Polarization properties of porous anodic alumina with Y-branched Cu nanowires

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Porous anodic alumina (PAA) templates with branch structure are fabricated by the two-step anodic oxidation processes, and then the Y-branched Cu nanowires are synthesized in the templates using an alternating current (AC) deposition method. We observe the morphology image of the samples by scanning electron microscopy (SEM), and measure the transmission spectrum and the polarization spectrum of the samples by the spectrophotometer. The results show that PAA films with Y-branched Cu nanowires have better transmittance in the near infrared region. An extinction ratio of $15-18$ dB and an insertion loss of $0.1-0.4$ dB are obtained in this region. Therefore PAA with Y-branched Cu nanowires can be used as a near-infrared micropolarizer, and this kind of micropolarizer would have a promising future in the field of photoelectricity integration.

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Recently, the low-dimensional nanostructures have been attracting wide attention because of their special optical, electronic, and magnetic properties[1−6]. A porous anodic alumina (PAA) with metal nanowires fabricated by electrochemistry method has a good transmittance and extinction ratio in the near-infrared (NIR) region, which has opened up a new approach to the research of micropolarizers[7]. Nowadays, Ni, Co, Ag, and Cu nanowires with excellent wire-grid have been synthesized using the porous alumina templates, and their polarization properties have also been studied[8−10]. In comparison with other traditional polarizers such as Glan-Thompson prism, Nicol prism, dichroic sheet, and wire-grid polarizers, this kind of polarizer has many advantages of smaller volume, simpler fabrication method, higher extinction ratio, and lower insertion loss, so it would have a promising future in the field of photoelectricity integration.

Porous alumina templates with Y-branched junction structure are fabricated by changing the anodic oxidation voltage. Branched nanotubes and nanowires have been synthesized by using this kind of templates[11−14]. In this paper, the porous alumina with Y-branched Cu nanowires is fabricated via a two-step anodization process and the alternating current (AC) deposition method. Spectrophotometry measurements show that the PAA with Y-branched Cu nanowires has a transmittance of 70%, an extinction ratio of $15-18$ dB and an insertion loss of $0.1-0.4$ dB in the NIR region.

The PAA templates with Y-branched structure were fabricated in dilute solution of sulfuric acid by two-step anodization process. Details of anodic oxidation and electroplating are described elsewhere. Briefly, anodization was carried out under a direct current (DC) voltage of U_0 ($14-24$ V) in a 15% (by mass) sulfuric acid solution at 0 °C for 30 min. Then, the disordered anodic aluminum forming in the last step was removed by the mixture of phosphoric acid and chromic acid at 60 °C for 30 min. In the second step anodization, the aluminum sheet was anodized under the same conditions as in the first step for 1 h to create the primary stem pores. Then, the anodizing voltage was reduced to U_1 ($U_1 = U_0/\sqrt{2}$) suddenly for another 1 h to form Y-branched pores. After the final anodization, Cu nanowires were electrodeposited into the pores of PAA templates by AC deposition method for another 2 hours. Finally, the remaining aluminum was removed in a mixed solution of Br and methanol.

The Y-branched Cu nanowires arrays embedded in PAA were characterized by the scanning electron microscopy (SEM, JSM-6700, JEOL, Japan) and spectrophotometer (UV-3101PC, Shimadzu, Japan). Before observing the SEM image, it is needed to strip the film and etch pores on the PAA template.

Figure 1 shows the SEM images of the upside and downside of the PAA template. It can be clearly seen that the pore diameter of upside is about 30 nm, and 40 nm for the pore distance; on the downside of the template, the pore diameter is about 15 nm, and 20 nm for the pore distance. The ratio of the upside pore density to that of downside is about 1:2, which means the ratio of the primary stem pores to the Y-branched pores is close to 1:2. Figure 2 shows the cross-section SEM image of

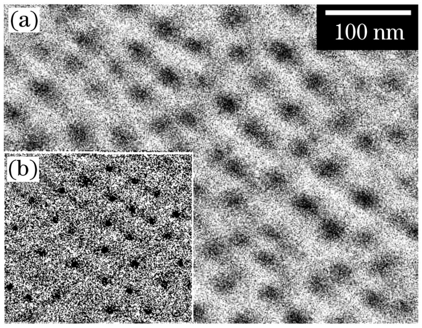

Fig. 1. SEM images of the (a) upside and (b) downside of the Y-branched PAA template.

