Proofing of photolithographic phase shift masks

A NEW OPTICAL PROOF SYSTEM EQUIPPED WITH AN EXCIMER LASER TESTS PHASE SHIFT MASKS UNDER THE CORRECT ILLUMINATION CONDITIONS

The semiconductor chips currently being produced for computers, cell phones, music players and other electronic devices often have circuit features as small as 65 nm. Now, a new excimer laser based system enables the measurement of all types of phase sensitive masks under their actual use conditions. Better still, the new system is already 45 and 32 nm capable.

UTE BUTTGEREIT
RALPH DELMDAHL

The current 65 nm feature size is already well below the traditional diffraction limit for the exposure wavelength of 193 nm that is used in the photolithographic fabrication process. Producing such small features requires the use of a number of very clever techniques to get around the resolution limitations posed by the wave nature of light. One of the most important of these techniques is the use of phase shift masks (PSMs).

The continuing trend to extract ever smaller feature sizes from 193 nm technology places ever tighter tolerances on the semiconductor fabrication process itself and makes the assessment of PSMs absolutely critical. In the past, the available tools for the task were not able to provide an accurate assessment of the PSM characteristics including proper consideration of diffractive and 3D mask effects, even though these very same effects play an ever more important role. Now, a new excimer laser based system enables the measurement of all types of PSMs under illumination conditions comparable to those during the semiconductor fabrication process.

Phase shift masks

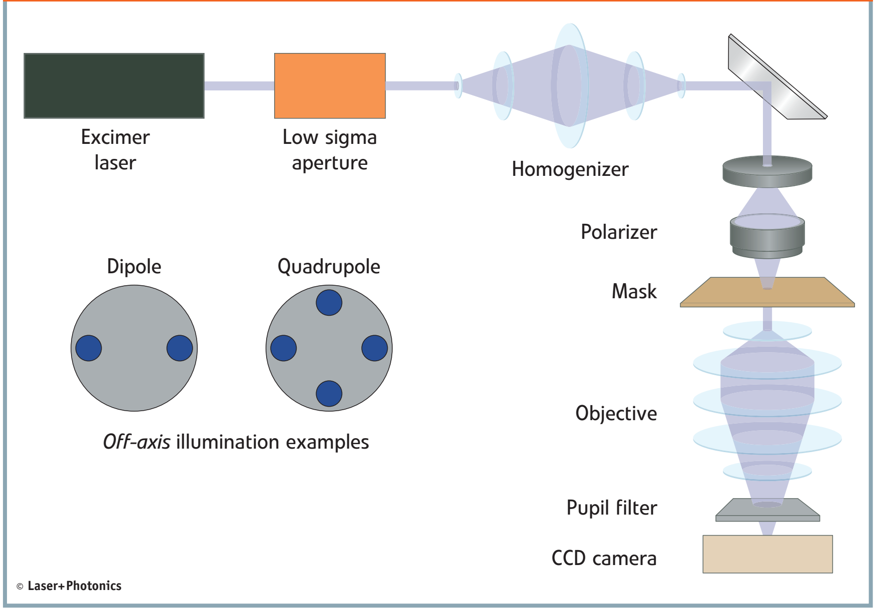
An integrated circuit (IC) consists of numerous electronic components constructed on a single, monolithic semiconductor wafer. The detailed structure of these devices is built up layer by layer in a process called photolithography. The first step in photolithography is to coat the semiconductor wafer with a light sensitive photoresist. A mask containing the desired circuit pattern is illuminated with UV laser light, and the mask pattern is projected with a factor four demagnification onto the wafer surface. The exposed resist is developed and the wafer is chemically etched to physically remove material from the exposed areas, thus producing the actual features on the wafer. This process is then repeated as many as 30 or 40 times to produce the entire circuit structure.

