Simple process for single-layer nanowire gratings

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A simple fabrication process for single-layer nanowire gratings (SLNGs) is proposed. On the basis of this process, an SLNG polariser with a 1.3 × 1.3 mm area of grating patterns and a 100 nm linewidth was successfully fabricated. First, the nanograting patterns were transferred from a metal master stamp to a soft IPS mould using the hot embossing process and the nanograting patterns on the IPS mould were transferred to the imprint resist layer by UV nanoimprint process subsequently; then, after a residual resist removal process, an aluminium layer was thermally evaporated on the substrate to form a bilayer nanowire grating structure; and finally, SLNGs were fabricated by an oxygen plasma ashing process. The inspection results show good consistency in the whole grating patterns area. The experimental result demonstrates that the proposed simple process can be adaptable to fabrications of high-density and large-area nanometal patterns.

1. Introduction: Single-layer nanowire gratings (SLNGs) are often used in various fields of applications, such as spectroscopy, high resolution microscopy and polarisation imaging systems because of their high extinction ratios, large working spectral range, good integrability and long-term stability [1]. Moreover, because of the high etching selection ratio to silicon and silicon oxide, SLNGs are used as the mask patterns for high aspect ratio dry etching processes [2]. Many studies have focused on the fabrication technologies of SLNGs. Interference lithography is commonly used for making SLNGs [3, 4] and electron beam (E-beam) lithography is an effective technology used in most of the research on novel nanoscale devices including SLNGs. Many SLNGs were successfully fabricated by E-beam lithography combined with the lift-off process [5] or the reactive ion etching (RIE) process [6]. However, E-beam lithography is not a cost-effective solution because of its low throughput and high cost of ownership for fabricating SLNGs with relatively large areas.

With the advantages of low cost, high throughput and high resolution, nanoimprint lithography (NIL) [7] has become an important nanofabrication technology. By imprinting the stamp into the resist, the nanoscale patterns on the stamp can be replicated to the substrate. Comparable to the E-beam lithography method, there are mainly two methods for SLNG fabrications by NIL: the RIE process and the lift-off process. Ahn *et al.* [8] fabricated aluminium (Al) SLNGs using the NIL and RIE processes [8]. The upper imprinted resist with nanograting patterns is used as the mask layer and the lower Al layer is etched by RIE and then forms the SLNGs. However, the RIE process requires a precise process control for reducing the lateral etching of Al nanowires in SLNGs. The metal lift-off process has also been used to form SLNGs after the NIL process in which polymethylglutarimide is commonly used as the sacrificial layer material [9]. The sacrificial layer should be thicker than the metal thickness of SLNGs and is etched by the RIE process in this multi-layer process. Therefore the precise control of lateral etching is also essential and difficult.

In this Letter, a simple fabrication process for SLNGs is proposed. The NIL process is used for the nanowire gratings pattern definition. After the thermal evaporation of Al, a bilayer nanowire gratings structure is formed [10]. Similar to the lift-off process, the upper nanowire gratings and the imprint resist TU-7 (used as sacrificial material) are then removed by plasma ashing process, leaving the lower nanowire gratings on the substrate. Compared with the other fabrication processes for SLNGs, the proposed process not only has the advantages of the NIL process, but also simplicity for the elimination of the RIE process of the metal or the sacrificial layer. Finally, with the proposed process, a SLNGs polarizer with a 100 nm linewidth was fabricated successfully.

2. Fabrication process: Fig. 1 shows the schematic representation of the fabrication process. The process can be divided into four sub-processes: (a) the nanograting patterns on a metal master stamp are transferred to a polymer mould using the hot embossing process; (b) an imprint resist layer is spin coated on a clean quartz substrate and the nanograting patterns on the polymer substrate are transferred to the imprint resist layer by simultaneous thermal and UV (STU) processes; (c) after the inductively coupled plasma (ICP) etching process for the removal of the residual layer, an Al layer is thermally evaporated on the

