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Predictive Modeling of Pattern-Dependent Etch Effects in Large-Area Fully-Integrated 3D Virtual Fabrication

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***Abstract* - We present a predictive modeling approach for pattern-dependent etch processes implemented in a 3D virtual fabrication software platform. This technique combines long-range effects using design data and short-range effects using predictive 3D models of the design-technology interaction. For the first time, this type of pattern-dependent predictive capability is integrated into a full 3D virtual fabrication environment to enable fast accurate structural modeling of complex advanced technologies such as FinFETs, 3D memory and BEOL interconnect.**

***Keywords* - 3D, etch, process modeling, virtual fabrication, pattern-dependent, design-technology interaction**

Introduction

As the semiconductor industry transitions to 3D devices to keep Moore's Law afloat, much of the pressure is being applied to the etch processes required to produce these structures. Developing these processes typically focuses on a small set of calibration structures. Unfortunately, variation in these etches is sensitive to design parameters and underlying topography, and has impact on the yield, reliability and performance of devices through the entire design space. Predictive modeling of these processes, specifically in the context of the overall integrated flow, delivers accurate sensitivity data across many designs in a small fraction of the time and cost of iterative in-fab experiments.

Virtual fabrication has been proven accurate and efficient for modeling design-technology interaction in complex process flows [1,2]. The challenge to properly model these pattern-dependent effects is the diversity of length scales in the sensitivities. Etch rates, anisotropy and taper angles can be dependent on pattern-density on the scale of 1-10um [3], which is often larger than the domain of virtual fabrication models. These same etch behaviors also depend on "feature-scale" pattern-dependence such as aspect ratio [4], with length-scales well within the typical modeling domain of virtual fabrication.

Modeling Methodology

While detailed modeling of pattern-dependent etch effects using first-principles physical models is possible, it is computationally expensive and relies on accurate characterization of material properties and etch chemistry [5]. We present a more efficient and novel pseudo-3D approach to pattern dependence modeling, based on 2D proximity functions, which can be easily calibrated to known structural data. Proximity functions have been previously reported for model-based OPC [6] and are used to sample pattern-density within a characteristic distance of a point of interest on the mask. In contrast to existing OPC techniques, this work combines masking information extracted from the 3D model with masking information from the layout to create a pattern-dependence mask (Fig. 1). Convolution of one or more proximity functions with this pattern-dependence mask yields a 2D loading map (Fig. 2), which modifies the behavior of a 3D behavioral etch algorithm.

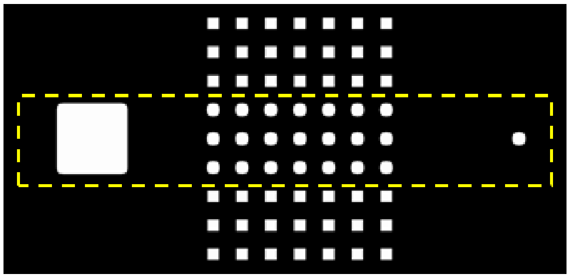

Figure 1. An example pattern dependence mask. Area inside the dotted line is extracted from the 3D model; remainder comes from layout.

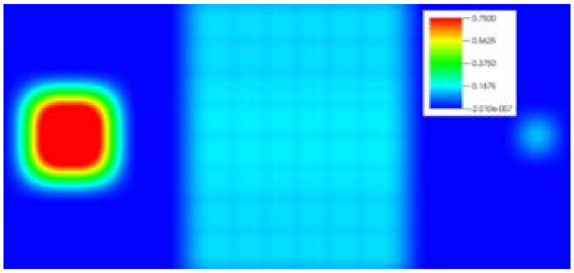

Figure 2. Convolution of the pattern dependence mask with a Gaussian proximity function.

Since the 3D modeling domain is typically smaller than proximity function radius, the combination of masking information from both 3D model and 2D layout is key to enabling optimal accuracy and speed. This model, with two proximity terms, is validated against silicon results from literature [7] (Fig. 3).

