New Localized Surface Plasmon Resonance Sensor Utilizing Nanoimprinting Technology

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ABSTRACT

We developed a new localized surface plasmon resonance sensor with a periodic array of metal nanostructures fabricated by applying the nanoimprinting technology. Nanoimprinting is one of the technologies attracting the greatest attention in the field of nanotechnologies. This technology enables the mass production of a chip with a nanostructure at low costs but with high accuracy. Since a localized surface plasmon resonance (LSPR) sensor can concentrate electric fields on nano-order metal structures, the sensing area can be localized to reduce noise and raise the sensitivity. By using this nanoimprinting technology and unique nano-order periodic structures, we demonstrated a biosensor chip of higher throughput, lower cost, and higher than ever sensitivity.

Keywords: Nanoimprint, plasmon, high sensitivity, high throughput, biosensor

1 INTRODUCTION

Various biomolecules, such as proteins, bear all life processes in the living body by promoting chemical reactions and regulating functions. Investigating the protein-protein interactions, therefore, will clarify the mechanisms of diseases and help develop new treatment methods and pharmaceuticals. A biosensor based on the surface plasmon resonance (SPR) sensor was recently put to practical use as a means of investigation [1]. This sensor has the advantage of characterizing binding reactions in real time without labeling requirements. But with SPR, the enhanced electric field for sensing is more than 100 nm in size, so the range of sensing is wider. Consequently, since environmental control of very high precision is necessary, a device using this sensor becomes large and expensive. To solve these problems, LSPR sensor that is hardly affected by environmental noise factors is now attracting significant attention [2].

One of the greatest features of LSPR sensor is that the electric fields generated by resonance leach out tens of nanometers, centralized near the electrodes on the sensing surface. Therefore, this resonance is not subject to noise by a temperature or density change of the specimen, other than biomolecular interaction, and is expected to reduce the device size and costs. For this kind of LSPR, metal nanostructures are necessary. Such metal nanostructures are fabricated by several methods: curing metal colloids on substrate [3], using nanosphere lithography [4], and using metallic nanopatterns fabricated by electron beam (EB) lithography [5]. However, all of these methods have problems with throughput, stability, or flexibility of fabrication. For example, the method using metallic colloids has a problem controlling the array of nanostructures and allows a random array. Therefore, it is difficult to obtain the desired characteristics, and array dispersion lowers the sensitivity. When nanosphere lithography is used, nano-sized balls are arrayed and metal is evaporated to fill the gaps. Then, the nano-sized balls are removed to fabricate a pattern. Since only fixed patterns can be fabricated, the freedom of design is low, and it is difficult to fabricate the desired structures. The method using EB requires many processes and takes time. Therefore, the fabrication throughput is very low. These are great obstacles to clear for putting the biosensor to practical use.

In the field of nanotechnologies, nanoimprinting is attracting attention [6]. This method has the advantage that an infinite number of comparatively free structures can be fabricated from a single mold. A new LSPR sensor is proposed by applying the nanoimprinting technology. More specifically, we fabricated a master with a periodic array of nano-order structures by using EB lithography. Based on this master, we fabricated a mold of the inverted pattern. By transferring the pattern to polymer resin, we obtained a pattern of the same structure as the original. Then, metal was evaporated onto the pattern to fabricate the desired LSPR sensor chip. This method allows the fabrication of a desired nanopattern at low cost with high throughput. In addition, the periodic array realizes a high-sensitivity biosensor with less dispersion of sensitivity. We designed and fabricated this biosensor chip, evaluated the sensing characteristics, and sensed the reaction of the absorbing biomolecules.

2 DESIGN

For the sensor chip, we are proposing to construct a thin metal deposition on a polymer resin nanopattern created by nanoimprinting as shown above (Fig. 1). Since this is the first known proposal for this type of sensor chip, it is not

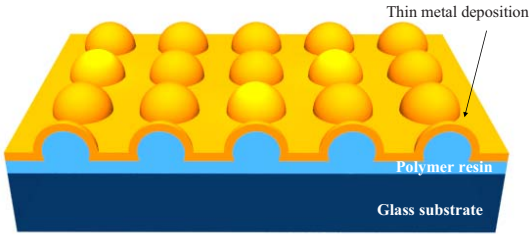

Figure 1: Schematic of the LSPR sensor chip produced with the nanoimprinting technique.

