Novel optical lithography using silver superlens

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This work has demonstrated that with silver superlens, the resolution of conventional optical lithography can be improved significantly. Experimental and simulative results are given to verify the facts that the resolution and the pattern fidelity are sensitive to the contact tightness between layers.

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From the late 1960s, because the linewidth of integrated circuits has dwindled from 5 μm to sub-100 nm, optical lithography finds wide applications in semiconductor industry. Since the possibility of imaging with subwavelength resolution, "perfect lens" was realized by double negative index material, reported by Pendry in 2000[1], and researchers commit themselves to improve the resolution of the conventional optical lithography by using planar superlens[2−4].

Here we propose a device with a simple configuration, capable of enhancing the resolution of conventional optical lithography significantly. A dielectric layer and a silver layer with certain thicknesses are sandwiched between the photomask and the film of photoresist. Thereby, we can obtain patterns with ∼ 100 nm linewidth using a mercury lamp.

Our experimental setup for silver planar lens imaging is shown in Fig. 1. A chromium mask is patterned onto a flat silica substrate before depositing dielectric spacer and silver layer. The obtained mask is then brought to contact with a resist-coated silica sample for lithographic processing, and then the resultant resist pattern is imaged using a scanning electron microscopy (SEM).

The mask was fabricated on a 10 × 10 × 1 (mm) flat silica substrate. First of all, an 80-nm-thick layer of chromium film was deposited on silica substrate using direct current (DC) magnetron sputtering (525 W DC power, evaporation rate 15 nm/min). After spin coating this chromium-coated substrate with a layer of polymethyl methacrylate (PMMA, MicroChem) of 100 nm, a grating with 500-nm period was patterned by using electron beam lithography (EBL) and developed in a solution of methyl isobutyl ketone (MIBK) diluted 1:3 by volume with isopropyl alcohol (IPA). The PMMA pattern was transferred into the chromium film by wet etching with mixtures of cerium ammonium nitrate (22%), acetate (8%), and DI water (70%). The chrome masks were approximated as a binary object, as shown in Fig. 2(a), after removing the left-over PMMA.

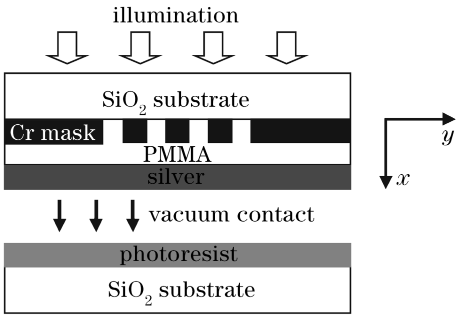

Fig. 1. Schematic diagram showing the experimental arrangement for silver planar lens imaging.

To avoid transfering the pattern on the chromium film to the silver layer, we spin-coated a layer of PMMA as dielectric spacer material to planarize it. A 40-nm-thick layer of silver, as a planar metal superlens, was evaporated over the 40-nm-thick PMMA spacer layer.

Another flat silica substrate was used for exposure, coated with a 1-μm-thick positive photoresist (PR) layer (RZJ-304, Suzhou Ruihong). We contacted this coated substrate with the substrate with silver layer and exposed it to a 200-W mercury lamp for about 20 − 30 s. We used the shorthand notation Sub/Mask/PMMA-40/Ag-40/PR/Sub to denote this structure. Similar extensions of this notation were used below. After developing for 20 − 30 s in 2.38% tetramethyl ammonium hydroxide (RZX-3038, Suzhou Ruihong), the resultant pattern was imaged using SEM, as shown in Fig. 2(b).

In order to explore the subwavelength imaging properties of silver planar lens, contrast experiments were conducted. In contrast experiment I, the silver layer of the above experiment was replaced by PMMA spacer with the same thickness, notated as Sub/Mask/PMMA-80/PR/Sub. In contrast experiment II, the silver layer was omitted, that is, Sub/Mask/PMMA-40/PR/Sub. In contrast experiment III, the photoresist layer was contacted with Cr mask directly and suffered to a normal lithographic process, that is, Sub/Mask/ PR/Sub. Through varying the exposure time from 10 to 80 s and the exposure time from 10 to 40 s, the best resultant patterns for every contrast experiment were obtained, as shown in Figs. 2(c)—(e).