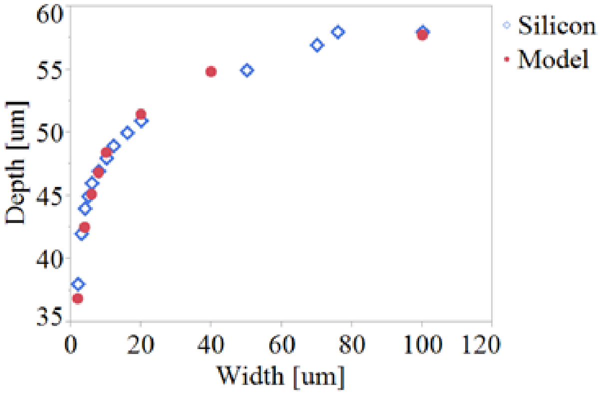

Figure 3. Validation of pattern-dependent depth data vs. silicon results from literature [7].

Table 1. Target dimensions of pattern-dependent etch for calibration.

Feature	Dense	Isolated
Top CD [nm]	100	85
Depth [nm]	250	140

Calibration & Application

A specific etch process was investigated using this modeling approach. This etch is implemented on via-like patterns with an 80nm size and 120nm minimum space. A simple calibration of pattern-dependent effects includes the CD and depth of a via in a dense array and a single isolated via (Table 1). This calibration is validated by 3D modeling of a template layout (Fig. 4) and automated virtual metrology. An optional additional calibration point improves prediction of open areas with negligible effect to other structures (Table 2).

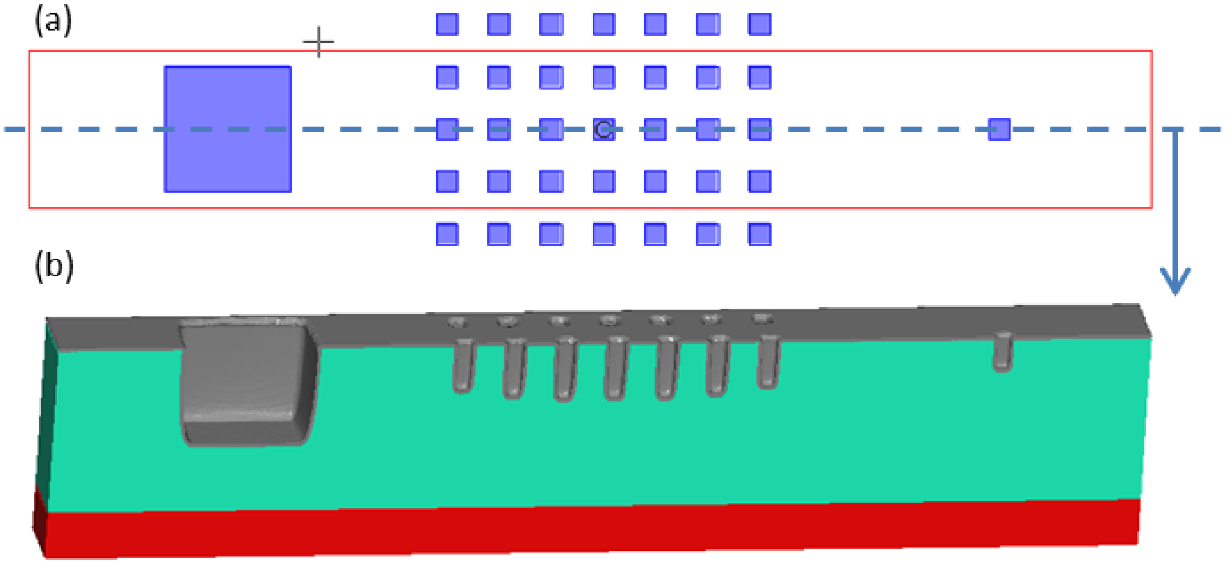

Figure 4. (a) Calibration template layout and (b) 3D model result from virtual fabrication of pattern-dependent etch on template layout, with decoration film.

Table 2. Results of automated metrology on 3D virtual fabrication calibration result.

