Photolithography for Thin Film MCMs

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The most advanced MCM has coarse features compared to semiconductors, therefore it is easy to underestimate the importance of the mask aligning equipment and the difficulties of thin film MCM photolithography.

It is as difficult to reproduce the features of MCMs as it is to reproduce the finer lines of semiconductors. Difficulties in photolithography are much more dependent on the line width to film thickness ratio than on actual linewidth.

Purchasing operating mask aligning equipment entails many engineering decisions. It has often been suggested that the used equipment market is the best source of mask aligners for MCMs because of the availability at low cost of obsolete machines discarded by the semiconductor industry. It is commonly believed that this obsolete equipment is adequate to reproduce 10 micron lines. This is a fallacy! The trend in semiconductors is to fabricate smaller and smaller geometries with individual circuits covering a small surface area[1]. By contrast, MCMs are very large area devices with a minimum linewidth limited by electrical performance characteristics.

Projection vs. Proximity

Defect control in MCM photolithography is dependent on frequent warpage of the substrates. This warpage is due either to internal film stresses bending the substrate or to lack of initial flatness of the substrates. Difficulties with warpage of substrates are seldom encountered in the semiconductor industry simply because the films are much thinner and in lesser number, and because silicon wafers have an outstanding high surface quality.

Combining the steep topography of a large number of thick layers and the initial wafer warpage leads many to think that optical projection aligners can solve the problem.

It is therefore useful to review the basic physics principles controlling resolution and depth of field of each alignment method.

Projection Alignment

The theoretical resolution of an *optical projection aligner* is given by[2]:

$$w = \frac{\kappa\lambda}{\mathrm{NA}}$$

where w is the minimum feature size, κ is an empirically determined process dependent constant between 0.5 and 1,0, λ is the wavelength of the exposure light and NA is the numerical aperture of the aligner's optics. Note that the numerical aperture is equal to 1/2f where f is the f-number of the projecting objective.

The theoretical depth of focus is derived from geometrical considerations, keeping in consideration the Rayleigh's criterion, and is given by:

$$\delta = \frac{\lambda}{2(\mathrm{NA})^2}$$

where λ is the depth of focus. The Rayleigh criterion states that an optical path difference of $+/- \lambda/4$ in the image plane does not seriously impair the image quality.

Shadow Printing

The resolution limit of shadow printing is due to diffraction effects. A common way of evaluating the resolution of this type of printing is to assume the reproduction of a grating with equal width lines and spaces. It follows that the basic equation to obtain the minimum printable linewidth is:

$$b_{min} = 3/2\sqrt{\lambda(s+d/2)}$$

where b is the grating linewidth, s is the gap between the mask and the photoresist and d is the photoresist thickness.

In the case of hard contact printing, the depth of focus is basically controlled by the resist thickness and by the possible lack of contact due to warpage and ripples between the mask and the substrate surfaces. For perfect contact: $s = 0$, we have a minimum reproducible linewidth of:

$$b_{min} = 3/2\sqrt{\lambda d/2)}$$

since the photoresist is the only spacer between the substrate and the mask.

In the case of MCMs, the photoresist can have significant thickness. This thickness adds to the lack of flatness of the substrate for the depth of focus requirements. The depth of focus equation for shadow printing applies here. Should the thickness of the photoresist be small compared to the printing gap, the depth of focus simplifies to:

$$b_{min} = 3/2\sqrt{\lambda s}$$

This equation applies to the newer SUSS large gap exposure equipment which features the large gap alignment system, an accessory to the Dual Video Microscope.

In the case of projection pattern printing, the depth of field is controlled by the numerical aperture of the aligner. For example, using an exposure wavelength of 451 nm (Hg g-line) and a numerical aperture of approximately 0.50, which is the practical economic limit for 1:1 projection printing, the depth of field is less than 3 microns. The practical resolution of the system will be in the order of 1 micron. The resolution is perfectly acceptable for the intended purpose of these mask aligners, but largely exceeds the needs in MCM applications. A higher numerical aperture would allow the depth of field to be increased. However, this is not economically practical.

Now, consider shadow printing with 50 microns total gap, and assume that the photoresist thickness is much thinner than the separation, and a g-line exposure system as before, then the linewidth resolution is approximately 7.5 microns. Since the resolution needed for the highest density MCMs is only 10 microns, the maximum separation can be just under 100 microns in the worse case.

