Aerial imaging as a unique photomask defect printability classifier

Amir Sagiv and Shmoolik Mangan

An extensive numerical study reveals features that explain the advantages of aerial imaging in distinguishing printing and nonprinting defects.

As the typical feature size of state-of-the-art integrated circuits continues to shrink, optical lithography—the cornerstone of mass manufacturing of electronic devices—faces ever more demanding challenges. Specifically, today projection lithography is used for printing features that are several times smaller than the wavelength used for photoresist exposure. This realm, also known as the ‘low-k₁’ regime, is typically plagued by a highly nonlinear impact of photomask errors on the size and fidelity of the features ultimately printed on the wafer. The accepted consensus is that the primary contributor to critical dimension (CD) variations in the patterned wafer is defects on the photomask. This makes photomask defect detection a crucial stage in any advanced IC manufacturing process.

A basic concept essential to mask defects is their printability impact, i.e., their ultimate effect on the sizes and shapes of the features eventually patterned on the wafer. Still, the traditional strategy for mask inspection is to try and detect the maximum number of defects, irrespective of their printability content, and later classify them using a filtering algorithm. As maximal detection sensitivity is the primary goal here, this strategy typically employs high-resolution optics, namely, a higher numerical aperture (NA), although the most common systems do not necessarily employ an illumination source at the lithographic exposure (‘actinic’) wavelength. This approach, albeit sensitive to smaller defects (an effect which is desirable for process control) unavoidably results in extremely high nuisance rates, owing to process variations that have a vanishingly small printability impact. An alternative approach, which has gained much attention recently, is focused scrutiny of precisely those defects that indeed lead to printable errors on the wafer. This method involves emulating the lithography stepper’s optics in order to generate a replica of the aerial image, hence the name ‘aerial imaging’ inspection.

Since aerial imaging inspection uses the identical optical setup as used in steppers, one anticipates a tight correlation between the printability content and the detection signal.
under aerial imaging conditions. In contrast, high-resolution inspection is expected to exhibit a much poorer correlation. In this article we briefly describe a numerical investigation\(^1\) (based on an analytic argument\(^2\)) of the relation between defect signals and their printed CD effects for different inspection methods. The results confirm the behavior mentioned above. This has important implications for the performance of the two detection approaches when considered as printability ‘classifiers.’

We simulated attenuated phase-shifting (molybdenum silicide—MoSi—6%) lines-and-spaces masks with 65 and 45nm half-pitch values, and also 32nm through double patterning (these are values on the wafer). The masks were populated with a variety of defects, such as chrome over MoSi, pinholes, pindots, and partially under- and over-etched bumps and divots. Wide ranges of defect sizes (X and Y), positions, and phases (as well as transmission factors) were considered. Three different imaging schemes were studied: aerial imaging, where the masks were illuminated with a dipole illumination at the actinic wavelength (\(\lambda = 193\text{nm}\)); high resolution (collection NA 0.75) at the actinic wavelength; and high resolution (collection NA 0.85) at a higher wavelength (\(\lambda = 248\text{nm}\)). From the resulting simulated images, we extracted the defect signal (defined as the maximum difference from the image of a defect-free mask) and the CD variation at the position of the defect (with the appropriate resist development intensity threshold).

A striking difference between aerial and nonaerial imaging detection is shown in Figure 1, where we plot detection signal as a function of CD variation for all defect types combined. Aerial imaging shows a tightly correlated linear behavior where the proportionality is independent of any of the defect attributes (such as type, size, shape, location, phase, and transmission) and of mask pitch (for resist threshold chosen independent of pitch, as is the case for single-patterning 65 and 45nm masks here). In contrast, as expected on theoretical grounds,\(^2\) high-resolution-based detection exhibits a poor correlation between detection signal and the associated CD variation.

These properties of aerial and nonaerial imaging detection have profound implications for their performance in discriminating between printing and nonprinting defects. The universal, tightly correlated linear signal-printability relation, which is the hallmark of aerial imaging inspection, implies that it allows, in principle, simultaneous detection of all defects that print ‘above spec’, without being subject to high nuisance rate, simply by setting the detection threshold to the appropriate level (see Figure 2). This also implies that aerial imaging inspection has excellent scalability properties that allow easy migration to more advanced technology nodes, including double patterning, again by shifting the detection threshold. On the other hand, with high-resolution-based inspection, one may be forced to seriously sacrifice the detection sensitivity in order to maintain an acceptable nuisance rate. Furthermore, the universal linear relation characterizing aerial imaging implies that the results are independent of the underlying defect distribution, whereas high-resolution inspection is highly susceptible to changes in the properties of this distribution. Aerial imaging is thus shown\(^1\) to be an optimal printability classifier.

**Author Information**

**Amir Sagiv and Shmoolik Mangan**  
Process Diagnostics and Control  
Applied Materials  
Rehovot, Israel  

Amir Sagiv joined Applied Materials in 2006, and works in R&D and technology projects in the Process Diagnostics and Control unit. He holds a PhD in theoretical astrophysics from the Weizmann Institute of Science.

Continued on next page
Shmoolik Mangan joined Applied Materials in 1995, working in R&D and technology projects in the Process Diagnostics and Control unit. He is a physicist with a PhD in molecular biology from the Weizmann Institute of Science.

References