Feature	Large (480nm)	Dense (Edge)	Dense (Center)	Isolated
Top CD [nm]	534.99	84.96	99.85	84.64
Depth [nm]	424.29	206.52	247.22	140.12

An alternate layout (Fig. 5), which includes a dense array of vias and boundary trenches, features not typically intended on this type of hole-like design layer, but occasionally employed for isolation, is examined through another virtual fabrication model. The same calibrated etch process model is applied to this layout, using the same dielectric film stack used for calibration. The resulting virtual fabrication model, after etch (Fig. 6) shows obvious significant CD and depth effects due to the design, specifically driven by proximity to the boundary trenches.

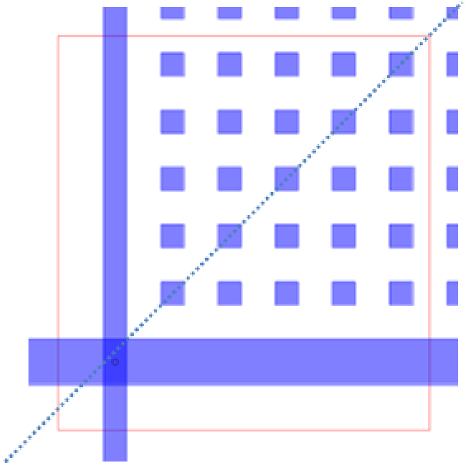

Figure 5. Layout of dense via array surrounded by boundary trench with cross-section indicated.

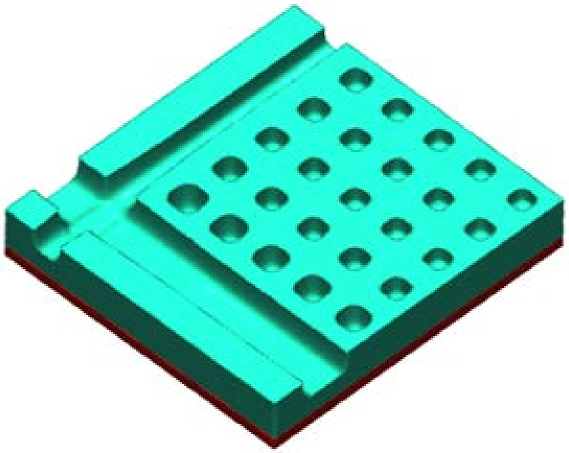

Figure 6. 3D virtual fabrication result from array corner pattern-dependent etch.

Visualizing the virtual fabrication model after the deposition of a decorating metal film and an angled cross-section provides a more clear view to the detailed physical behavior of the trenches and the vias at different distances from the two boundary trenches.

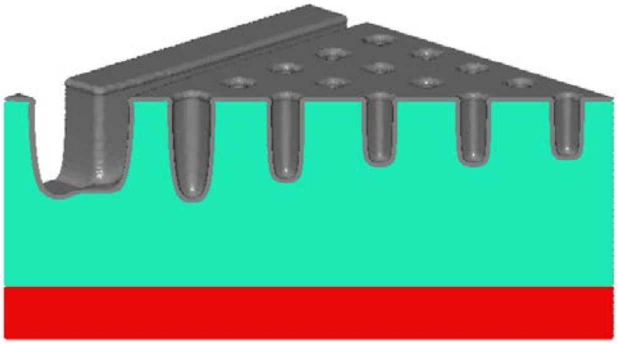

Figure 7. Angled cross-section of 3D virtual fabrication result with decoration film.

The associated virtual metrology show significant CD and depth effects driven by proximity to boundary trenches. The via closest to the boundary trench corner is 55% deeper with a CD 32% larger, relative to vias in the center of the array. The depth dependence impacts vias in the first three rows and columns relative to the boundary, while the CD dependence strongly affects the row next to the wider trench, but less so in rows and columns further away (Figs. 8-9). The vias far from the boundary trenches behave as expected for vias in a large dense array, despite being at the edge of the model. This is accomplished through use of the combined density information: 3D structural information from inside the modeling domain and 2D design data from outside the modeling domain.