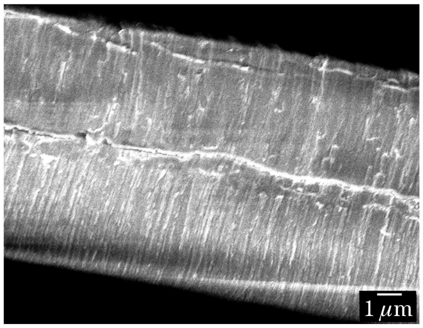

Fig. 2. Cross-section SEM image of the sample.

the PAA film with Y-branched Cu nanowires. As the picture shows, the thickness of the samples is about 10 μm, which is divided into two layers with about the same thickness. The density of the downside metal nanowires is obviously higher than that of the upside, and the metal nanowires are not vertical to the surface.

Meng *et al.* have recently reported a powerful approach to rationally design multiply connected and hierarchical PAA templates[11]. With these templates, the multi-walled carbon nanotubes and branched Ni nanowires were fabricated. They proposed that the reduction factor of the anodizing voltage should be $1/\sqrt{n}$ (n represents the number of branches). In our experiment, U_0 was taken as 20 V and U_1 as $20/\sqrt{2}$ V. The ratio of the pore density between the upside and downside templates and the cross-section of the samples indicate that the PAA with Y-branched Cu nanowires has been obtained.

The reason why the metal nanowire arrays have the polarization properties is that the loss mechanisms to the p and s polarizations are different. It can be seen from Fig. 3(a) that, for the oblique-incidence light upon the surface of the sample, only the p polarization has the electric field component parallel to the nanowires' direction[9]. Therefore, the absorption and reflection of the metal cause greater loss of p polarization when it goes through the sample. On the contrary, the movement of electrons is restricted in the direction of s component because of the thinner Cu nanowires. In this dimension, only the Cu nanowires have the Rayleigh scattering to the incident light. Therefore, the s component loses smaller when it goes through the sample. Thus, the incident light becomes the partial polarized light after it has penetrated through the sample.

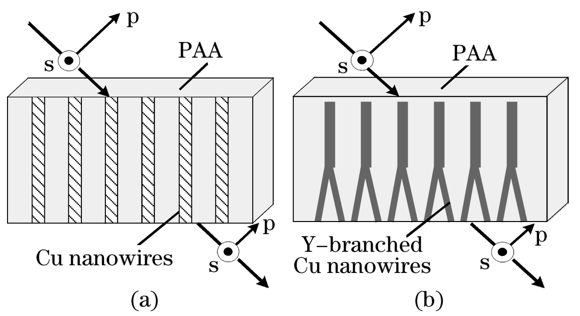

Fig. 3. Schematic diagrams for the route of the incidence light to the different samples with (a) ordinary Cu nanowires and (b) Y-branched Cu nanowires.

Although this kind of micropolarizers has many merits, its extinction ratio could not meet the requirement of the practical application enough. Different methods have been proposed to enhance its extinction ratio. Saito *et al.* once made the incident light vertical to the nanowires' direction by an optical fiber[7]. However, the method did not obtain a significant enhancement to the extinction ratio. In our experiment, the PAA with Y-branched Cu nanowires are fabricated to obtain a higher extinction ratio.

Figure 3(b) shows the route of incident light to the sample. In comparison with the ordinary vertical nanowires, the angle between one of the branches and the incident light for the Y-branched nanowires is reduced. Therefore, the electric field component of the p polarization parallel to the nanowires' direction has increased. As a result, the extinction ratio of this kind of micropolarizer is increased due to the more absorption of the p polarization and the smaller influence on the s polarization.

Transmittance and extinction ratio are two important parameters of the micropolarizer. Before the measurement of the polarization spectrum of the sample, it was adhered between two glass prisms with bromonaphthalene ($n = 1.65$). The schematic diagram for polarization measurement is shown in Fig. 4. The prism was cut diagonally by a cubic $\mathrm{LaK_2}$ glass ($n = 1.67$), and the two cross-sections and two slopes which the incident light went through were polished. The reason for choosing bromonaphthalene and $\mathrm{LaK_2}$ glass is that their refractive indices are similar to the PAA template ($n = 1.6$). On measuring the sample, the incident light is vertical to the surface of prism and with an oblique-incidence angle of 45° upon the surface of sample.

