Rudolph's JetStep Lithography System Maximizes Throughput while Addressing the Specific Challenges of Advanced Packaging Applications

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ABSTRACT

Rudolph's JetStep™ Lithography System combines an innovative optical design and numerous time-saving system features to maximize throughput and minimize cost of ownership while addressing the specific challenges of advanced packaging applications. Its large exposure field, twice the size of the nearest competitor, reduces the number of exposures required per wafer or panel and combines with other time-saving features to significantly increase the number of products processed per hour. At the same time, it has the resolution and depth of focus required to tightly control critical dimensions and sidewall characteristics in thick layers; and its long working distance avoids lens contamination when working with the thick, outgassing photoresists used in many advanced packaging applications. The system can handle round, square or rectangular substrates (Si wafers, reconstituted wafers, or panels) from 200mm, 300mm and 450mm wafers up to Gen 3.5 panels (720mm x 600mm). In addition, the JetStep System is designed to be tightly integrated with Rudolph's inspection and data analysis systems to provide unprecedented control and analysis of the complete photolithography process.

INTRODUCTION

Semiconductor manufacturers have always used photolithography to create the intricate patterns of layered materials that constitute an integrated circuit. A key component of any photolithography process is the exposure tool, which uses light to transfer a pattern from a photomask to a layer of photoresist. The exposure tool must be able to precisely replicate the mask pattern in the photoresist and align the pattern with previously fabricated structures in underlying layers. Several types of exposure tool exist: aligner, scanner, stepper, and step-and-scan.

Aligners (sometimes also known as proximity or contact printers) are used when the exposed layer contains only relatively large features, larger than 10µm. They transfer the pattern by shining collimated light through a full wafer mask held in close proximity to the wafer surface. Scanners use an optical system to project the image of the wafer mask onto the wafer surface. They can deliver higher resolution and longer working distances than proximity printers, but still require a full wafer mask. Step and repeat systems (steppers) expose only a portion of the wafer surface at one time, then step to an adjacent location and repeat the exposure. The mask covers only a fraction of the wafer surface and the stepper may reduce the size of the projected pattern (relative to the mask) by as much as 5X, both of which make the mask easier and less expensive to produce and maintain. Step-and-scan systems offer the highest resolution of currently available exposure systems and are used almost exclusively in front-end applications where features sizes may be as small as a few tens of nanometers. Like a stepper, a step-and-scan system exposes only a small portion of the wafer, but it does so by scanning a line of light over the exposure field. It then steps to the next location and repeats the scan. Compared to the full field exposure of a stepper, the step-and-scan strategy reduces the size, and therefore the cost, of the very expensive optical system needed to achieve the highest possible resolution.

Historically, shrinking feature sizes drove front-end manufacturing to move from aligners, to scanners, to steppers and, finally, to step-and-scan systems. Similarly, in the back-end, increases in the number, and resulting decreases in the size, of the I/O connections required from the integrated circuit through the package to the outside world, have driven growth in the use of steppers in advanced packaging applications. Although this trend seems likely to continue, package feature sizes are not likely to shrink beyond the resolving capability of steppers in the foreseeable future. And while step-and-scan manufacturers will continue to invest heavily in the development of new systems and technologies for front-end applications, a significant market has emerged for steppers designed to meet the specific needs of advanced packaging applications in the back-end.

Advanced packaging refers generally to the collection of technologies used to route signals from the integrated circuit (the chip or die) to the outside world. As noted, the size of these connections has shrunk as their number has grown. Packaging operations are extremely sensitive to cost, so the primary driver in system development is, and is likely to remain, cost of ownership. The JetStep System was designed specifically to increase throughput, and thereby reduce cost of ownership, while also addressing the unique challenges of advanced packaging applications.

