Polymer thickness effects on Bosch etch profiles

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Time-multiplexed etching, the Bosch process, is a technique consisting of alternating etch and deposition cycles to produce high aspect-ratio etched features. The Bosch process uses SF_6 and C_4F_8 as etch and polymer deposition gases, respectively. In these experiments, polymer thickness is controlled by both C_4F_8 gas flow rates and by deposition cycle time. The authors show that polymer thickness can be used to control wall angle and curvature at the base of feature walls. Wall angle is found to be independent of trench width under thin-polymer deposition conditions. Experimental results are compared to results obtained by other researchers using the more conventional simultaneous etch/deposition technique.
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I. INTRODUCTION

Emerging through-wafer interconnect technologies have created a demand for etch processes capable of producing deep features with exceptional anisotropy and high etch rates. Deep reactive ion etching processes, including the Bosch process, have evolved around this need.[1,2]

The Bosch process[3] (Fig. 1) is a series of alternating etch and deposition cycles, each lasting only a few seconds. Each deposition step coats the feature with a polymer layer, preventing lateral etching by radicals. When the ion beam has removed the polymer from the bottom of the feature reactive radicals, assisted by the incident ions, etch the underlying silicon. Prior studies[3–5] document changes in etched features as a function of deposition-to-etch-rate ratio for processes with simultaneous etch and deposition.

Coburn[6] describes a method of analyzing feature profile in such codeposition etch processes. The polymer deposition rate is controlled by the ratio of fluorine-to-carbon in the source gas (Fig. 2). When sidewall etching exceeds the deposition rate, an isotropic process results. At high deposition rates, a thick coating builds up on the sides of the feature. A smaller mask opening leads to a reduced ion flux exposure area at the bottom of the feature, and slower etch rate outside the exposed area. The feature narrows as trench depth increases and polymer buildup continues.[6] Between the extremes, vertical walls occur at a critical point where the horizontal etch rate is neutralized by the polymer growth.

These studies suggest that Bosch etch profiles will change as polymer thickness increases. This article examines changes in trench profile for the Bosch process as a function of polymer thickness. We compare the results to the changes observed in codeposition processes.

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II. EXPERIMENTAL CONDITIONS

Experiments were performed on an Oxford Instruments Plasmalab System100 etcher. Substrates were boron-doped ⟨100⟩ *p*-type Si wafers, 10–25 Ω cm. Masks were AZ P4620 photoresist with a hexamethyl disilizane adhesion promoter. The masks had a thickness of 10 μm. Wafers were baked at 70 °C for 60 min prior to etching, to drive out residual moisture. Unless otherwise specified, trenches were 50 μm wide and the total process time was 45 min.

Polymer thickness was varied by changing the length of the deposition cycle or alternately, by varying the flow of deposition process gas, C_4F_8. In either case, all other process factors were held constant. The remaining process conditions are given in Table I. When the deposition cycle time is varied, the flow rate is fixed at 60 sccm.

Increasing the duration of the deposition cycle without altering the total process time reduces the total time spent

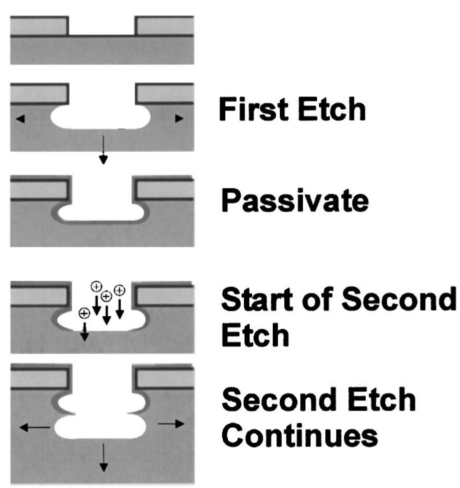

FIG. 1. Bosch etch process consists of alternating etch and deposition cycles. The etch cycle may be isotropic without affecting anisotropy of the feature.

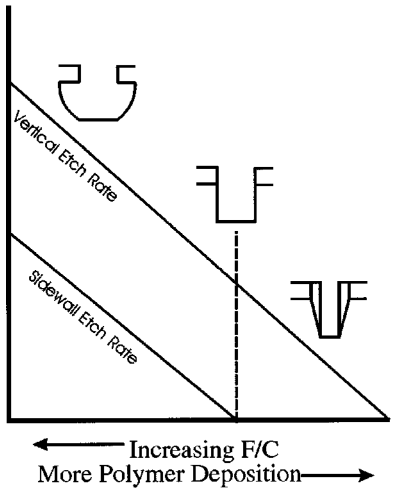

FIG. 2. Profile evolution in a codeposition etch process. Polymer deposition rate controls trench profile (see Ref. 6).

etching. To prevent confusion of the effects due to prolonged total etch time with those due to thinner polymer layers, a series of etches were performed where cycle times were fixed at 10 s and the polymer thickness was controlled with C_4F_8 flow, from 5 to 80 sccm. Scanning electron microscopy images supply trench wall angle, α, and the radius of curvature, R, at the base of the wall (Fig. 3).