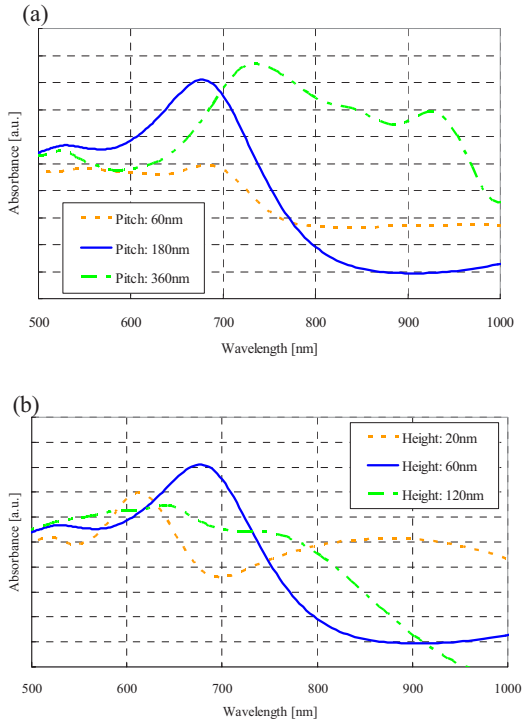

Figure 2: Calculated absorbance spectra of the nanoimprinted LSPR sensor chips as a function of the pattern pitch (a) and pattern height (b).

totally understood how LSPR occurs and exactly how the structure is formed. Therefore, we first designed the structure by simulation using the Finite Difference Time-Domain (FDTD) method (OptiFDTD, Optiwave Co.). FDTD is a technique of solving Maxwell equations by changing space into meshes. This technique has the advantage that an arbitrary structure can be analyzed comparatively easily, but it also has the disadvantage that it requires enormous memory space and computation time to handle 3D space. Considering the computer capacity, an

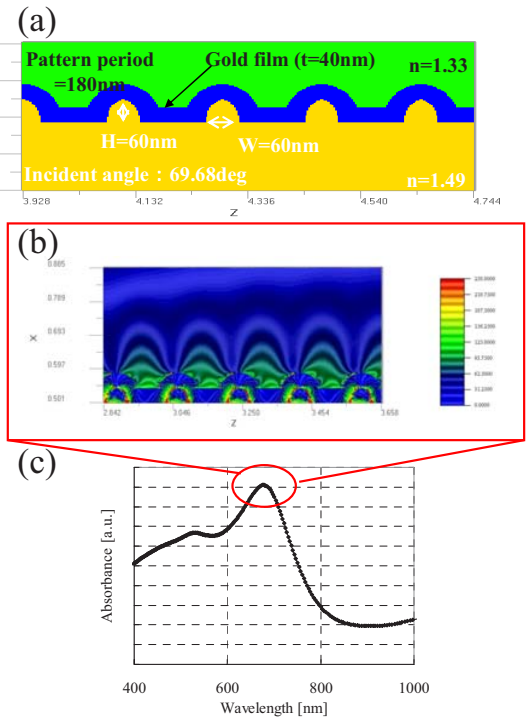

Figure 3: (a) Simulation model,
(b) Results of the simulated electric field distribution around the nanopattern,
(c) Results of the simulated optical characteristics.

approximate design is created in 2D space. Since several structural parameters are limited by the fabrication process, we identified the pitch and height of the nanostructure as parameters comparatively easy to control by the fabrication process. The width was set to 60 nm because the nanoimprinting causes great dispersion of structure during fabrication if the width is less than 60 nm. The thickness was set to 40 nm because the signal intensity is high when the thickness is about 40 nm [7]. A stable fabrication technology for patterns smaller than 60 nm is a future subject to solve. The material parameters were gold for the metal material and polymer resin with a refractive index of 1.49. Gold was selected not only for easy detection because it causes SPR resonance in a visible area, but also for chemical stability because it does not cause a reaction with the analysis specimen. This resin was selected as the UV-curing resin for nanoimprinting, and its refractive index is 1.49.