Advanced packaging technologies use processes similar to front-end interconnect processes to fabricate connections through the layer by layer deposition of patterned conductors and insulators (Figure 1). However, advanced packaging lithography also confronts a set of challenges that are unique to the application. Feature sizes range from micrometers to hundreds of micrometers and often require photoresist or dielectric layers much thicker than those found in front-end photolithography. The lithography system must be able to supply enough energy to activate the photosensitive material (e.g. resist, polyimide, dielectric, etc.), while maintaining focus throughout the thickness to precisely control critical dimensions (CD) and sidewall profiles. Some types of photosensitive materials emit significant amounts of gas during exposure, which can contaminate optical elements located close to the wafer surface. A wide variety of substrates are used, including silicon wafers, thinned wafers, reconstituted wafers (in which separated die are embedded in a polymer compound), glass and more. The substrates may exhibit several millimeters of warp, and there may also be significant die-to-die and within-die topography resulting from embedding and bumping processes.

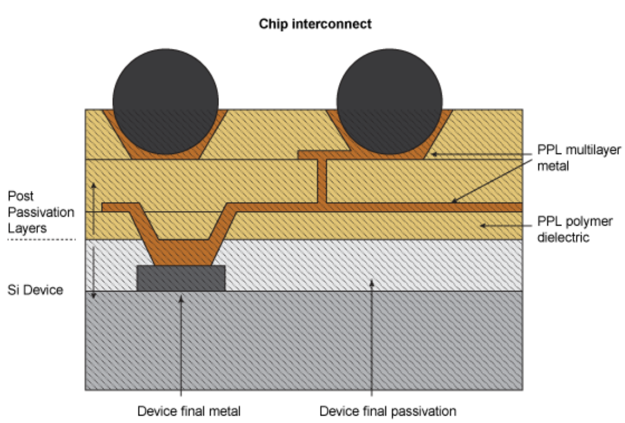

Figure 1. As the number of I/O lines per chip continues to grow rapidly, advanced packaging processes provide a means to route signals through the package to the outside world. Many advanced packaging processes are similar to front-end interconnect processes, which use patterned layers of conductive and insulating materials. Advanced packaging layers are applied on top of the passivation layer after chip fabrication is completed.

The remainder of this discussion will focus on the characteristics and capabilities required to optimize the performance and minimize the cost of aligners and steppers used in advanced packaging applications. Before proceeding, a note on terminology is in order. In casual discussion, steppers currently available in the commercial market are sometimes referred to by their reduction (demagnification) ratio, as a “1X” or “2X” stepper. Knowing that front-end steppers operate at 4X or 5X, it is tempting to arrange all steppers on a performance continuum using magnification as the figure of merit. While the system magnification does impact some aspects of performance, it is certainly not a primary criterion. Indeed, magnification alone is not a very good measure of optical performance. The system must be evaluated on its ability to perform against the requirements of the application. In the case of advanced packaging lithography the overriding performance goal must be maximizing profitability in the implementation and execution of advanced packaging processes. Design decisions for all aspects of the JetStep System, including the optical design, were made with this goal in mind. It may well be two times better than the “1X” competitor, but not because of the choice of magnification. Unfortunately, other forms of reference, such as catadioptric versus dioptric, are just a little too clumsy and the use of “X” terminology in casual discussion seems likely to persist.

OPTICAL DESIGN

Aligners

Aligner optical systems are relatively simple (Figure 2). A broad band light source is designed to provide uniform collimated illumination over the entire mask/wafer surface. There is a direct one-to-one correspondence between the mask and the pattern on the wafer. A microscope objective is used to align marks on the mask with marks in the underlying layers. The resolution of the system is determined primarily by the size of the gap between the wafer surface and the mask, the smaller the gap the better the resolution. At some point the gap becomes so small that yield loss and mask damage resulting from unintended contact between mask and wafer cannot be avoided. Generally, aligners can be used for feature sizes down to about 10µm.

Another issue for aligners is the requirement that the mask cover the entire wafer. As wafers (and other substrates) get larger the mask becomes difficult to manufacture and maintain, and prohibitively expensive. When an aligner can be used, its simple design and high throughput offer significant cost advantages compared to a stepper. As advanced packaging processes continue to evolve toward more complex connections with smaller features, the need for steppers is likely to increase.