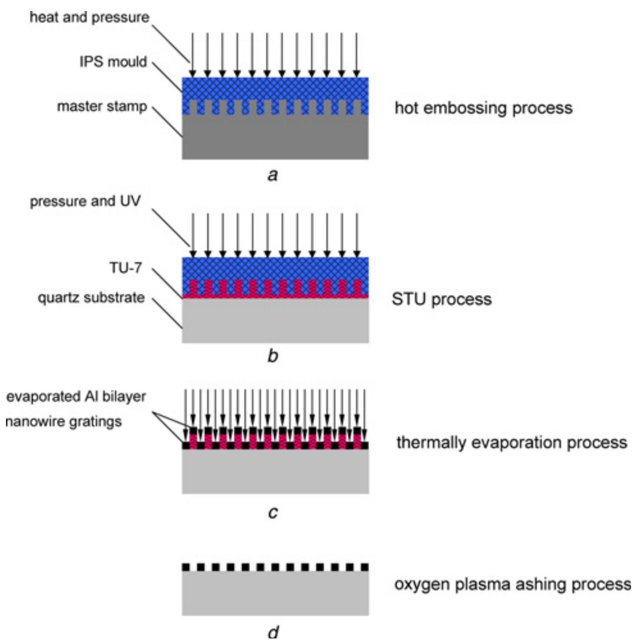

Figure 1 *Schematic representation of the fabrication process for SLNGs*
a Hot embossing process
b STU process
c Thermal evaporation process
d Oxygen plasma ashing process

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Table 1 Parameters of hot embossing process

Parameter	Value
imprinting pressure	40 bar
imprinting temperature	160°C
imprinting time	120 s
remoulding temperature	115°C

etched resist layer and a bilayer Al nanowire gratings structure is formed; and (d) the resist layer and the upper nanowire gratings are removed by oxygen plasma ashing process simultaneously and SLNGs are finally fabricated.

3. Experiments: On the basis of the proposed fabrication process, a SLNGs polariser was fabricated successfully. The nickel master stamp was duplicated from a silicon mould which was fabricated on a 2-inch silicon wafer by NIL Technology ApS (NILT, Denmark). The replication process is proposed in our earlier paper [11]. The geometric parameters of the master stamp are as follows: a period of 200 nm, a linewidth of 120 nm and a height of 220 nm. The overall size of the grating patterns is 1.3 × 1.3 mm. The surface of the master stamp was treated with an anti-sticking monolayer of $CF_3(CF_2)_7CH_2CH_2PO_2(OH)_2$ (Hansa Fine Chemicals, Germany) [12] by liquid phase deposition process for the reduction of adhesion between the stamp and the polymer during the demoulding process.

The NIL process was carried out on an Eitre 6-inch nanoimprinter (Obducat AB, Sweden). As is shown in Fig. 1*a*, the master stamp was first transferred to a soft IPS® (Obducat AB, Sweden) substrate based on the hot embossing process. As a soft embossing process using compressed air and a soft IPS mould, uniform imprinted nanostructures can be provided by the nanoimprinter and the damage to the master mould can be mitigated. The fabrication parameters of the hot embossing process are shown in Table 1.

After the cleaning process of the quartz substrate, a 115 nm TU-7 120 was spin coated on the substrate with a speed of 4000 rpm and baked at 95°C for 3 min subsequently. Then, the resist was imprinted by the STU process, as is shown in Fig. 1*b*. In this process, the TU-7 was imprinted using the IPS mould by the hot embossing process and the simultaneous UV exposure process was carried out for the light curing of TU-7. The fabrication parameters of the STU process are shown in Table 2.

To remove the residual resist, an ICP etching process was carried out using an AMS 100 etcher (Alcatel, France). The radio frequency power was 200 W, the bias power was 40 W, the gas flow of oxygen was 200 sccm, the chamber pressure was 4.6×10^{-3} mbar and the etching time was 20 s. Fig. 2 shows the scanning electron microscope (SEM) cross-sectional image of the imprinted resist after the ICP process. As shown in Fig. 1*c*, 90 nm Al was thermally evaporated on the nanogratings structure. After the metal deposition process, a bilayer Al nanowire gratings structure was formed. The SEM image of the bilayer gratings structure is shown in Fig. 3.

Table 2 Parameters of STU process

Parameter	Value
imprinting pressure	40 bar
imprinting temperature	70°C
imprinting time	120 s
UV exposure time	50 s
remoulding temperature	70°C