The first masks used for photolithography were binary. In a binary mask, the desired circuit pattern consists of a series of opaque and transmissive features. Binary masks are typically constructed using a fused silica substrate with a chrome coating. Unfortunately, uncontrolled diffraction and interference effects limit the smallest feature size that can be produced using binary masks. Reliably producing feature sizes of 65 nm and below requires the use of more sophisticated PSMs which creatively use phase and interference effects to far surpass the traditional diffraction limit.

The two main types of PSMs are ›embedded attenuated phase shift masks‹ (EAPSMs) and ›alternating aperture phase shift masks‹ (AAPSMs). In an EAPSM the features are not entirely opaque; this is achieved by using a coating material such as molybdenum silicide rather than chrome. The molybdenum silicide attenuates the light enough so that the intensity is not sufficient to expose the resist, but the layer still induces a phase shift of 180° relative to the clear fused silica areas. The resultant interference sharpens the edges of features that might otherwise appear fuzzy due to diffraction.

In an AAPSM a chrome coating is used and portions of the fused silica substrate are physically etched to a precise depth in order to yield precision phase shift structures. Once again, the etched areas introduce a phase shift of 180° relative to the unetched areas, and the resultant optical interference enables production of features on the wafer significantly smaller than the wavelength of the illumination.

Getting the light just right



1 Optical schematic of the Phame system

2 Installation of the Phame measurement system

PSM measurement

A full set of masks for an integrated circuit typically costs in the range of 1 million Euro, and, in some cases, can be significantly more expensive than that. In a complete set, the more costly PSMs are usually only employed for the most critical layers while the remaining masks are only binary. Any errors in the PSMs themselves will lead directly to defects in the circuitry produced from them. Because of their high cost of replacement and the critical nature of their performance, semiconductor manufacturers implement a cycle of mask metrology, inspection and repair. While the exact figures for how long masks are used, and how often they are inspected and repaired, is closely guarded by manufacturers, it seems fairly certain that masks are typically inspected at virtually every use.

There are several methods available for mask repair – laser repair, focused ion beam, nanomachining or mask repair ▶

▶ based on electron beam methods. The latter technique makes use of various gas reactions in order to add or subtract material from the mask. One system, developed by Carl Zeiss and named ›MeRiT‹, is the only technology available on the market actually capable of repairing the ever smaller defects on masks.

Until recently, there were only two tools available for PSM metrology; atomic force microscopes (AFMs) and interferometer based systems. The AFM can measure feature depth and size very accurately. The main drawback of this technique is that simply measuring physical feature sizes does not directly yield the optical performance of the mask. This would require a computer simulation that also takes into account so-called 3D mask effects – the phase and diffraction effects that will occur under actual illumination conditions, and incorporating information on the numerical aperture and polarization characteristics of the input light. The inability to properly quantify every single input parameter for the simulation means that its accuracy is limited.

A more direct approach is to use an interferometer to measure the actual optical performance of the PSM. Unfortunately, the conventional interferometry tools currently in use can only measure features of a certain size and shape, and these features must typically be at least an order of magnitude larger than the most critical features encountered on a PSM. This means that large ›reference features‹ must be included on the mask specifically for measurement purposes. Furthermore, the interaction of light with these reference features does not represent the phase behavior of actual production features, especially when the dimensions of those production features are close to the illumination wavelength.

3 Coherents ›IndyStar‹ excimer laser, the model adopted by Carl Zeiss SMS for the new PSM proof system

A new approach for ›in-die‹ measurements

While the AFM and interferometry tools both have their use, neither method can accurately predict mask performance under realistic conditions by directly measuring ›in-die‹ features. Zeiss has met the need for accurate PSM performance characterization with a new type of metrology tool named ›Phame‹. The optical path in the Phame system is comparable to the illumination system of an actual photolithography scanner. The use of a 193 nm excimer laser, combined with a low sigma aperture, beam homogenizer and polarizer, provides coherent, on-axis illumination of the mask. Furthermore, testing with off-axis illumination of the mask (dipole or quadrupole) is also supported.