We performed a simulation at the nanopattern pitches of 60, 180, and 360 nm. The optimum pitch was found to be 180 nm because interaction with adjacent patterns occurs if the pitch is too small and because diffraction occurs if the pitch is too great (Fig. 2 (a)). We also performed a simulation at the nanostructure heights of 20, 60, and 1200 nm. From the viewpoint of sensing, the optimum height

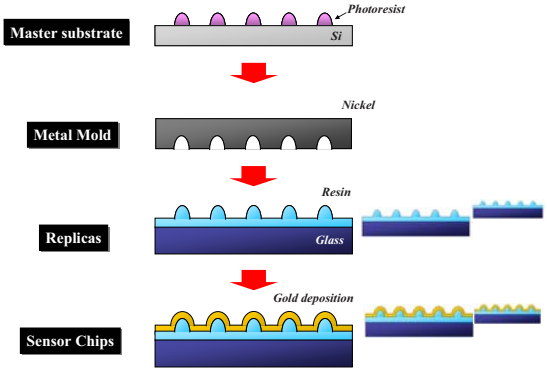

Figure 4: Process flow diagram for LSPR sensor chip fabrication.

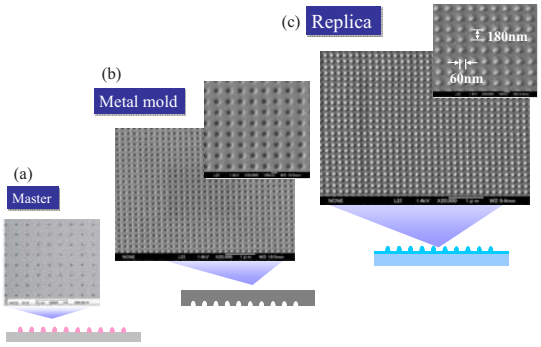

Figure 5: SEM images of the fabricated patterns of the master (a), metal mold (b), and replica (c).

was found to be 60 nm because the generation of LSPR decreases if the height is too small and because a higher mode occurs if the height is too great (Fig. 2 (b)). Figure 3 shows the results of the simulating electric field distribution and optical characteristics by the FDTD method under the above conditions.

3 FABRICATION

Here, we fabricated a chip, designed as stated above, by nanoimprinting (Fig. 4). For the master, we fabricated a pattern of a resist cast on a substrate in a 5-mm square area by using EB drawing equipment (ELS-7500, ELIONIX) (Fig. 5 (a)). From the master, a mold was fabricated by sputtering (CS-200S, ULVAC) and electroplating (SA2000, Digital Matrix). First, we constructed a 120-nm conductive film of nickel on the front side of the master by sputtering, and then we formed a 250-um support layer of nickel by electroplating. Finally, the resist cast was removed by using developer to complete the mold (Fig. 5 (b)). The mold was pressed onto the polymer resin to print the nanopattern. UV-curing resin was used for this reproduction. Using our

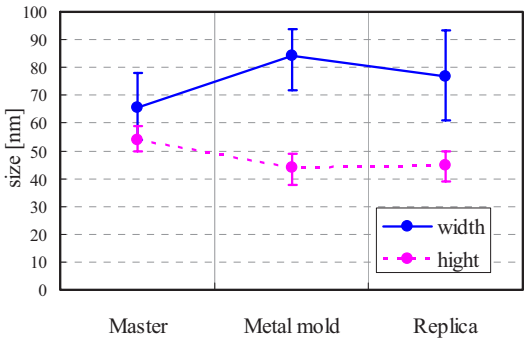

Figure 6: Nanopattern size measurements.

own equipment, we applied a pressure of about 1.2 kgf/mm^2 and irradiated UV of 1500 mJ (Fig. 5 (c)). This method can fabricate a lot of chips from a single mold.

Figure 6 shows the sizes of patterns fabricated at each process. The nanostructure widths were measured by using a scanning electron microscope (SEM) (JSM7400F, NIPPON LASER & ELECTRONICS) and nanostructure heights were measured by using an atomic force microscope (AFM) (NanoScope Ⅳ, Veeco Instruments). The data of nanopattern size obtained by measuring the master is almost as designed. The data of nanopattern size from the mold, however, shows a greater nanostructure width and smaller height. This is probably because the heat of the nickel sputtering during the process of fabricating the mold from the master deformed the pattern resist cast on the master. In addition, the data of nanopattern size from the replica shows a smaller width. This is probably because the resin partially failed to enter the nanostructure concaves of the mold and the width became small on average. In the future, the processes will be improved to enhance the pattern copy accuracy during each process. Finally, the replica chip was gold-sputtered (CS-200S, ULVAC) to fabricate a chip almost as designed.