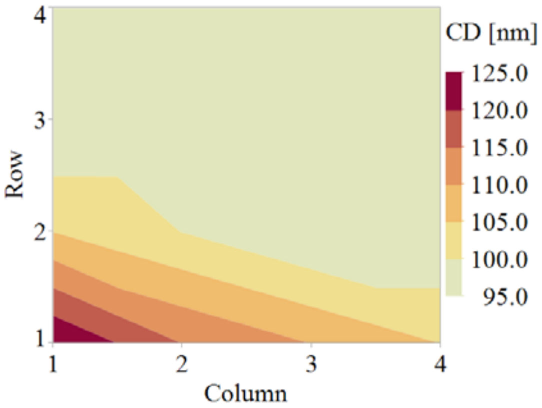

Figure 8. Contour plot of via top critical dimension (CD) vs. position in bounded array.

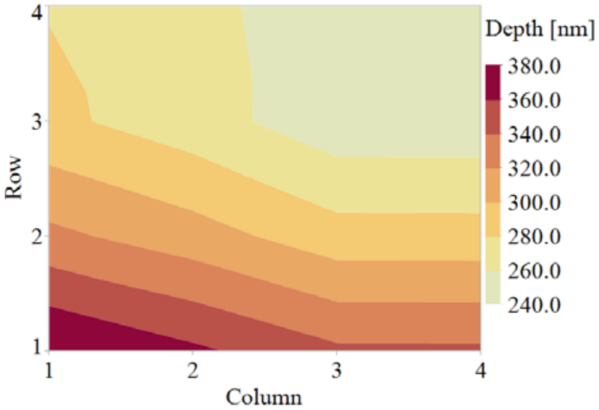

Figure 9. Contour plot of via depth vs. position in bounded array.

Finally, the effects of this pattern-dependent etch on a device-representative film-stack are examined. The virtual fabrication begins with the deposition of appropriate films, including an etch-stop nitride layer and a repetitive series of polysilicon and oxide device layers. The top oxide layer is thicker than the underlying device layers. When the same calibrated pattern-dependent etch process model is applied to this device-representative stack, the result includes punch-through of the etch-stop layer in the trench and nearby vias, despite reaching proper depth in vias at the center of the array (Fig. 10).

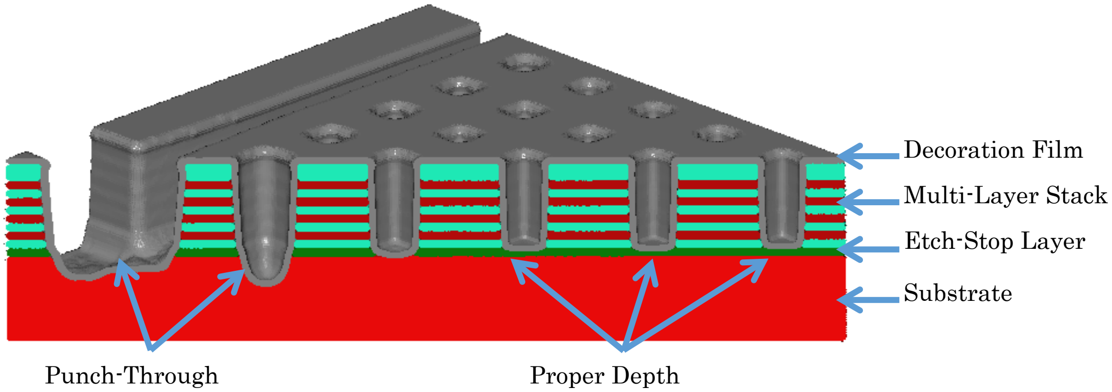

Figure 10. Angled cross-section of 3D virtual fabrication result when pattern-dependent etch is applied to appropriate device film-stack, illustrating punch-through of the etch-stop layer and depth variation of vias across the bounded array design.

Conclusion

Predictive modeling of pattern-dependent effects is critical for advanced technology development and design enablement. The results above illustrate a potential failure mechanism that must be addressed with process modification or design rules restricting active feature distance from boundary trenches. This capability is available in the 2014.000 version of Coventor™ SEMulator3D™ virtual fabrication platform.

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