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Lift-off process, Bilayer lift-off process, Photolithography, Patterning, S1813, LOR 3A, Development

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Optimization of Bilayer Lift-Off Process to Enable the Gap Size of 1 μm Using LOR 3A and S1813

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Bilayer lift-off process for 1 μm feature size is demonstrated using LOR 3A and S1813 photoresist. The thickness of photoresists was fixed, whereas development time is varied. The process was further investigated by measuring the undercut depth and undercut rate by scanning electron microscopy. An optimized and reproducible recipe is provided.

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I. Introduction

The lift-off process (LOP) is a photolithographic technique in which a metal layer is patterned by removing the metal layer deposited on the photoresist (PR) while the metal layer deposited on the surface remains.[1] Therefore, the tone of the resulting metal pattern is inverted, as opposed to conventional lithography and subtractive processing, where the metal layer exposed to an etchant is removed. Despite its drawbacks such as metal residue redeposition and 'fencing,' where the metallized resist sidewalls are removed but the metal remains, LOP is often used in research since it provides a means to pattern metal when etching is difficult.[2–4]

The LOP can be done with one layer of negative PR or two layers of resist, one of them being photosensitive. A single-layer lift-off structure is easy to fabricate, but the shape of the 'undercut' structure, which is a key factor for a successful LOP, is difficult to control. On the other hand, the bilayer LOP (BLOP) enables facile control of the undercut depth.[5]

The BLOP is done by first spin-coating and baking the photo-insensitive lift off resist material (LOR), and then spin-coating PR.[6] Then the two resists are developed, followed by metal deposition. During the resist stripping process, the solvent dissolves the LOR and PR and metal layer all together. Therefore, it is crucial that there is a discontinuity in the metal layer to expose the resists to the solvent. The lack of discontinuity necessitates the use of ultrasonication during the resist stripping process.

Although the BLOP procedure suggested by Microchem recommends ultrasonication, ultrasonication may damage the micro- or nanostructures patterned on the wafer.[7,8] In addition, ultrasonication produces micro- and nanoparticles from the bulk metal, which is difficult to remove.[9] Therefore, to facilitate the resist-stripping step, gentle agitation by pipetting is preferred over ultrasonication.

The discontinuity in the metal layer is formed by the undercut structure in the resist stacks.[10] However, excessive undercut depth may lead to unstable structure, limiting the gap features' feature size since weak supporting LOR layer cannot sustain the upper layer (Fig. 1). Therefore, the BLOP recipe has to be balanced between having a sufficient undercut to give the discontinuity in the metal layer and having a concrete support LOR layer to maintain the pattern fidelity.[10]

The undercut in the resist stacks is generated when the developer compatible with both PR and LOR first develops the upper PR layer and then isotropically dissolves the underlying LOR layer. The parameters to control the undercut depth are the baking temperature of LOR and develop time. The recommended baking temperature range for LOR is given as 160 °C to 210 °C. Higher baking temperature slows the develop process, which

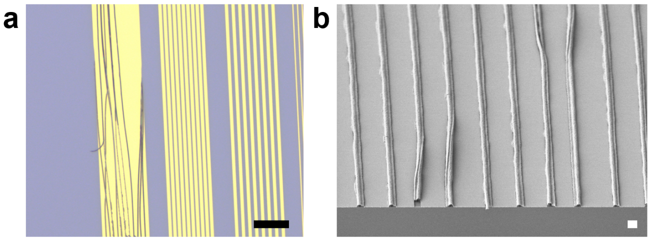

FIG. 1. Pattern delamination due to excessive development (a) Optical microscope (OM) image of the pattern shows the displacement of the gap feature in line features with 2μm width gap, which was printed as 1.1 μm (scale bar: 100 μm). (b) The distortion of the pattern is caused by weak LOR support layer, due to deep undercut (scale bar: 1 μm).