Both the grating and characters on the photoresist can be distinguished very clearly with a little bit of line broadening in Fig. 2(a). Contrastly, patterns on the photoresist are so blurry that cannot be identified at all with PMMA spacer layer of different thicknesses (80 nm, 40 nm and 0 for contrast experiment I, II, and III) and without silver planar lens.

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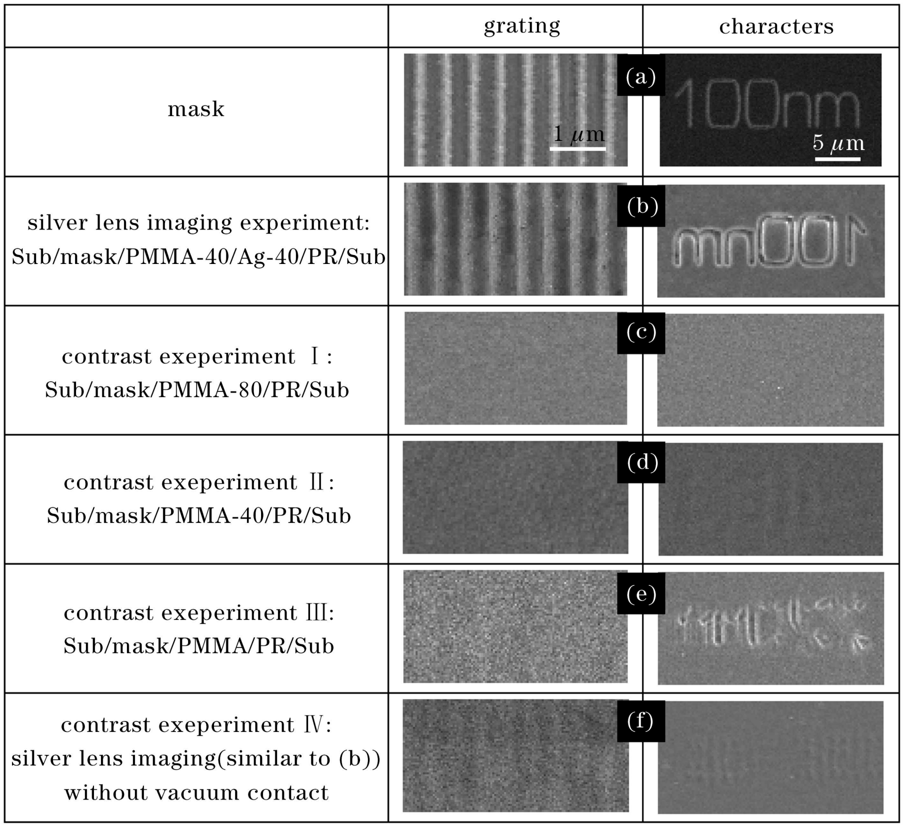

Fig. 2. Comparison of SEM images of (a) the Cr mask, resultant patterns on photoresist causing by (b) silver lens imaging, (c)—(e) contrast experiments without silver lens, and (f) contrast experiment without vacuum contact. On the mask, the grating period is 500 nm and the linewidth of the characters is ~ 100 nm.

The silver planar lens imaging experiment is very sensitive to the distance between the silver lens and the photoresist. Vacuum contact is very necessary to guarantee the photoresist contacts with the silver lens tightly. By comparison, exposure by normal contact induces an air spacer between the silver layer and the photoresist. Accordingly, the pattern on the photoresist becomes undistinguishable and undiscernible, as shown in Fig. 2(f).

Due to the strong dispersive property of noble metals, the selection of illumination wavelength (λ_0) is critical to the superlens design. $\lambda_0 = 365$ nm was selected in the experiment for the following reason: the relative permittivity of silver (ε_m) is negative ($\varepsilon_m = -2.4012 + i0.2488$ at 365 nm)[5], and its real part matches closely with that of the dielectric PMMA ($\varepsilon_\text{d} = 2.2201$ at 365 nm).

