Chirality of Ladder-shaped Nanostructures on Polystyrene Microspheres

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***Abstract*—We fabricated regular ladder-shaped nanostructures on polystyrene microspheres by oblique angle deposition (OAD) technique. The results show that the nanostructures exhibit chirality and their circular dichroism (CD) signals can be enhanced by adjusting the gradients of the structures or the angles between the steps. Such structures have potential applications in optical devices.**

Keywords—oblique angle deposition; circular dichroism; ladder-shaped Structures; polystyrene microspheres

I. INTRODUCTION

Chiral meta-materials refer to man-made structures that can not overlap with their mirror images through rotation or translation [1]. Generally, linearly polarized light can be decomposed into left-circular polarization (LCP) and right-circular polarization (RCP) light. Polarization introduces different absorption losses when passing through chiral metamaterials, and therefore different transmission rates are obtained. This phenomenon of different absorption degrees is called circular dichroism (CD) [2]. Compared with the chiral molecules such as shells, DNA double-helix structures, and amino acid molecules that exist in nature. The three-dimensional chirality is displayed by these natural structures,it is relatively weak and difficult to increase, and thus it is not easy to obtain practical applications. The artificial chiral metamaterials can not only improve chiral characteristics and electromagnetic response properties, but also control the physical parameters of metamaterials to get response in different frequency ranges [3]. At present, there are many teams that study the CD properties of metal micro-nanostructures. In order to produce a strong CD effect, the researchers designed a variety of metal chiral nanostructures and explored their mechanisms, such as planar chiral structures, metal helices [4], multilayer structures [5], etc. Common techniques for preparing these chiral structures are electron beam lithography, laser direct writing, molecular self-assembly [6] and grazing angle deposition [7]. In this paper, considering the preparation conditions and efficiency of artificial nanostructures, the trapezoidal nano chiral structures with polystyrene arrays as template are finally prepared by the combination of nano-particle self-assembly technique and oblique angle deposition technique.

II. EXPERIMENTAL SECTION

A. Materials

First, 500 nm diameter PS nanospheres (HUGE BIO-TECHNOLOGY, DR500) were used as the monolayer template. The monolayer was deposited on clean glass slides. Silver granules (99.999%) were made by Zhongnuo New Material (Beijing) Technology Co. Ltd. Ultrapure water (18.25 MΩ) was used throughout the experiment.

B. Fabrication Produres

500nm colloid monolayer preparation: A certain amount of ultrapure water was added to dilute the original 500 nm diameter polystyrene microspheres solution, afterwards the same amount of ultrapure water was increased for centrifugal cleaning microspheres, then the solution diluted to a 2:1 ratio using ethanol. The microsphere solution was dripped into the water through syringe. The water spread out after dripping. After a period of time, an iridescent film was formed. After the film had been formed, the teflon ring was placed on top of the film. Ultrapure water was injected in to raise the water level, and then we put glass in the bottom of the water, removed the ultrapure water from the petri dish and waited for substrates to dry.

Trapezoidal nanostructure preparation: The colloid monolayer substrates were fixed in a rotatable sample stage of a custom-built e-beam deposition system and rotated to an incident angle of θ = 86°. Under ultra-vacuum conditions, silver was first deposited at a thickness of t_a. At this time, the rotation angle of the sample table was 0°, and then the sample table was rotated clockwise by 30° or 60° or 90° or 120° to deposit silver with a thickness of t_b. Finally, the sample stage was again rotated 120° clockwise to deposit silver with a thickness of t_c. In order to prevent the over-thickness of silver in one direction from causing structural faults, we deposited 25 nm thick silver in each direction and achieved the desired thickness by repeatedly rotating and repeating the deposition. At the same time, in order to prevent the sedimentation parameters of the deposition system from affecting the experimental results, all the depositions were performed at the same vacuum (5×10^{-7} pa) and deposition rate (0.1 nm/s).

C. Charaterization Produres

A field emission scanning electron microscope was used to collect scanning electron microscope (SEM) images, as shown in Fig. 1. The optical properties of samples were measured with a self-built UV-VIS spectrometer. The light source is a quartz tungsten halogen lamp (200-900 nm Ocean Optics, SHL-LP) that spreads divergent light after being connected to a fixed light holder through an optical fiber. The lens L1 (f = 15 cm) collimated the divergent light and passes light through an iris I1 (*diameter* = 1cm). Then the parallel light traveled through a Glan-Talyor linear polarizer, LP (Thorlabs, DGL10) and a quarter wave plate, QWP ((Thorlabs, AQWP05M-600, 400–800 nm), to generate ciruclarly polarized light. A lens L2 (f = 15 cm) was used to focus the beam on the sample, the spot size was approximately 12.56 mm^2. The sample was placed on a fixed support frame and a lens L3 (f = 7.5 cm) was placed behind the sample to collect the light passing through the sample into the signal receiver.