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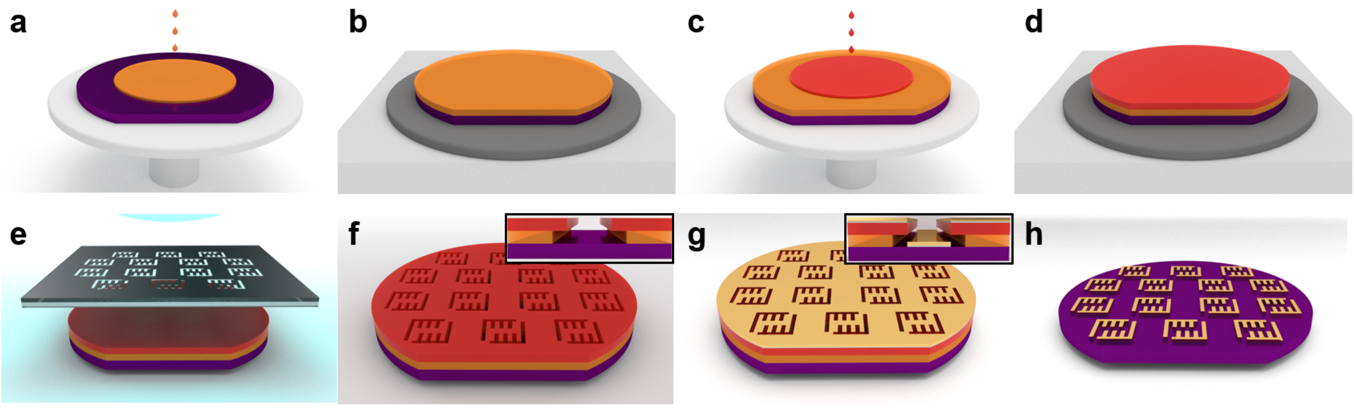

FIG. 2. Schematic illustration of LOP process flow (a) LOR 3A is first spin-coated onto the substrate and, (b) baked for 5 min at 180 °C. (c) S1813 overlayer is spin-coated, then (d) baked for 60 s at 115 °C. (e) PR is exposed and (f) developed. The cross-section of resist stack with undercut is shown in the inset. (g) Cr-Au metal bilayer is evaporated. The inset highlights the discontinuity of the metal layer, generated by the undercut. (h) Metal is patterned by removing the resist and metal stack.

gives a broader time window for the develop process.[11]

In this report, the undercut depth and rate of LOR 3A and S1813 photoresist was investigated by varying the development time, while the thickness of photoresists and soft-bake time remains constant. We propose a BLOP recipe for 1 μm features.

II. Experiment

The schematic illustration of the process is shown in Fig. 2. After the dehydration bake of the wafer at 180 °C for 180 s, the LOR layer (LOR 3A, Kayaku Advanced Materials) was spin-coated onto the Si wafer at 3000 rpm for 45 s, followed by soft-baking at 180 °C for 5 min. Then positive photoresist S1813 was spin-coated at 3500 rpm for 45 s, and soft-baked at 115 °C for 60 s. The hexamethyldisilizane (HMDS) priming step was omitted since it is not required for LOR.[7] The wafer was exposed using MA6 SUSS mask aligner with the dose of 70 mJ/cm^2 in a vacuum contact mode. The mask used in this study consists of feature sizes of 1, 2, 5, 10, and 20 μm with various pattern density. The wafer was then diced into 2 x 2 chips. To investigate the correlation between the pattern fidelity and develop time, chips were developed in AZ 300 MIF developer with manual agitation for varying times, ranging from 30 s to 70 s, where the chips were held and shook back and forth. Organic residues remaining on the surface was cleaned by oxygen reactive ion etching (RIE, Oxford Instruments Plasma Lab 80+) for 30 s with the power of 100 W, oxygen flow of 20 sccm, and the set pressure of 60 mTorr. After descum, either 120 nm thick monolayer Cr or 20 nm thick Cr followed by 100 nm thick Au was evaporated by an e-beam evaporator. For the resist stripping process, the chips were soaked in remover PG or remover 1165 media for 10 min at 60 °C for two times, with manual agitation by pipetting. The chips were then rinsed with DI water twice. As-obtained chips were analyzed by optical microscopy (OM, Zeiss Axio Imager M2M) and scanning electron microscopy (SEM, JEOL 7500F HRSEM).