III. RESULTS

Thick-polymer films develop on Bosch etched features as a result of both long deposition times and high C_4F_8 flow rates. Profile development mirrors that observed in codeposition processes when high deposition rates are used. Polymer builds up on the sidewalls of trenches. Where polymer thickness is a significant proportion of the trench width, the incident ion flux is restricted. Narrow trenches converge more rapidly than wide ones, as a greater proportion of the width is obscured (Fig. 4).

TABLE I. Bosch etch process conditions.

Factor	
SF_6 etch gas	85 sccm
Etch pressure	30 mTorr
Etch coil power	450 W
Etch platen power/plasma bias	30 W/150 V
Etch cycle time	15 s
C_4F_8 deposition gas (varies)	5–80 sccm
Deposition pressure	35 mTorr
Deposition coil power	450 W
Deposition platen power/bias	15 W/110 V
Substrate temperature	15 °C
Deposition cycle time (varies)	5–15 s

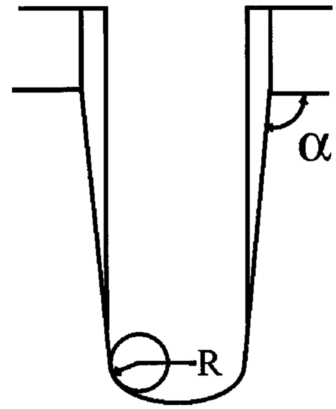

FIG. 3. Trench profile, measured elements α, and R.

Also observed as a result of thick-polymer deposition is the development of compound curvature at the bottom of trenches. In contrast, trenches with thin-polymer deposition, develop a simple convex curvature at the bottom of the feature [Fig. 5(a)]. Compound curvature is reduced or eliminated in narrow features (Fig. 4).

Thin-polymer layers result from short deposition cycles or low C_4F_8 flow (Fig. 5). Below the critical point, where the wall angle is 90°, there is a trend to smaller angles, resulting in a negative or reentrant profile.

The trench walls remain straight until the polymer becomes very thin, as in the 10 sccm C_4F_8 flow rate case. At this extreme, the walls become subject to bowing. Scattered ions remove the thin protective coating and wall curvature

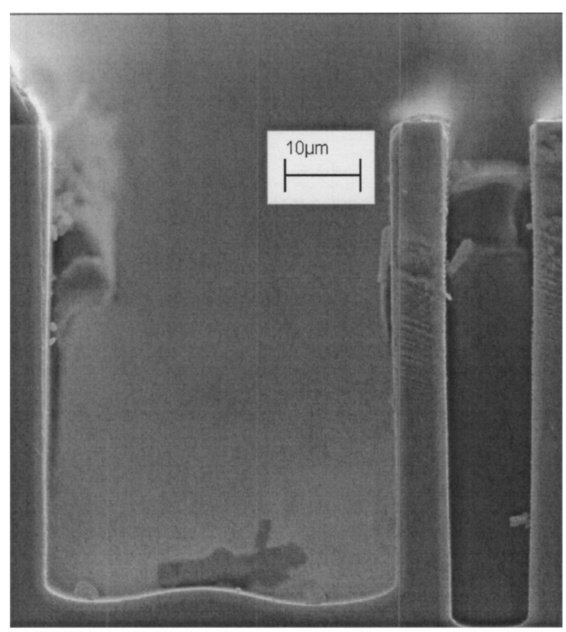

FIG. 4. Polymer accumulates on trench walls. Narrow trench converges as ion beam is restricted.

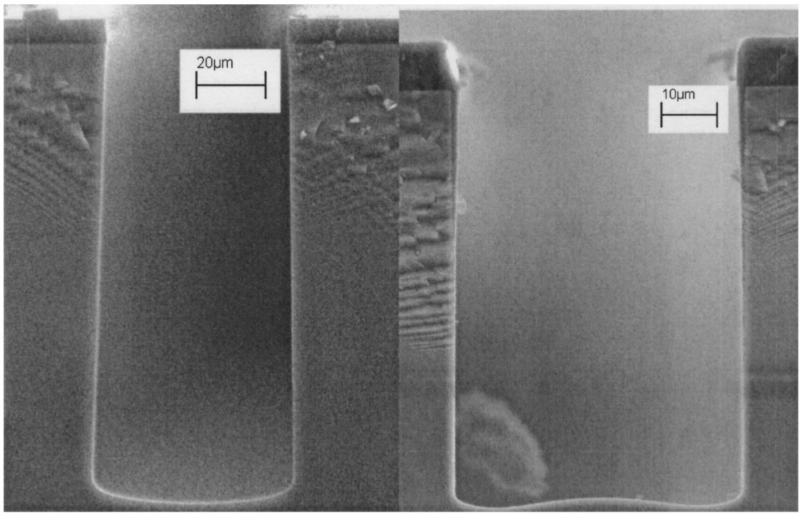

FIG. 5. (a) Trench with thin (5 s) polymer deposition. Negative profile and simple convex bottom curvature result. (b) Thick-polymer (12 s) case. Bottom of trench develops compound curvature.

results from the ion assisted etching. In the thin-polymer case, the wall angle is independent of feature width for a series of etched trenches (Fig. 6).