Curve B in Fig. 5 shows the transmission spectrum of the PAA with Y-branched Cu nanowires. The transmittance of the sample comes up to 70% in the NIR region. In addition, an obvious absorption peak of Cu is observed near 530 nm, which indicates that the sample includes the

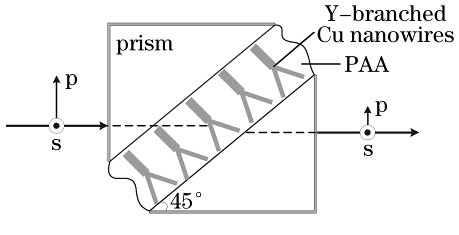

Fig. 4. Schematic diagram for the measurement.

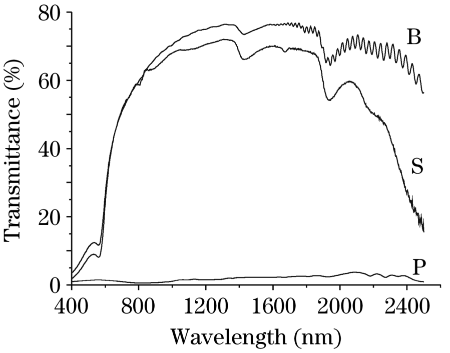

Fig. 5. Transmission spectra of the PAA with Y-branched Cu nanowires.

massive copper. Curves P and S denote the transmittance of p polarization and s polarization, respectively. It can be seen that the transmittance for s polarization (near 70% in the NIR region) is much higher than that for p polarization (4% for the NIR region). The difference in transmittance between p and s polarizations demonstrates the evident optical anisotropy of the sample.

The optical loss spectrum of the sample can be calculated with

$$\xi = 10 \times \lg(T/T_B), \tag{1}$$

where T_B is the transmittance of the sample, T denotes the transmittance of p or s polarization. Figure 6 shows the calculated spectra. In this figure, curve E represents the extinction ratio of the sample calculated with Eq. (1) (here T denotes the transmittance of the p polarization), and curve I is the insertion loss of the sample calculated with Eq. (1) (T denotes the transmittance of s polarization). These curves reveal the special polarizing properties. In the NIR region, an extinction ratio of $15 - 18$ dB and an insertion loss of $0.1 - 0.4$ dB are obtained.

The extinction ratio of the PAA with Y-branched Cu nanowires, however, is lower than the expected value. There are several possible reasons which can account for this phenomenon. Firstly, though the reduction of the angle between one of the branches and the incident light may increase the absorption of the p polarization, the reflection and scattering of the metal can be increased, and the transmittance of the s polarization would be decreased. Secondly, the optical loss of the measurement device may be great, and the precision of the measurement machine will also influence the experimental result. In the experiment, optimizing the preparation conditions and improving the measurement method, we would fabricate the excellent polarized material of PAA with Y-branched nanowires.

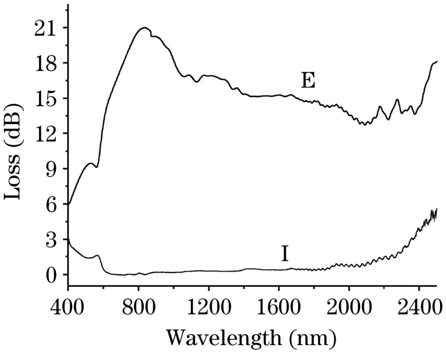

Fig. 6. Polarization spectra of the samples. Curves E and I denote the extinction ratio and the insertion loss, respectively.

Having analyzed the polarization principle of the parallel metal nanowires, the Y-branched structure would increase the extinction ratio of the nanowire arrays due to the more absorption of the p polarization and the smaller influence on the s polarization. The experimental results indicate that, such PAA films with Y-branched Cu nanowires have better transmittance and extinction ratio in the NIR region. Owing to the simple processing techniques, high efficiency, and low cost, the PAA Y-branched structure would be a potential approach to the research of micropolarizers.

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