III. Results and Discussion

Fig. 3 shows the OM image of the patterned metal and the cross-section SEM image of the resist stack formed after the develop time of 40 s. The thickness of the LOR 3A ranged from 312.0 nm to 315.31 nm. A thicker LOR layer is preferred when a thicker metal layer is to be deposited, where the LOR layer should be thicker than the metal thickness by 1.2 to 1.3 times.[7] 2 μm metal features were printed as 2.4 to 2.5 μm, and 2 μm gap features were printed as 1 to 1.2 μm due to diffraction; and the gap features as narrow as 1 μm were patterned without distortion. The cross-section of the resist stacks for 40 s developing (Fig. 3 (c-d)) also

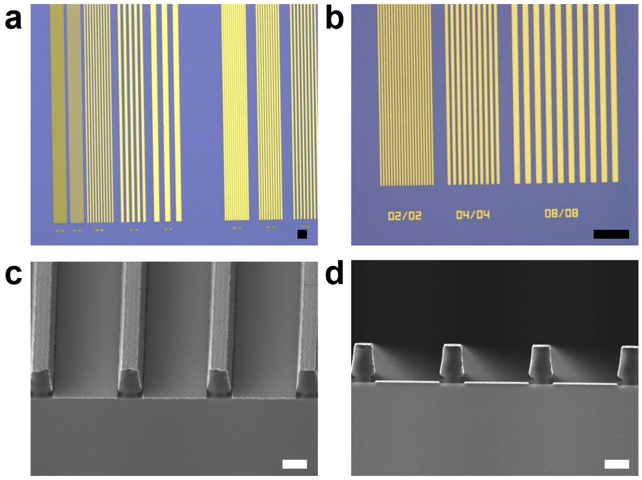

FIG. 3. Optimized recipe result (a-b) Optical microscope (OM) image of the line pattern with 1 μm gap, obtained by developing for 40 s. (scale bar: 50 μm) The cross-section SEM of the resist stacks, which results in gap features, at tilting angle of (c) 45° and (d) 90°. (Scale bar: 1 μm)

