Lithography for sub-60 nm resist nanostructures

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As the semiconductor community continues to follow the Semiconductor Industry Association Roadmap, resist structures are being printed further into the nanometer domain. However, a persistent issue for successful sub-60 nm resist patterning is mechanical stability at high aspect ratios. The objective of this article is to understand what processing conditions facilitate processing resist nanostructures with useful aspect ratios for the fabrication of sub-60 nm transistors. We have found that, in aqueous based development and rinse, if the resist thickness is reduced, then the aspect ratio is sacrificed for the sake of resolution. The implication is that there is a resolution limit at which resist structures will have aspect ratios that are useful for device fabrication. We have also found that there are development effects that occur in the thick film regime that are not reproducible with thin films. The best resolution structures we have been able to print are lines of 28 nm in width using direct write electron-beam lithography on negative chemically amplified resists NEB-22 and NEB-31 (Sumitomo Chemical Inc.) with an aspect ratio of about 3. To put this result in perspective, this is about 40 molecules wide. © *1999 American Vacuum Society.* [S0734-211X(99)14506-2]

I. INTRODUCTION

As the semiconductor community continues to push the limits of device dimensions, the need for high resolution lithography increases. Sub-100 nm resist structures are now feasible and devices are being made from these structures. Etched gates of the order of 60 and 40 nm have been reported,[1,2] and are operational at 60 nm gate lengths.[1] There is a continuing push towards even smaller gate lengths, and this is pushing the resolution limit of the resists used.

Direct write electron-beam lithography has demonstrated ample resolution in positive insensitive resists down to about 5–10 nm.[3,4] For negative chemically amplified and nonchemically amplified resists, resolution has been shown down to 30 nm,[5,6] with aspect ratios of 2–3. This is, though, only part of the picture in the fabrication of the device. The next step is to prove that these high resolution structures can be used to fabricate operational devices. In recent device technology[1] the resist is required to withstand an etch of a 100 nm hard mask, which precedes transfer to the gate stack. This puts a requirement of an aspect ratio of at least 3 in the resist structure for this etch process. We propose NEB-22 and NEB-31 (Sumitomo Chemical) as candidates for this structure. We observed, however, that NEB-22 had the needed chemical resolution, but its mechanical stability was not sufficient above 0.25 μm resist thickness to implement 60 nm structures reliably. This began an effort to understand the limitations on aspect ratio for resist nanostructures in the sub-100 nm domain, and motivated the exploration of a series of enhancements to our previous development–rinse–dry process. Surface tension effects on the mechanical stability of resist structures have been studied extensively.[7,8] However, those studies addressed structures above the 100 nm and it is not clear that those results are necessarily transferable to the sub-100 nm domain, as we will show in this article. Furthermore, we explored cold development conditions (5 °C), for which reported results were not readily found.

II. EXPERIMENT

Our exploration starts with investigating what processing options can be used to enhance the resolution of sub-100 nm nanostructures, in particular, sub-60 nm structures for device fabrication using the NEB-22 formulation. The first option investigated consisted of thinning the resist film. This work provided information on maximum aspect ratio as a function of thickness and therefore aspect ratio as a function of feature sizes. The next option was to investigate a less sensitive resist formulation, NEB-31, to see if a higher resolution resist would provide higher aspect ratio structures. The final option explored was the effect development process temperature may have on the resolution of sub-100 nm structures.

All resist exposures were performed with a JEOL 6000 direct write tool at 50 kV acceleration voltage, with currents down to 20 pA. The postapply bake (PAB) and postexposure bake (PEB) conditions were varied to provide the best imaging profiles depending on the experiment. The developer used was MF-321 (Shipley), which is a TMAH 0.21 N aqueous developer. The rinse was done in de-ionized water, and the dry was done gently with a nitrogen gun at low pressure.

III. THIN RESIST FILMS

Samples were prepared with NEB-22 as the resist at different thicknesses ranging from 1.0 down to 0.110 μm. In Figs. 1(a) and 1(b) the highest resolution achieved and the maximum aspect ratio obtained at room temperature are plotted as a function of film thickness. It is evident that the

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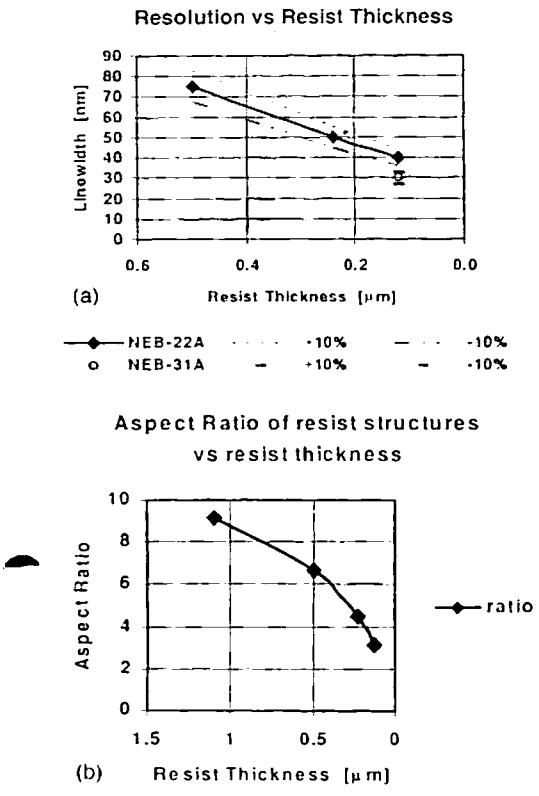