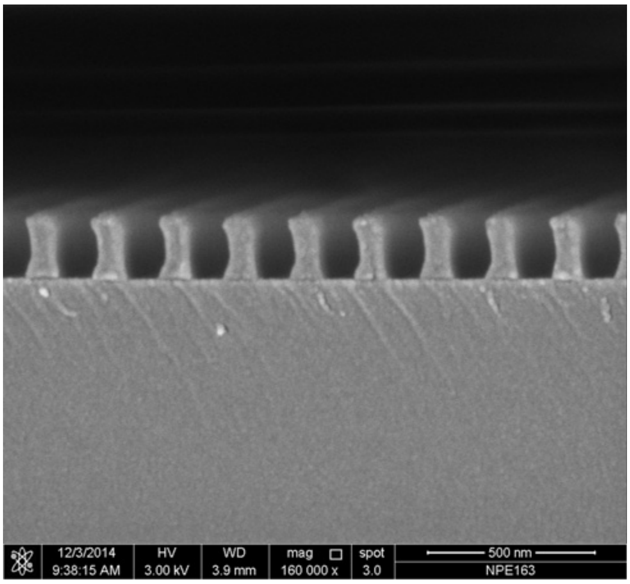

Figure 2 *SEM cross-sectional image of the imprinted resist after the ICP process*

Finally, as an isotropic etching process, the plasma ashing process was used to remove the upper nanowire gratings (Fig. 1*d*). In this process, the imprint resist TU-7 was used as the sacrificial material. The upper nanowire gratings and the TU-7 were removed together by oxygen plasma, leaving the lower nanowire gratings on the substrate. SLNGs were successfully fabricated as a result. The substrate was processed in a vacuum plasma reactor (K1050X plasma asher (Quorum Emitech, UK)) for 3 min at an intensity of 40 W. The vacuum level for the treatment was 5×10^{-1} mbar. Fig. 4 shows the SEM cross-sectional image of the fabricated SLNGs. It can be seen that the pitch, the linewidth and the thickness of the nanowire gratings are about 200, 120 and 90 nm, respectively. The top view images of three different locations of the fabricated grating patterns on the substrate were observed by the SEM and the observations are shown in Fig. 5. The inspection results in Fig. 5 show good consistency in the whole 1.3 × 1.3 mm area of grating patterns. However, a significant roughness can be observed in the fabricated gratings. As the nanostructure of the imprinted resist

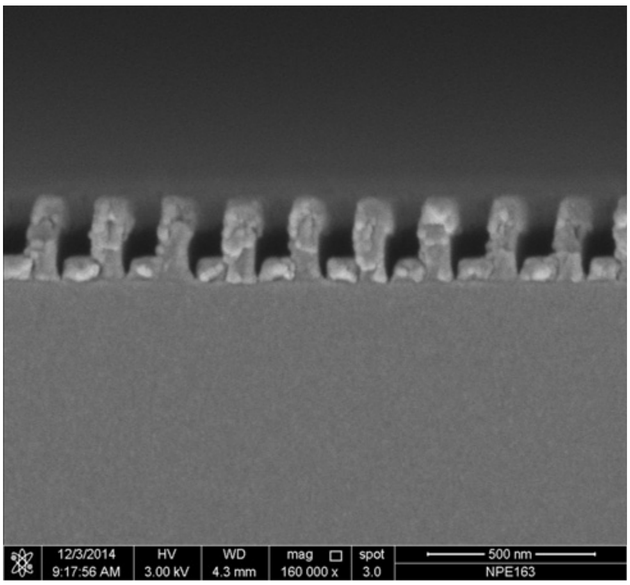

Figure 3 *SEM image of the bilayer gratings structure*

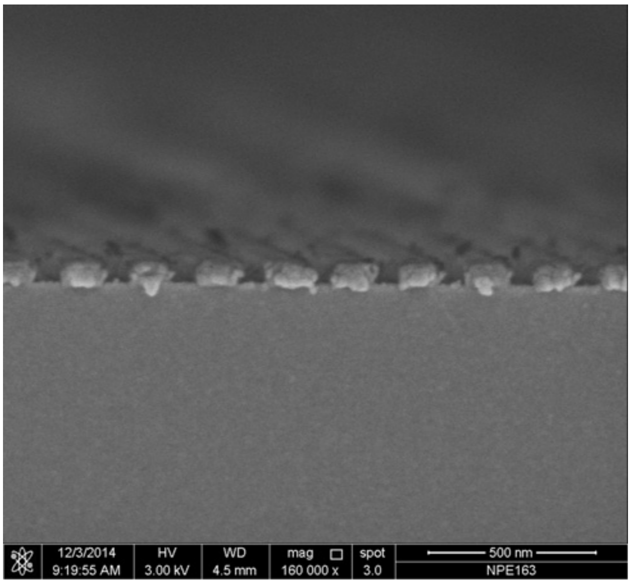

Figure 4 *SEM cross-sectional image of fabricated SLNGs*

after the ICP process is uniform and smooth, the significant roughness of the nanowire may be caused by the inconstant metal deposition process. Therefore, to improve the processing quality, a lower evaporation power will be used for a more constant deposition process in future studies.