We used the transfer matrix method to compute the transmission coefficients for all the spatial harmonics (including the evanescent components) of the two slits radiation and obtained the images of the two slits. We considered both the transmission coefficients in the transverse magnetic (TM) and transverse electric (TE) polarization.

From Fig. 3, we can find only the TM component waves can excite surface plasmons on the silver surface and get a comparable flat transmission function even in the region of the evanescent components (i.e., the transmission coefficients of TM mode evanescent components corresponding to the imaging in Fig. 2(b) are amplified and become comparable to the transmission coefficient of propagation components in a wider scale). Although there is amplification of evanescent components under the condition Fig. 2(c), small local amplification will lead to wrong high-frequency oscillation and large sidelobes in the imaging. Here we only considered the TM polarization. Although we tried to make the distance D_ap

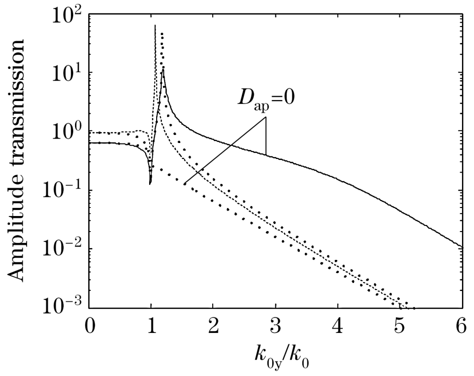

Fig. 3. Transmission coefficient as a function of k_z/k_0. Two curves are for $D_\text{ap} = 0$ (i.e., the distance between the sliver layer and photoresist is zero) in Fig. 2(b) with different polarizations. The other two curves are for the two polarization condition in Fig. 2(c). The two dotted curves are for the TE polarization and the other two curves are for the TM polarization.

between the sliver layer and the photoresist close to zero (i.e., the vacuum contact), it is very difficult to realize vacuum contact in the experimental process.

From Fig. 4, we can find that when D_{ap} increases from zero under the silver planar lens imaging conditions in the Fig. 2(f), the image intensity decreases and becomes closer to the numerical imaging results in Fig. 2(c).

This work has demonstrated that silver superlens can improve the resolution of normal optical lithography significantly. Inserting a dielectric layer and a silver layer with certain thicknesses between the photomask and the photoresist, patterns with $\sim$ 100-nm linewidth can be transferred to the photoresist with just a little line widening, exposing to a broad band, unpolarized light source.

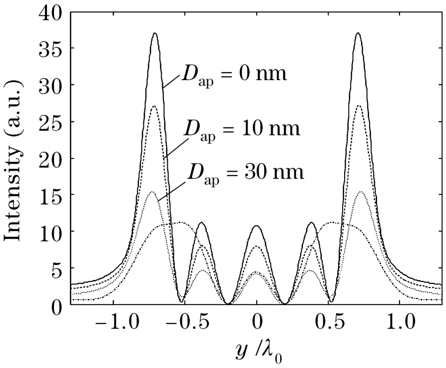

Fig. 4. The solid, dashed and dotted curves correspond to the numerical images results on the surface of the photoresist in Fig. 2(b) when D_{ap} equals to 0, 10, and 30 nm, respectively; The dashdot curve is the numerical result under the condition in Fig. 2(c).

However, the fidelity of this improved lithographic technology has been found sensitive to the tightness of the contacting between different layers. It is really a dilemma of keeping close contact and advoiding damaging them. A compromise should be found in further study.

We improve the conventional optical lithographic technology by inserting a dielectric layer and a silver layer with certain thicknesses between the photomask and the photoresist layer. Exposing to a mercury lamp, patterns with $\sim$ 100-nm linewidth can be transferred to the photoresist with just a little widening. For silver superlens to achieve commercial quality sub-100-nm linewidth patterns, the manufacturing process must be carried out not only to improve the precision of the thickness of each layer, but also to keep appropriate close contact between them.

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