After transiting the mask under test, the light is collected by an objective which has the same numerical aperture (on the collection side) as the optics used in an immersion stepper system having a numerical aperture of 1.6 (on the focusing side). However, the objective in the Phame system magnifies the mask, rather than demagnifying it, as is done in an actual stepper. Furthermore, the Phame system objective has a small field-of-view (about 10 µm x 10 µm), whereas a true scanner objective images the entire mask at once. This reduced field of view and magnification factor makes the Phame objective significantly less complex, less costly and physically smaller than an actual scanner lens.

After the objective, the light passes through a pupil filter and is captured by a CCD, which is positioned in the same plane a wafer would be in an actual scanner. The magnification of the mask image produced by the objective enables the CCD to achieve the necessary spatial resolution for defect detection. The CCD itself utilizes a specialized construction to allow it to directly detect 193 nm light, and to withstand long term exposure to this wavelength. In particular, the CCD does not use the standard silicon oxide gate construction found in ordinary CCDs, as this material is opaque below 200 nm. Additionally, the gate geometry itself has been modified to suit the needs of this application, and the camera is actively cooled to minimize noise and optical damage.

A proprietary method, combining hardware and software algorithms, is used to measure the electrical field in the image plane and convert the information into accurate phase information about the mask. Specifically, the system can deliver a phase image, or a numerical value of phase for the entire mask or a region of interest. A profile of the mask can also be produced.

The primary benefit of the Phame sys-

CONTACTS

Carl Zeiss SMS GmbH
07740 Jena, Germany
Tel. +49 (0)3641 642563
Fax +49 (0)3641 642938
www.smt.zeiss.com/sms

Coherent GmbH
37079 Göttingen, Germany
Tel. +49 (0)551 69380
Fax +49 (0)551 68691
www.coherent.de

tem is that it accurately measures the phase characteristics of actual, in-die features, rather than having to rely on much larger reference features. Specifically, the system can detect errors with a spatial resolution of 120 nm. Furthermore, the system duplicates actual scanner illumination conditions (including on- and off-axis illumination) closely enough to reliably reproduce imaging dependent, 3D mask and polarization effects. Finally, the 1.6 numerical aperture of the system makes it capable of measuring masks for both the 45 and 32 nm nodes. Together, this makes the Phame system useful for mask metrology after fabrication, and for assessing masks before and after repair processes.

Putting things in the right light

The excimer lasers used in photolithography steppers cost over 1 million Euro and are physically cumbersome. The Phame system is built around a smaller excimer laser, the Coherent ›IndyStar‹. The IndyStar provides the necessary optical output characteristics to duplicate the scanner, but at a fraction of the cost. The primary considerations in selecting a laser source for the Phame system were high repetition rate output, good output stability and excellent uptime/reliability characteristics.

The Coherent IndyStar is a 193 nm ArF excimer laser that delivers 8 W of average power at a repetition rate of 1 kHz. This repetition rate is necessary to achieve the desired system throughput, as each exposure requires several pulses. The IndyStar, which is primarily used in industrial processing tasks such as marking and micromachining, utilizes Coherent's ›Almeta‹ tube technology – all organic materials are eliminated from the laser tube and the electrode capacitors are located inside the tube to reduce the number of feedthroughs. This increases both static and dynamic gas lifetimes because it lowers leakage and reduces the numbers of o-rings (which can outgas). This results directly in reduced cost of ownership. Lifetime is further extended through the use of corona pre-ionization, which avoids the sparking that occurs at the pins used in ceramic pre-ionization.

Summary: Improved quality and process control

In conclusion, PSMs are a critical enabling technology for photolithography at the 65 nm node and beyond. The Phame system allows ›in-die‹ characterization and metrology of these masks using scanner-relevant parameters and providing for improved process control, mask design optimization and optimal wafer printing.

AUTHORS

UTE BUTTGEREIT is Product Manager for the Phame PSM proof system at Carl Zeiss SMS in Jena.

Dr. RALPH DELMDAHL is Product Marketing Manager for excimer lasers at Coherent in Göttingen.

■ **www.laser-photonics.eu**
You can find this article online by entering the document number ***eLP110005***