FIG. 1. (a) Improved resolution of sub-60 nm nanostructures printed in NEB-22 and NEB-31 (Sumitomo Chemical) using direct write electron-beam lithography. (b) The aspect ratio becomes the limiting factor for resolution at a given resist thickness.

aspect ratio decreases with film thickness and it is also clear that there is a direct relation between aspect ratio and feature size. As we go down to the 30 nm regime, aspect ratios of 3 are the best we can achieve to date. Given the process required to fabricate the sub-60 nm transistors by Timp *et al.*, this may not be sufficient. Recently, 40 nm gates have been fabricated with 50 nm lithography[2] using resist structures with an aspect ratio of 4.

IV. HIGH RESOLUTION RESISTS

We wanted to see if a less sensitive resist with apparently more chemical statistics due to the higher dose would actually prove stiffer and provide high aspect ratio structures in the 30 nm domain. We have obtained 28 nm resist structures in NEB-31 at 110 nm thickness, giving an aspect ratio of about 3.8 (Fig. 2). Clearly this is an improvement, but 25 nm structures were already collapsing which shows aspect ratios above 4 were not possible. The process conditions used were vendor recommended, without further enhancement: soft baked 100 °C, 2 min, postexposure bake 90 °C, 1 min, developed in MF-321, 2 min.

V. COLD DEVELOPMENT AND RINSE PROCESSING

Finally, an investigation on the effect of lowering the development and rinse process temperatures from 22 down to

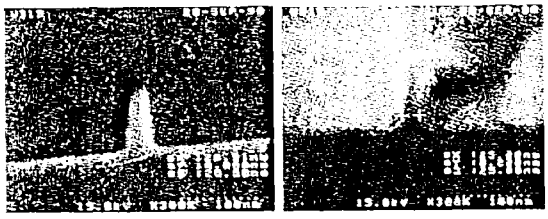

FIG. 2. Isolated structures in NEB-31, 28 nm (left) and 25 nm (right) isolated lines. The resist appears to exhibit resolution down to 25 nm but lacks mechanical stability.

about 5 °C was undertaken. The rationale was that, since the processing temperature is farther from the resist glass transition temperature, the material would be stiffer and might be able to overcome the capillary forces encountered during the dry step. When the resist is in the rinse process, it is a solid of density 1 surrounded by a liquid of density 1. When the dry process occurs, clearly there is a dramatic change to a medium of minimal density (air). Therefore it is necessary to have a very stiff structure in the sub-100 nm domain.

The initial effort to see if a high temperature rinse[8] would permit further crosslinking of the defined resist structures after development was unsuccessful (Fig. 3), and quickly abandoned. This was the first demonstration that with sub-100 nm structures there would be differences in the effect of the changing development–rinse process than there would be the thicker films and larger structures studied in Refs. 7 and 8. This result added to our motivation to study cold processing. Because work on cold development was not readily found, we started our efforts on thick films (1 μm) and then on thinner films (110 nm). We printed the smallest structures possible in each case. For the 1 μm films the best we could do were 120 nm lines, and for the thinner films 35 nm structures were achieved.

For the cold experiments, the developer and the rinse were prepared beforehand. Since the silicon wafer thermalizes rapidly, there was no significant delay in starting the development and rinse processing. We varied the processing conditions between 22 and 5 °C by permutating the rinse and development temperatures. The development and rinse times were also permutated between 5 and 10 min. At low temperatures we found that the development time was similar to that at room temperature. At 5 °C, the rinse time had to be increased because the developer solubility in cold water decreased. This was made evident by the presence of a signifi-

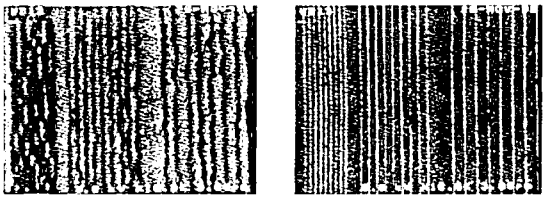

FIG. 3. Isolated 50 nm structures in NEB-22. A hot rinse (left) and room temperature rinse (right) are compared. The micrographs show that other factors besides resist baking and development conditions can affect patterning capability of a resist.