Both the wall angle and base radius change abruptly as the polymer layer becomes thin (Fig. 7). The trend as a function of deposition time appears to match the more slowly changing portion of that curve (Fig. 8). These trends were consistent with data for processes not presented here, in vias as well as trenches.

IV. DISCUSSION

Flow rate is a more precise control of polymer thickness than deposition time. Deposition time can only be set for integer values over a small range, while a broad range of C_4F_8 flow rates produce usable results. A critical point may be found associated with a film thickness that produces vertical feature walls. Changing the flow setpoint results in a change in the critical deposition time, and vice versa.

The wall angle in the thin-polymer extreme will be dependent on the angular distribution of incident ions. Several mechanisms influence this distribution. These include scattering collisions, space-charge effects, feature wall charging, and scattering off of the photoresist mask. So, process conditions, not associated with polymer thickness, will influence the wall angle. Critical settings for flow and deposition time will depend on other process conditions for this reason.

V. CONCLUSIONS

Polymer thickness can be used to control the wall angle and base radius of curvature in features etched with the Bosch process. This is independent of the parameter used to control polymer thickness. C_4F_8 flow is a more precise control of polymer thickness than deposition cycle time. In set-

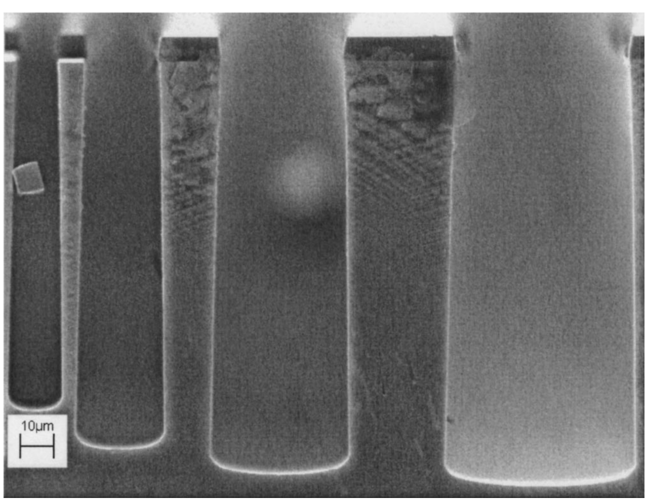

FIG. 6. Features with thin polymer (6 s). Wall angle is independent of feature width.

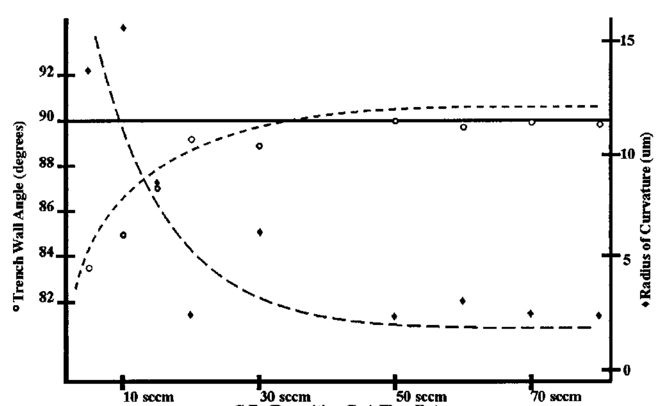

FIG. 7. Trench wall angle and base radius of curvature as a function of deposition gas flow rate, deposition cycle time of 10 s.

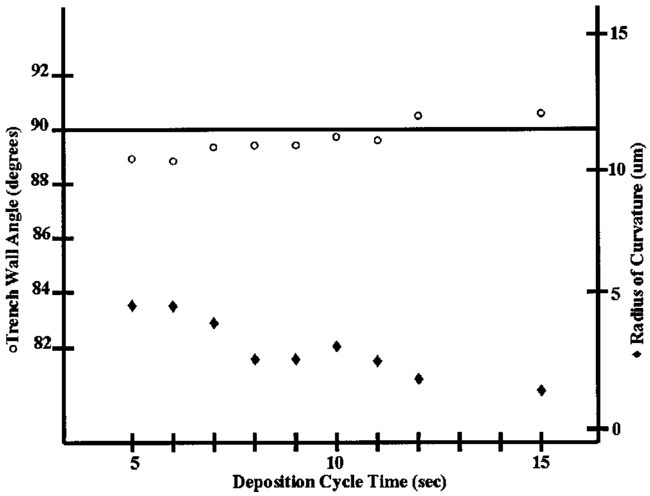

FIG. 8. Wall angle and base radius of curvature as a function of deposition cycle time, C_4F_8 flow of 60 sccm.

ting the desired wall angle, deposition cycle time should be used as a coarse control, with C_4F_8 flow used to refine the desired angle. The wall angle is independent of feature width when the polymer layer is thin relative to the critical point. It is dependent on polymer deposition rate above the critical point. Above the critical point, results are consistent with models of codeposition etch processes. The wall angle changes rapidly with polymer thickness below the critical point, slowly above it. Well above the critical point, compound curvature of the feature floor can be observed. This is a function of trench width, and is not observed in narrow trenches.

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