub>2</sub>). Al<sub>2</sub>O<sub>3</sub> material was e-beam evaporated after ICP etching process (the resist remaining), then metal lift-off was performed. The thickness of the evaporated Al<sub>2</sub>O<sub>3</sub> layer was similar to the etching depth of the Si ridge (~230nm); in this way, the surface was flattened for further processes. Second EBL patterning with positive resist and ICP etching were applied to fabricate the grating couplers for light in-out coupling at each end of the device. After removing the resist, plasma enhanced chemical vapor deposition (PECVD) was performed to add a thin SiO<sub>2</sub> layer (~50nm). Then, the third EBL patterning with positive resist was used to open the areas of plasmonic layer and optical-thermal absorber. E-beam evaporation and lift-off processes followed again to form the final optical component.

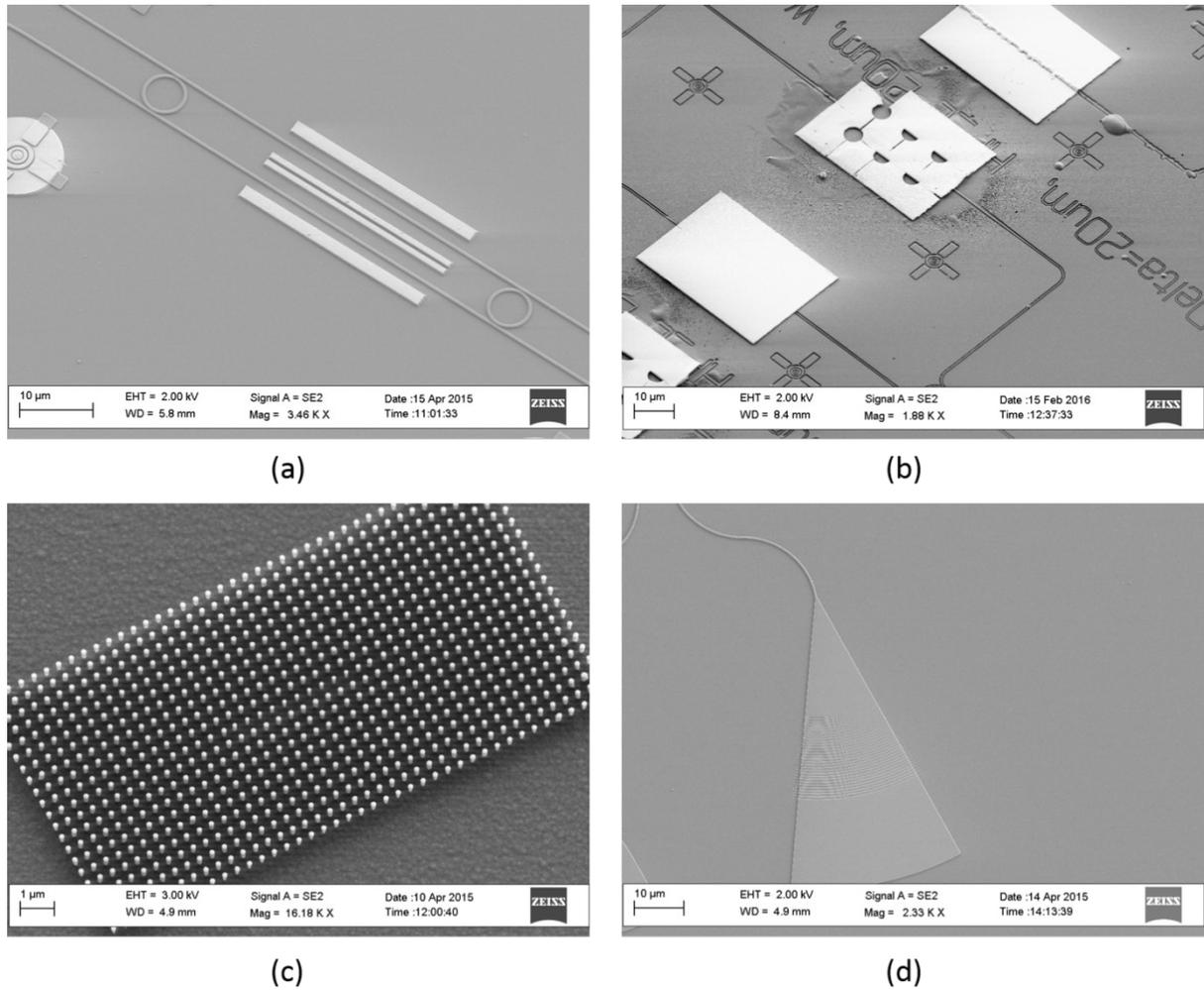


**Figure 2:** Scanning electron microscope (SEM) images of HP donut resonator with optical-thermal absorber and the fabrication processes.

## 3. Other works

Figure 3 shows several other works fabricated by EBL systems. All of them require high resolution lithography process, which is accomplished with the help of Albanova EBL system. The negative and positive resists are MaN2403 and ZEP 7000, respectively. One should notice that some of the processes require thick resist to sustain deep etching

or lift-off, which can be done by multi-spin-coating. For example, the spin-coating thickness of ZEP7000 with 3000rpm is about 200nm. After three times spin-coating process, the thickness can reach larger than 500nm with no noticeably influence of the resist.



**Figure 3:** (a) Thermal tunable EIT device. (b) MZI sensor based on hollow HP waveguides. (c) Pillar photonic crystals. (d) High efficient grating coupler.

### Conclusion and some practical issues

EBL is the key step for the fabrication of compact photonic on-chip devices. Normally, several times patterning processes are required to accomplish complicated structures. In this case, the yields of each step are required to be high. To increase it, several practical issues are provided:

1. Negative resist, Ma-N 2403, is easy to be flowed away during the development process. To increase the adhesive strength, one can increase the baking temperature (no higher than 110°C) and baking time.
2. When developing negative resist, make sure the developer and DI water are clean enough.
3. When exposure with both normal and FBMS mode, use both writing field alignment and tracking beam alignment.
4. When precise alignments are required (less than 200nm error), one can make three-point alignment within one writing field.

### **Related publications**

[1] Xu Sun and Lech Wosinski. "Double-slot hybrid plasmonic cavity used for phase modulation and sensing." Optical Fiber Communication Conference. Optical Society of America, 2015.

[2] Xu Sun, et al. "High-sensitivity liquid refractive-index sensor based on a Mach-Zehnder interferometer with a double-slot hybrid plasmonic waveguide." Optics express 23.20 (2015): 25688-25699.

[3] Xu Sun, Lars Thylén and Lech Wosinski. "Slot Hybrid Plasmonic Ring Resonator Used For Optical Sensors and Modulators." Asia Communications and Photonics Conference. Optical Society of America, 2015.

[4] Xu Sun, et al. "Double-Slot Hybrid Plasmonic Ring Resonator Used for Optical Sensors and Modulators." Photonics. Vol. 2. No. 4. MDPI, 2015.

[5] Xu Sun, et al. "All-optical switching using a hybrid plasmonic donut resonator integrated with photothermal plasmonic absorber." (submitted)