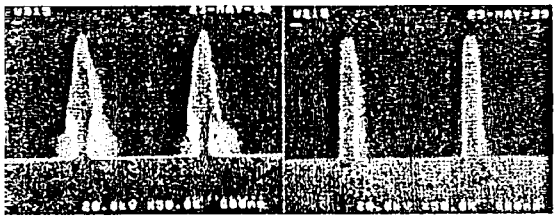

FIG. 4. Effect of development and rinse temperature on the image formation in 1 μm thick NEB-22 resist, isolated lines. (Left) Room temperature processing; (right) processing at 5 °C. Better profiles are achieved at 5 °C.

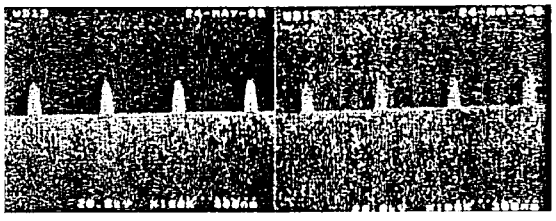

FIG. 6. Effect of development and rinse temperature on the image formation in 110 nm thick NEB-31 resist. (Left) Room temperature processing; (right) processing at 5 °C. The final result is similar. Both processes rendered 35 nm structures.

cant amount of developer residue on the wafer at shorter rinse times. In terms of mechanical stability, we observed that there was no significant improvement with regard to the ratio of the foot of the structure to the film thickness but a clear improvement in the profile of the structure for thick resist films (see the 120 nm structures in Fig. 4). Under room temperature development conditions we observe what appears to be a swelling effect when we processed 1 μm thick resist films. Whenever the development was done at 22 °C, this bulge at the midsection of the structure appeared. On the other hand, whenever the development temperature was 5 °C, the profiles were straight regardless of the rinse time. A significant improvement of resist contrast was seen when inspecting gratings of 360 nm pitch, Fig. 5. At room temperature development of the same structure did not resolve at all. This leads to the conclusion that 5 °C processing has more effect on the dissolution characteristics of the resist than on its mechanical stability.

Finally, we tried cold processing of the high resolution resist NEB-31 of 35 nm gratings, Fig. 6. The bake conditions used were the same as the results presented in Fig. 2. We found that there was no significant difference in the resolution achieved for the same resist thickness and that the profiles look quite similar. This leads us to believe that if higher aspect ratios are needed, then other processing options are needed, or that the etch selectivity of the hard mask under the resist needs to be improved so that high aspect ratio structures are no longer necessary. On the other hand, it is clear that at these dimensions molecular forces begin to dominate. A line 35 nm wide corresponds roughly to 50 molecules. Recent molecular modeling in nanolithography[9] suggests that surface states in polymer systems can extend 10 nm from the surface, leaving in this case only 15 nm of "bulk" resist. Therefore 63% of the structure is composed of the surface interface, where bulk resist characterization methods are no longer valid.

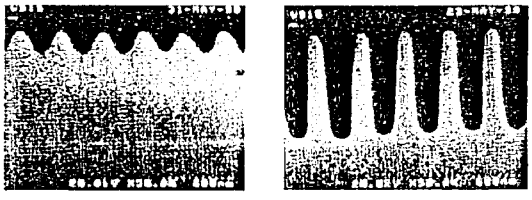

FIG. 5. Effect of development and rinse temperature on the image formation in 1 μm thick NEB-22 resist, 120 nm lines, and 240 nm spaces. (Left) Room temperature processing; (right) processing at 5 °C. The structures did not resolve at room temperature.

VI. SUMMARY AND CONCLUSIONS

We have shown the results of our work in exploring not only the resolution limits of resist structures in negative chemically amplified resists, but also the maximum aspect ratio achieved and the processing options we explored to improve it. We have found that, in aqueous development and rinse, if the resist thickness is reduced, then the aspect ratio of the resist structure is sacrificed for the sake of resolution. The implication is that there is a resolution limit at which resist structures will have aspect ratios useful for device fabrication. We have also found that previous results obtained with thick resist films cannot necessarily be extrapolated to the sub-100 nm regime. There are development effects that occur in the thick film regime not reproducible with thin films, especially using cold development. Finally, we found that in the 110 nm film thickness regime there seems to be no striking advantage to cold development over room temperature development. We have not been able to significantly improve the resolution or the achievable aspect ratio of the resists used by lowering the developer temperature when processing thin films. We were able to print 35 nm lines in NEB-31 resist with both cold and room temperature development. This seems to be our limit and raises the question as to whether aqueous based developed chemically amplified resists have reached their resolution limit, or whether there is now a need for alternative development–rinse–dry environments such as supercritical CO_2.[10] It is also clear that the dimensions we are working in are within the molecular domain, and molecular-level calculations are needed.

ACKNOWLEDGMENT

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