Ultra precision fabrication of plasmonic nano waveguide using focused ion beam milling

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Plasmonic structures to enhance electromagnetic field have been researched intensively to amplify non-linear electromagnetic behavior such as surface enhanced Raman spectroscopy (SERS) or high harmonic generation. The amount of field enhancement depends on the quality of plasmonic structure. However, there has been a practical gap between theoretical expectations and experimental results due to the fabrication errors in plasmonic structure. Especially, the surface roughness or geometrical errors in actual plasmonic structure reduces the level of field enhancement. Various fabricating tools are suggested to improve the precisions in plasmonic structure. The Focused ion beam(FIB) is a widely used in nanoscale fabrication because of its unique characteristics enabling 3-dimentional arbitrary fabrication. In this study, we report FIB milling techniques for fabricating a 3-dimentional plasmonic structure with high precision. As an example, we demonstrate the fabrication of hollow tapered waveguide to concentrate near-infrared femtosecond pulse. The numerical simulation was proceeded to compare the experimental results. The calculation showed that enhancement factor was 350, mainly appeared in the air gap region. Experimental verification was performed to evaluate the quality of plasmonic structure by detecting high harmonics with injection of moderate power of femtosecond laser and Xe gas. Field enhancement more than 200 was achieved from the fabricated plasmonic structure.

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1. Introduction

Plasmonic structures to enhance electromagnetic field have been researched intensively to improve non-linear effect from the target. Non-linear optical behavior such as Raman effect is dependent to power of illuminated laser. Therefore, higher intensity of excitation light source is required to increase non-linear signal emitted from the target. However, too intense laser field also cause the unwanted physical process such as thermal melting. Therefore, plasmonic structure is a key tool to observe non-linear phenomena by enhancing intensity of illuminated light without any increment of incident power of laser.[1] Indeed, various metallic films, trenches, tapers, gaps and tips have shown promise for unprecedented control and delivery of optical energy into nanoscale regions, but fabrication process prohibit the realization of plasmonic nanofocusing structure. Up to now, 2-dimensional planar structures like the bow-tie nanoantenna having a small gap between two triangular patches were widely used for enhancing electromagnetic field by inducing localized surface plasmon resonance (LSP). Due to its well-known optical properties and fabrication method, bow-tie structure have been widely investigated both in theoretically and experimentally. Here, we report the novel 3-dimentional plasmonic structure having 3 order of magnitude larger field enhancement areas than conventional bow-tie nanoantenna. Overall shape of structure is similar to the tapered hollow funnel which end is opened. To realize the structure, surface plasmon polariton (SPP) was applied for enhancing electromagnetic field instead of LSP. Numerical simulation showed that the maximum intensity enhancement is 350, mainly appeared in the air gap region, so interaction with gaseous atom or molecular for observing optical responses is more active than the planar plasmonic structure. Experimental results showed that the magnitude of enhanced intensity inside the plasmonic structure reaches very high intensity level of 10^{13} W•cm^{-2} which was not reported yet from the conventional plasmonic structure.

2. Fabrication methods & results

The 3-D silver-air-silver tapered plasmonic waveguide was fabricated using the Focused Ion Beam (FIB) technique while the actual fabrication process was monitored real time. FIB milling technique allows the fabrication of 3-dimentional arbitrary shape. As a first step of waveguide fabrication, a 10-μm thick silver layer was deposited onto a substrate that is a commercial cantilever-based NSOM probe having a hollow pyramidal gap located at the end of its thin and long cantilever. Because the designed plasmonic device has a 3-dimensional geometry, multiple masks with different sizes were loaded onto the used FIB machine as illustrated in figure 1. About 30 images are serially progressed with the decreasing order in size. In other words, the waveguide milling process proceeded with repetitive removal of thin disks. As a result, an elliptical tapered cone is formed at the center of the NSOM probe tip. After that, the bottom surface of the NSOM probe tip was polished until the output aperture has a 100 nm diameter in the minor axis direction at the end of the waveguide.

