Process Window Engineering for Void-Free STI Gap Filling Using Integrated PEALD and Virtual DOE

EXPERIMENTS

Experiments were conducted on Lam Research Striker® FE—the latest generation PEALD platform, with ALD deposition and etch step switchable in chamber. In this case, the STI trench angle exceeds 86°, making HARP unable to achieve void-free gap filling, as Figure 1 shows. HDP led to device CP (Chip Probe) failures due to PID; thus, we utilized Striker® FE's AEA(ALD-Etch-ALD) functionality to optimize void-free gap filling. We hypothesized that AEA's etch behavior depends on CD, aspect ratio, and the balance between chemical etch and ion etch.

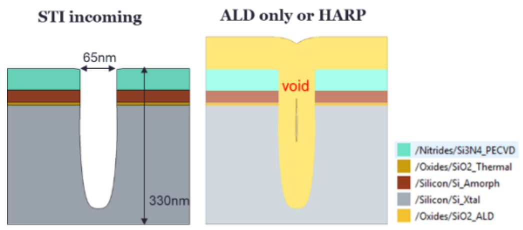


Figure 1: void exist after HARP or ALD only dep

Virtual DOE Set up:

Limited wafer resources restricted DOE experiments, so Lam Research SEMulator3D® software was used to simulate STI structures at a 1:1 scale. Conformal deposition and adjustable lateral/vertical etch ratios controlled isotropic/anisotropic balance. Void-free filling was defined by zero void volume post-filling, with simulations visualized as animations (e.g., Figure 2). For Virtual DOE, chemical-to-ion etch ratios were categorized into 11 groups (10:0 to 0:10), with 200 virtual DOEs per group, varying deposition and etch thickness. Analysis of 3200 virtual DOEs identified process windows for void-free filling across aspect ratios from 1:1 to 6:1. The optimal deposition-to-etch ratio and chemical/ion etch balance were determined for successful gap filling.

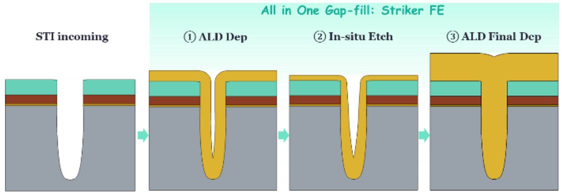


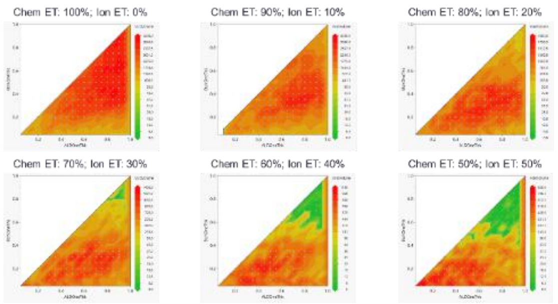
Figure 2: an illustration of Striker® FE's ALD deposition & etch combination process

RESULTS AND DISCUSSION

I. Analysis of Chemical Etch and Ion Etch on Gap-Fill Results

Using SEMulator3D® virtual DOE and JMP contour plots, Figure 3 illustrates how dep/etch thickness ratios and chemical-to-ion balances affect void volume. The X-axis represents the ALD deposition thickness ratio to incoming open CD, while the Y-axis shows the etch amount ratio to open CD. The triangular chart indicates etch must be less than deposition thickness. Green denotes void-free filling, while red indicates increasing void volume. Analysis reveals ion etch expands the void-free process window, while 100% chemical etch fails to achieve void-free outcomes. Increasing deposition thickness under fixed chemical-to-ion etch ratios aids void elimination.

Ion etching is anisotropic, driven by energetic ions striking the surface perpendicularly under an electric field, enabling precise vertical material removal, reshaping overhangs, and sharpening trench profiles (Figure 4a). Chemical etching is isotropic, relying on chemical radicals to remove material uniformly in all directions, preserving structure shape without correcting bowing or overhangs (Figure 4b).



