A Cleaner Approach to Ion Milling

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Ion milling is a well-established technique for subtractively patterning materials where the chemistries necessary for reactive ion etching do not exist. It is therefore essential for patterning many of the transition elements and their compounds. However, because ion milling relies on sputtering to remove material, redeposition on the mask frequently results in the formation of unwanted features that are difficult to remove. Milling at multiple azimuthal and polar angles can be effective, but complicates the process.

These issues can be avoided by using an undercut or re-entrant mask profile. This strategy enables clean removal of the masking layer and prevents the formation of "veils" by ensuring that there is no physical connection between the material deposited on the substrate and material deposited on the resist sidewalls. This approach is well known in the case of metal lift-off. However, in the case of ion milling, the fact that the source of the redeposited material is the feature being milled makes the situation more complex. We develop an analytical model of the redeposition profiles on the various surfaces of the resist, and on the sidewalls of the milled feature itself. The model can incorporate either a Lambertian or $\cos^n\vartheta$ emission profile. We use the model to develop a set of design rules linking the feature size, tolerances, milled depth and resist profile.

Figure 1 shows the parameters in the model for a bilayer resist mask. By varying the length of the mask overhang and the thickness of the underlayer, we can control the angles subtended by those surfaces relative to the milled feature, and thus modify both the amount and profile of the redeposited material (Figure 2). Assuming a required relative feature size tolerance of ε, we find that the maximum milled depth is $D_{max} \approx 2\varepsilon W$, driven by redeposition in the milled feature itself. The minimum mask overhang is $l \geq D/2$ for small D. Generally, this implies that the minimum pitch achievable for this approach is $\approx P + D + W$. Interestingly, the thickness of the upper layer has no influence on the process, and can thus be optimized to balance the need to avoid capillary-force-induced collapse against lithographic pattern fidelity. In addition, the use of a non-lithographic underlayer can greatly facilitate removal of the mask using an appropriate selective etch. We will present details of the model and a comparison with experimental results.

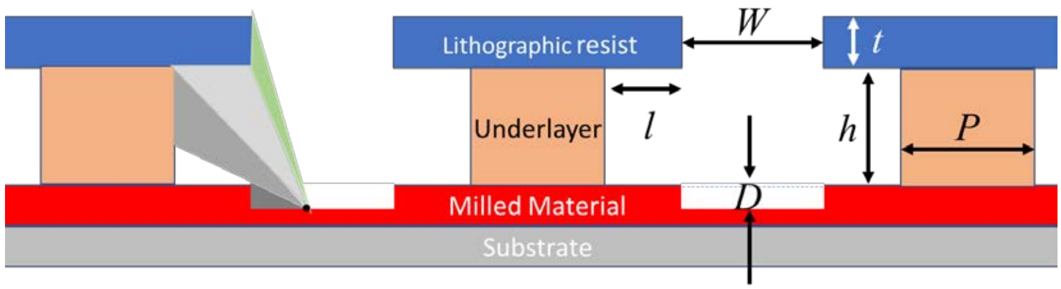

Figure 1. Schematic illustrating the instantaneous material fluxes from a point on the milled feature impinging on the various surfaces of the milling mask and milled feature (left), and parameters used in the model (right).

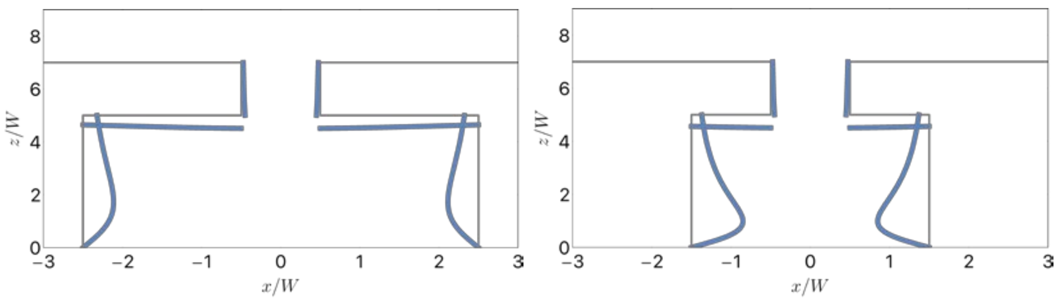

Figure 2. Relative redeposition profiles for different surfaces for two different overhang lengths, l/W=2 (left) and l/W=1 (right), for a shallow trench. The redeposition is scaled so that the profile is clearly visible. The setback of the underlayer sidewall (l in Fig.1) prevents redeposition near the intersection of the underlayer and milled material to enable lift-off and prevent unwanted features.