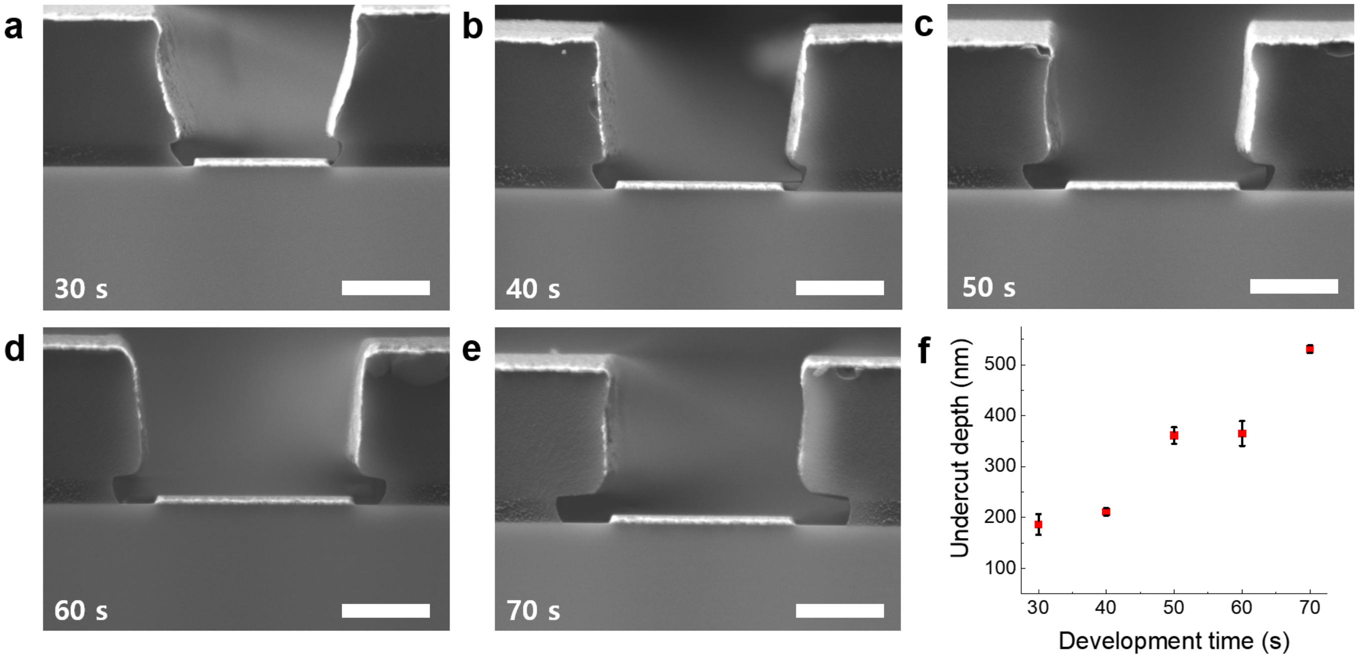

FIG. 4. Undercut depth by develop time (a) The undercut of resist stack for develop time of 30 s (b) 40 s (c) 50 s (d) 60 s and (e) 70 s. (f) The undercut depth by develop time. (Scale bar: 1 μm)

shows that the gap features were developed without any distortion while having a sufficient undercut to prevent fencing or bridging of the metal layer. The optimized recipe successfully printed the 1 μm gap features. However, it should be noted that the process is optimized exclusively using the AZ 300 MIF developer, and the use of different developers may give different results.

To calculate the undercut rate of AZ 300 MIF for LOR 3A, the undercut depth of resist stacks of varying develop times was measured using cross-section SEM (Fig. 4). The undercut depth was measured using the 5 μm pitch feature, which has a 1 μm-wide metal and 4 μm gap features. The distance between the edge of the metal line and the bottom part of the undercut was chosen as undercut depth. The undercut depth for 30 s, 40 s, 50 s, 60 s, and 70 s developing was 186 nm, 211 nm, 361 nm, 365 nm, and 530 nm, respectively. The shift in the deposited metal bar contributed to errors in the undercut depth measurement. The undercut rate calculation was done only using the 40 s to 70 s develop time since S1813 was also being developed between 30 s and 40 s, which is evidenced by the increase in the metal line width and the change in the slant angle of the sidewall. The undercut rate was calculated as 106 Å/s. When even more delicate features are to be printed, one may consider increasing the baking temperature, which gives slower undercut rate.[7]

The S1813 layer was clearly underdeveloped when developed for 30 s. 60 s develop time resulted in the delamination of 1 μm gap features in some cases. Therefore, the safe range of develop time for BLOP can be considered to be 40 s to 50 s, while the development time of 40 s gives the most stable result for 1 μm gap features.

IV. Summary

The optimization of BLOP using LOR 3A, S1813 photoresist, and AZ 300 MIF developer was described. Optimal develop time was found to be 40 s, in which the undercut was sufficient to facilitate the BLOP and give a stable resist stack structure. The undercut depth at 40 s was measured to be 211 nm, where the undercut rate was 106 Å/s. The optimized process flow for BLOP is as follows;

1) Wafer dehydration bake: 180 °C, 180 s
2) LOR 3A spin-coating: 3000 rpm, 45 s / bake 180 °C, 5 min
3) S1813 spin-coating: 3500 rpm, 45 s / bake 115 °C, 60 s
4) Exposure: 70 mJ/cm^2, vacuum contact mode
5) Develop: AZ 300 MIF developer, 40 s (+ 2x DI rinse)
6) O_2 Descum: O_2 20 sccm, power 100W, set pressure 60 mTorr, 30 s
7) Evaporation: 120 nm metal film (Cr 20 nm followed by Au 100 nm or Cr 120 nm)
8) Lift-off: PG remover or remover 1165, 60 °C, 10 min 2x, + 2x DI rinse

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