4 RESULTS

By observing the reflected light spectrum, we verified the localized surface plasmon resonance on the fabricated chip. With a halogen lamp as the light source, we obtained the total reflected light from the back of the chip by using a prism and observed the reflected light spectrum with a cooled CCD camera (DU420-OE, Andor). An absorption peak was observed around 600 nm, and localized surface plasmon was confirmed almost as simulated. When the specimen's refractive index on the metal surface was changed, the absorption peak shifted. This verified its basic characteristics as a sensor. The refractive index sensitivity by the wavelength shift was 1.4×10^2 nm/RIU, which is almost equal to that of a metal colloid chip (1.5×10^2 nm/RIU). In addition, the gradient of the reflection characteristic was found to be steeper than that of the

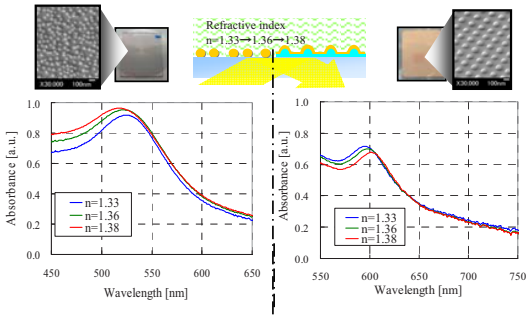

Figure 7: Absorbance spectra of specimens with refractive indexes of 1.33, 1.36, and 1.38 : (a) LSPR of metal colloid chip, (b) our LSPR.

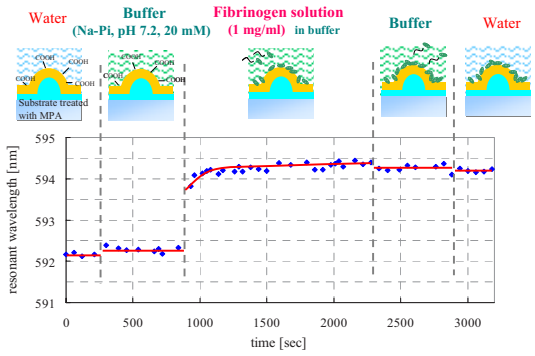

Figure 8: Shift in the absorbance peak commensurate with the absorbance of fibrinogen (1 mg/ml).

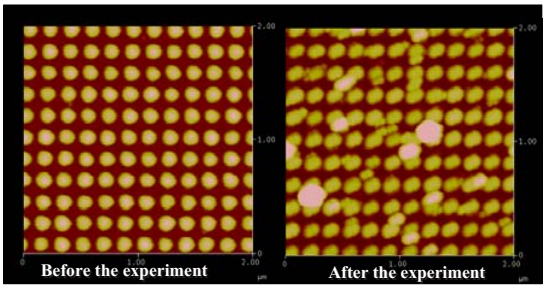

Figure 9: AFM images before and after fibrinogen absorbance.

aforementioned metal colloid chip (Fig. 7). This indicates a great degree of change. In other words, our chip has higher detection accuracy than the metal colloid chip.

To verify the chip's function as a biosensor, we treated the metal surface with MPA (mercaptopropionic acid) [8] and applied fibrinogen protein (340 kDa) at a rate of 1 mg/ml. The fibrinogen was absorbed on the metal surface. The absorbance of fibrinogen caused a signal change equivalent of the refractive index unit resolution, 1.4×10^{-3} [RIU] (Fig. 8). We checked for absorbance or no absorbance by AFM to prove our proposed sensor is capable of sensing fibrinogen absorbance (Fig. 9).

5 CONCLUSION

Using the nanoimprinting technology which has recently been attracting attention in the field of nanotechnologies, we have proposed and demonstrated a new localized surface plasmon resonance sensor. We will improve the fabrication accuracy, reduce the nano-order size, extend the packaging area, and optimize the design parameters to clarify the relationship between the structure of the metal on the resin nanopattern and the generation of the SPR, and then we will complete a theoretical model. Thus, we will realize an accurate biosensing chip at a very low cost.

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