Shadow printing is therefore better suited to MCMs since it can accommodate imperfect substrates and thick resists.

Proximity Aligners

In addition to superior depth of field, proximity printing offers mechanical and optical component simplicity. It follows that there is a strong economical advantage to proximity alignment. The difference in cost may be as high as 4 to 1.

For MCM use, proximity alignment is also preferable to contact printing because of the defects invariably induced when a mask contacts the MCM. Because of the excellent resolution, however, it is a good usable technique, only for small and extremely flat wafers. Small particles often cause defects because of high pressure points on the photoresist which cracks the resist. The resulting minute defects are difficult to detect without a thorough inspection. Positive photoresist is particularly sensitive because of its inherent brittleness in the thicker layers necessary in MCM work.

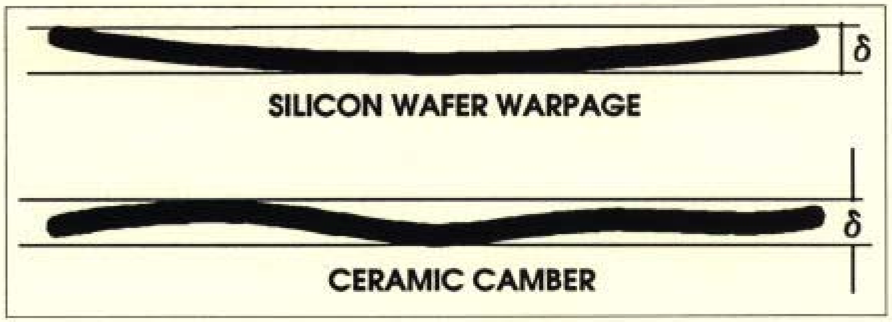

Figure (1): Flatness deviation is commonly observed in HDI substrates: a - silicon wafer stress warpage; b - ceramic substrate camber.

Silicon wafers often suffer from stress bow and ceramics substrates from waviness as shown in Figure (1). The lack of flatness will create points of contact against the mask during the alignment procedure. With the large surface area of MCMs, only a few defects per layer result in zero yields.

Chuck Control

Proximity aligners must accurately and repeatably control the separation between the wafer surface and the mask. Most aligner types will place the wafer on the chuck and hold it with a vacuum. The vacuum strength and its repeatability will influence the flatness of thinner wafers. For example, silicon wafers can be drawn flat on the chuck by atmospheric pressure if the vacuum holes are in the proper place and the vacuum flow is adequate; an excessive vacuum may distort thin wafers.

Separation Control

The purpose of the separation between the mask and the substrate is to prevent possible damage which would occur should the substrate inadvertently come in contact with the wafer. To set the separation between the mask and the wafer, a reference point must be established. Most aligners sense the relative position of the mask and wafer by raising the substrate until it touches the surface of the mask. A sensor detects the pressure applied when the mask and the wafer are in contact or near contact, then the wafer is lowered by a predetermined amount. Although the operators may be unaware of it, the substrate and the mask make contact briefly, thereby creating immediate and permanent damage.

The gap setting mechanism is one of the most critical parts in the operation of the mask aligner. Some aligners such as the SUSS machines are designed to eliminate potential damage by using clever gap setting schemes which minimize the wafer to mask contact area. Small precision balls of known thickness can be interposed between the mask and the substrate during the gap setting cycle.

The reference height is established by contact, but the miniature balls limit the potential damage to three small predetermined unused areas on the periphery of the wafer. Since the thickness of the ball is known, the gap can be accurately set from the reference point. This mask-wafer gap setting scheme guarantees that the wafer will not contact the mask during the gap setting operation, providing the wafer's flatness tolerance is kept within the gap setting dimensions. A view of this scheme is shown in figure (2).

Aligners with poorly designed gap control can ruin parts, even before the gap is established, with of course disastrous consequences on yields.