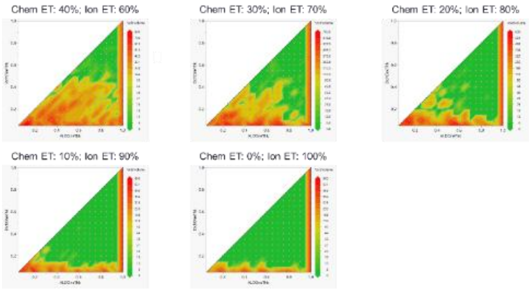


Figure 3: Contour plot of void volume as a function of dep/etch ratio under varying chemical-to-ion etch ratios

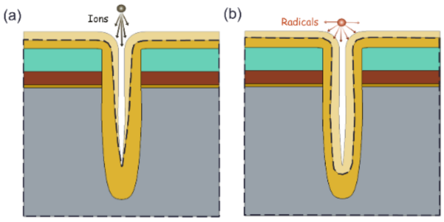


Figure 4: (a) Ion etch provides more vertical etch to shape the trench profile; (b) chemical etch provides more conformal etch

II. Analysis of Trech Aspect Ratio on Gap-Fill Results

Figure 5 illustrates the final gap-fill performance under different incoming aspect ratios. From the figure, it is evident that as the aspect ratio decreases, the void-free process window expands. When bowing or overhangs are present, larger CD allows thicker sidewall deposition before merging, granting latitude for etch-driven morphology repair. If bowing is defined as half the difference between CD_2 and CD_1 as Figure 6 (a) showed, the deposition thickness must exceed this bowing to enable etch correction. Conversely, smaller CD can merge early with thin film, depriving etch of the opportunity to fix bowing as Figure 6 (b) demonstrated.

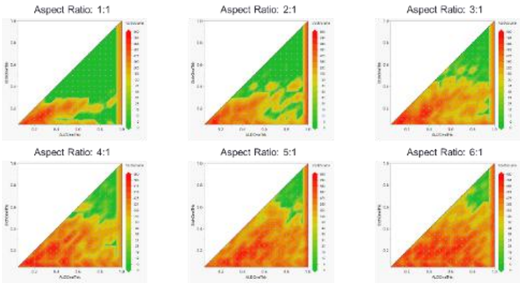


Figure 5: Contour plot of void volume as a function of dep/etch ratio under varying incoming aspect ratios

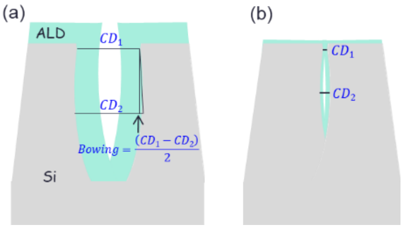


Figure 6: Schematic diagram of as-dep under different open CD conditions

III. Practical optimization experiment

In the real case, with a ±12.5% CD variation, the incoming CD was normalized to 0.75–1, and the process tuning target was defined within the green box in Figure 7. The initial ALD deposition was set to 73–94% of the incoming CD, while ion etching was optimized by increasing LF power to 50% of the total power. The etch time was adjusted to achieve an etch amount of 62–80% of the incoming CD, ensuring both deposition and etch amounts remained within the void-free window. Within this process window, TEM analysis confirmed void-free gap fill across all trenches.

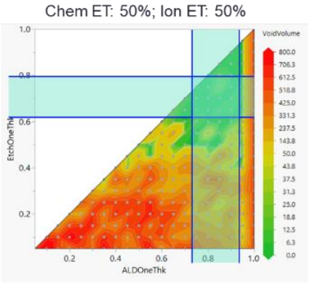


Figure 7: The actual defined process tuning target range

CONCLUSION

This work presents an innovative STI gap fill method integrating the AEA process into a single tool, reducing complexity, cost, and cycle time while ensuring void-free gap fill. Using Lam Research's SEMulator3D® software, over 3200 virtual DOEs analyzed key parameters like deposition-to-etch ratio, ion vs. chemical etch balance, and trench geometry. Larger incoming CD, higher deposition, and increased ion etch prone to achieve void-free results. The SmartFill approach combines AEA with AI-driven SEMulator3D®, enabling reliable gap fill and rapid process optimization for advanced semiconductor gap-fill.