III. RESULTS AND DISCUSSION

Since the produced templates were arranged in different cycles, the trapezoidal chiral structures were also arranged periodically. At the same time, when the beam was obliquely incident, the actual thickness deposited on the sample was not the same as the thickness set by the device [8]. This article used the self-built spectrograph to measure the circular dichroism of the sample. At room temperature, trapezoidal chiral structures were excited by normal incidence and the spectral lines were collected in the 400-800 nm band. It is known that the transmittance is defined as the ratio of the outgoing power P_{out} through the trapezoidal chiral structure to the incident power P_{in} of the entrance, that is, $T = P_{out} / P_{in}$. The circularly polarized light is perpendicularly irradiated on the array structure, and the transmission coefficient under right-handed (left-handed) light irradiation is T_{RCP} (T_{LCP}), and the circular dichroism is represented by the ellipticity, which is shown in (1).

$$\eta = \arctan\left[\left(\sqrt{T(RCP)} - \sqrt{T(LCP)}\right)/\left(\sqrt{T(RCP)} + \sqrt{T(LCP)}\right)\right] \quad (1)$$

In order to study the effect of gradient difference on the chirality of the trapezoidal chiral structure, CD spectra of trapezoidal chiral structures with different deposition gradients were collected. As shown in Fig. 2, the black solid line indicates gradients of 0 nm, the red dash indicates gradients of 50 nm, the blue dot indicates gradients of 75 *nm*, and the green dash dot indicates gradients of 100 nm. The 100 nm gradient difference is used as an example to set the deposition thickness in three directions, t_a = 100 nm, t_b = 200 nm, and t_c = 300 nm, respectively. For the right-handed chiral structure, there is no obvious CD signal when the gradient difference is 0 *nm* at 650 nm wavelength, and as the thickness increases, the CD signal intensity gradually increases.

In order to study the effect of gradient and angle difference on the trapezoidal chiral structure CD, the CD spectra of trapezoidal chiral structures with same deposition gradient and different deposition angles were prepared. As shown in Fig. 3, the solid black line indicates that the three incident angles are 120°, 120°, 120°, the red dash indicates the included angles are 90°, 120°, 150°, and the blue dot indicates the included angles are 60°, 120°, 180°, green dash dot indicates that the included angles are 30°, 120°, 210°. At 500 nm wavelength, when the included angles are 120° evenly distributed, there is no obvious CD signal, but with the angle difference increases, the CD signal gradually also increases and the peak position red-shifts.

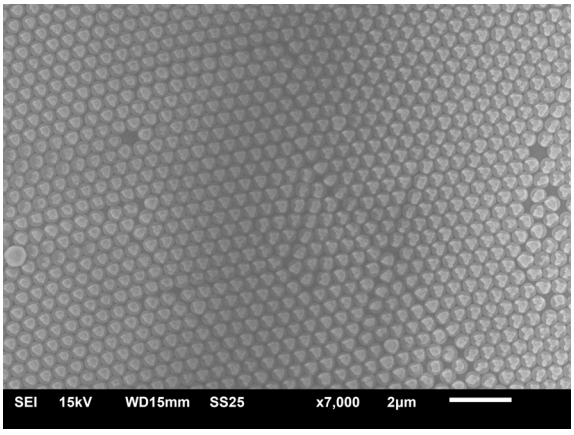

Fig. 1. SEM images of Ladder-shaped nanostructures on D = 500 nm PSs.

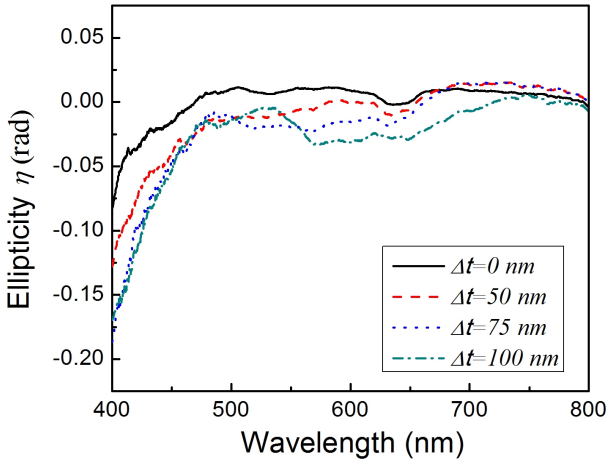

Fig. 2. Ellipticity of nanostructures with different gradients.

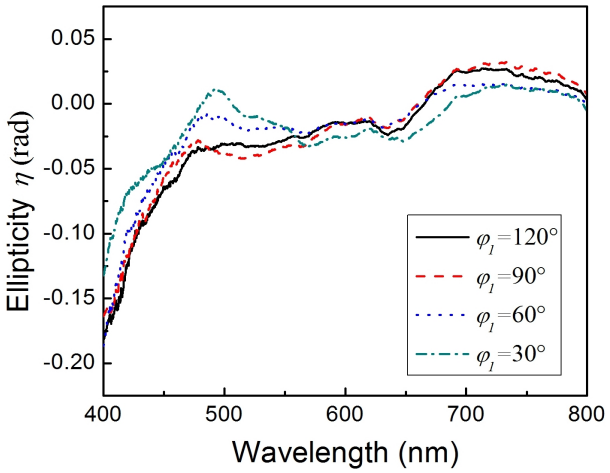

Fig. 3. Ellipticity of nanostructures with different included angles.

IV. CONCLUSION

we have used nano-particle self-assembly technology and oblique angle deposition technology to prepare a regular polystyrene microsphere template on the substrate, and then used multiple deposition in three different directions on the template to prepare a large-area array. The stepped nanostructures with ordered and controllable morphology have different thicknesses or deposition direction intervals by adjusting the directions or thicknesses of each deposition. Effects of the gradients or step spacing angles on the CD signal intensity are studied in this paper. The results show that the CD signal can be enhanced by appropriately increasing the step thickness or increasing the deposition interval angle. These results not only help us to better understand the physical mechanism of the CD effects, but also potentially develop into optical devices.

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