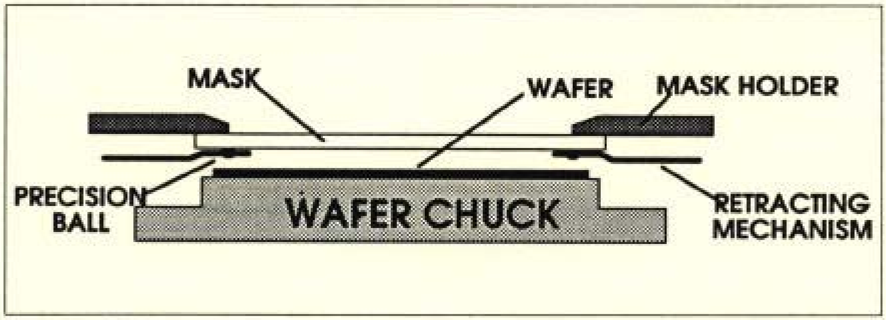

Figure (2): Height sensing scheme used in setting the proximity gap of some mask aligners. This clever scheme eliminates possible direct contact between the mask and the wafer in normal operation. The balls retract afterwards.

The size of the gap must be set in such a way as to avoid any possibility of the wafer dragging on the mask during the alignment phase. Dragging would have a terrible effect, possibly both on the mask and the wafer. The gap size setting may be inferred from substrate camber measurements or must be determined experimentally. In this case, the operator may have to readjust the gap immediately, should drag between the mask and the substrate be sensed. Hence, the importance of using flat substrates. The linewidth dimensions of even the densest MCM allows unusually large gap settings. Gap settings of 50 microns and up are reasonable since they stay well within the resolution limits and allow for a reasonable tolerance in lack of flatness from the substrates. Silicon, properly processed, will have an overall warp staying well below 50 microns across a 150 mm diameter. Ceramics, although not appreciably warping, can be problematic as fired and must be lapped.

Polishing of the ceramic after lapping is optional. Flatness is more important for the photolithography than absolute smoothness because of the relative size of the MCM features and the levelling properties of most polymers. Silicon wafers are always lapped and polished to very high standards[3].

Dual Focus Light Sources

From the earlier theoretical considerations, it is advantageous to reduce the exposure wavelength since it allows the gap to be increased at equal resolution or conversely to use smaller gaps to increase the resolution. The latter consideration is the basis for new excimer laser based aligners[4]. These are used in semiconductor work where the increased resolution is critical. Note that in the case of projection printing, although reducing the wavelength allows also to reproduce finer lines, it simultaneously reduces the depth of focus. Reducing wavelength makes these machines even less practical for MCM work. It also poses other strategic problems, such as availability of photoresists, greatly increased exposure times, increased cost of the optics and the light source[5], etc.

Most readily available positive and negative acting photoresists are designed for exposure to mercury arc lamp g-line[6]. It is not cost effective to deviate from these commonly available resists for MCM fabrication since the needs are adequately covered. It is however very important to have proper exposure control and to have the mercury arc lamp light source under close loop control for repeatability. Older aligners available on the used equipment market often lack tight control of the lamp intensity. Close loop control has been available for many years[7], albeit as an optional feature that was not always considered necessary.

Alignment Optics

The depth of focus and resolution equations apply to the alignment microscope optics as well as the imaging system. Since proper alignment requires higher resolution than the linewidth reproduced, the depth of focus available at the focusing microscope is low. This leads the mask aligner operator to constantly shift manually the focal point of the microscope from the mask level to the substrate level.

The problem has been solved electronically in the newer aligners[8]. This is done by storing the image of the substrate registration marks and using the live image of the mask during the mask aligning process.

Conclusion

Many high density thin film MCM development laboratories have been equipped with projection aligners in the belief that because the image is projected, few defects will occur[9]. This, of course, ignores the linewidth and depth of focus trade-offs and assumes that better capabilities for semiconductors is automatically better for MCMs. Contact printing is also impractical because of the damage to the brittle resist and the mask wear caused by high contact pressure points from particles or the circuit topography.

Having eliminated projection and contact printing, the choice of proximity mask aligner is clear for technical as well as cost considerations. Among the proximity aligners available today, the choice of machines that meet the specific MCM requirements imposed on the gap setting mechanism is limited. Because most aligners have their design roots in the semiconductor market and the market pressures in the semiconductor market demand higher and higher resolutions, no new aligner design work has been done to address the high density MCMs requirements except at Karl Suss.

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