A functional characterisation of the fabricated polariser was carried out. The characterisation system mainly includes an integrating sphere, a polariser mounted on the injection hole of the integrating sphere, a precision rotating platform and a bandpass filter (420–480 nm). The fabricated polariser was mounted on a commercial complementary metal-oxide semiconductor imaging sensor (MT9M001C12STM, Aptina Imaging Corporation, USA) fixed on a rotating platform. Moreover, a computer was used for the rotating platform control and sensor data recording. Fig. 6 shows the characterisation result. From the experiment result, it can be obtained that under an incident light condition in the range of 420–480 nm, the extinction ratio and the transmittance of the fabricated polariser are about 5.618 and 44.9%, respectively.

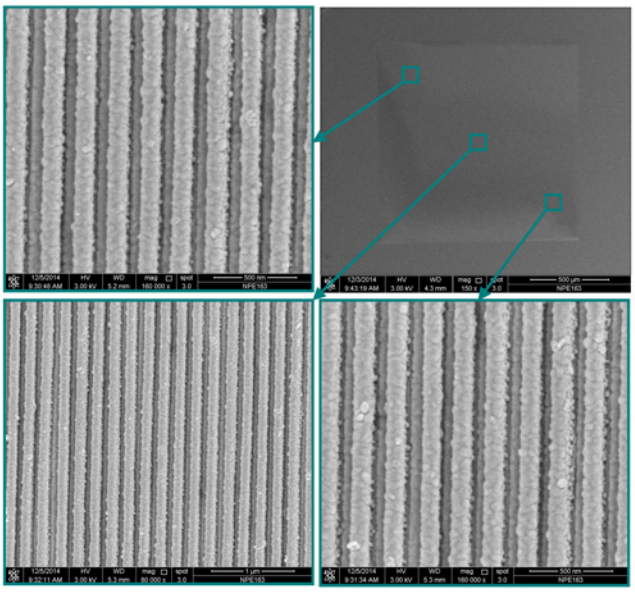

Figure 5 *SEM images of three different locations of the fabricated grating patterns on the substrate*

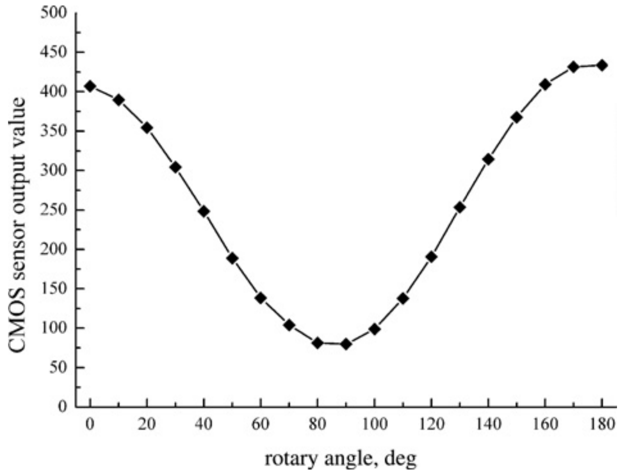

Figure 6 *Characterisation result of the fabricated polariser*

The performances indicate that the roughness of the nanowire has a limited impact on the performance of the fabricated polariser.

4. Conclusion: In this Letter, we propose a simple process for SLNGs. The process consists of four basic steps: replication of IPS nanoimprint mould, nanostructure transfer using the STU process, metal deposition to form the bilayer nanowire grating by thermal evaporation, and fabrication of the SLNGs by oxygen plasma ashing process. The major advantage of this process relies on the multiple roles played by the nanoimprint resist which greatly simplifies the fabrication process: the structure definition for the nanopatterns and the sacrificial material in the ashing process. Compared with the other fabrication processes for SLNGs, the proposed process not only has the advantages of the NIL process, but also simplicity for the elimination of the RIE process of the metal or the sacrificial layer. On the basis of this process, the fabrication of an SLNGs polariser with a 1.3 × 1.3 mm area of grating patterns and a 100 nm linewidth was successfully carried out. The inspection results of the SEM show good consistency in the whole grating patterns area. The experiment result demonstrates that the proposed process is adaptable for the fabrication of high-density and large-area nanometal patterns.

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