FIB milling is a material removal process that sputters using accelerated Ga+ ions. During sputtering, atoms from a solid surface are removed by the bombardment of energetic particles. The momentum transfer leads to the ejection of Ag atoms, thus generating the desired topography. The surface roughness of fabricated sidewall of waveguide is influenced by the surface roughness of evaporated silver surface. The surface roughness of plasmonic waveguide is critical issue because the propagation loss is significantly affected by its surface roughness. Direct FIB milling of waveguide onto this surface leads to the highly rough sidewall of tapered waveguide. To reduce surface roughness of waveguide, FIB-assisted thin Platinum deposition was applied to smooth the first layer to be milled. From the experimental result, a 300 nm thick Platinum layer can reduce the surface roughness down to few nm. As another consideration for fabrication process, the long duration of FIB milling process cause the occurrence of surface charge inside the fabricated structure. These charges drift the direction of Ga+ ion beam during the fabrication, resulting shifted tapered waveguide structure.

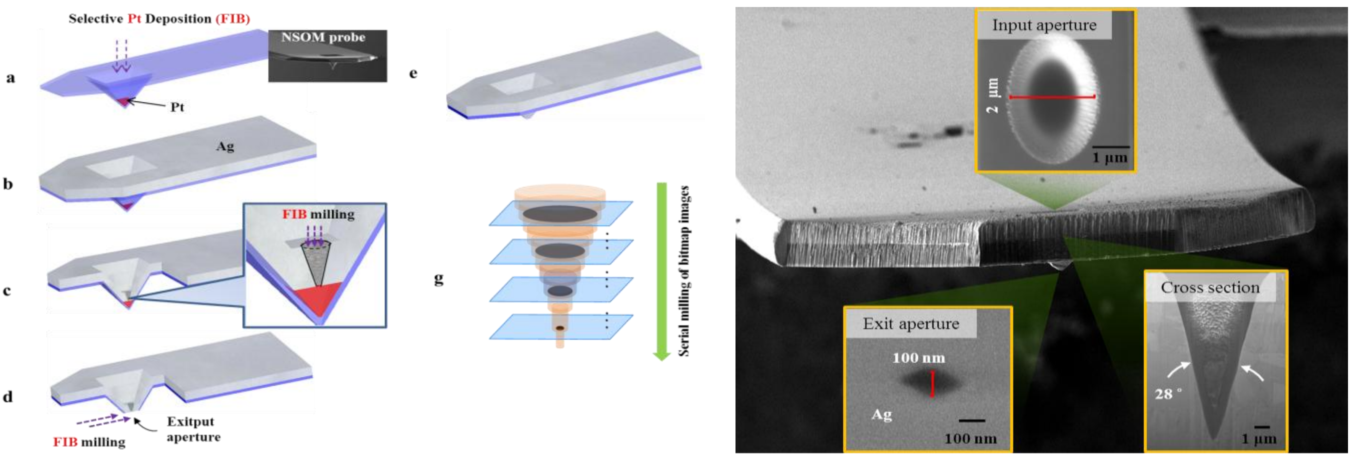

Fig. 1 Fabrication procedure of 3-dimensional tapered waveguide(Left) and SEM images (Right)

The scanning electron microscope (SEM) images show the fabricated results. It shows the overall image of tapered waveguide structure embedded in a NSOM probe tip. As verified with SEM, the desired waveguide shape was successfully achieved. Three insets are magnified images of input aperture (top), exit aperture (bottom left) and cross-section (bottom right) of waveguide. The ion beam configurations for milling the tapered waveguide were acceleration voltage of 30 kV, ion beam current of 12.7 pA, milling depth of 220 nm and dwell time of 50 µs for each image mask.

3. Conclusions

The proposed design of improved tapered waveguide structure will lead to large increase in non-linear optical conversion efficiency, which in turn opens a wide way to access future application areas such as high field optical technology.

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