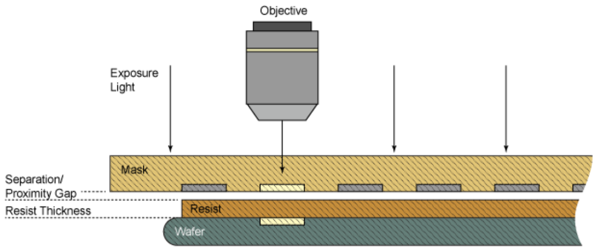

Figure 2. Aligners are relatively simple optical systems that use collimated light to transfer the pattern from a mask held in close proximity to the wafer surface.

1X Catadioptric Stepper

One commercially available stepper widely used in advanced packaging application implements a 1X catadioptric (containing both reflective and refractive elements) optical design known as the Wynne-Dyson form (Figure 3). The basic Dyson form, of which Wynne-Dyson is a variation, has no working distance (clearance between the final optical surface and the image plane) for the object (reticle) and image planes. It shares a common object and image space. Since the light projected reflects back upon itself, less than half the total field of view can be used. One side projects light through the reticle and the other side images on the wafer.

The Wynne-Dyson form adds an optically refractive doublet, combining at least two different materials, to provide some working distance (~2mm) and to provide additional axial chromatic aberration correction. Often a third material may be used between the doublet to couple the light and prevent total internal reflections between the doublet materials. To obtain the best performance and to help reduce heating from gradient index absorption, the doublet materials may be i-line grade, which has higher transmission and lower absorption than standard grade materials.

The Wynne-Dyson form uses reflecting folding prisms of an additional material to separate the reticle plane from the image plane. These may also be coupled to the other materials. Reflections off of the folding surfaces of the prisms require six times tighter surface flatness control than the equivalent refractive surfaces to control image placement errors. The primary mirror requires four times the surface quality of refractive surfaces over a much larger diameter.

The primary advantage of the Wynne-Dyson form is its relative simplicity and small number of optical elements. Since it is symmetric, certain aberrations cancel (odd order Siedel aberrations: coma, distortion and lateral chromatic aberration). However the form does have field curvature, astigmatism and axial chromatic aberration that need to be corrected in the design. The form is telecentric on both the object and image side, which, along with the short working distance, makes it very difficult to break symmetry and vary the magnification to correct for large process scale variations. The simplicity of the Wynne-Dyson form is somewhat deceiving since it is very limited in degrees of freedom for correcting manufacturing variations, and performance is difficult to fine tune.

The ghi power density of this dual illumination stepper is 2200 mW/cm2 at the image plane covering an exposure field of 68mm x 26mm. The power at the reticle is slightly higher than at the image plane, with transmission losses occurring over the double pass through the refractive elements and the object and image prisms. Therefore, the effects of reticle heating for opaque reticles are much larger than a dioptric reduction system.

Pellicles used to protect the reticle and the bottom of the lens from contamination must be located in very close proximity because of the small working distance. Outgassing from the photoresist may require frequent replacement of the pellicle at the image plane to avoid photo deposition dependent degradation.

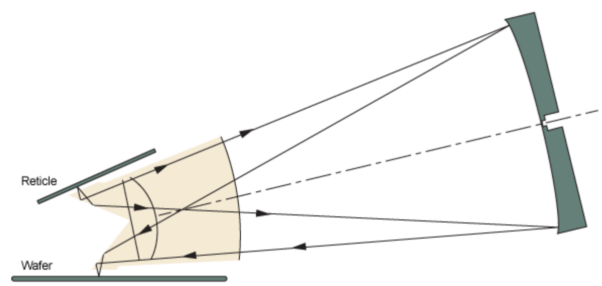

Figure 3. The 1X Catadioptric design mixes reflective and refractive optical elements to project the pattern from the reticle to the wafer with unity magnification. Although it is relatively simple, the design allows only a couple of millimeters of working distance between the optics and the wafer, and it is difficult to tune for optimal performance.

2X Single Telecentric Dioptric (JetStep System)

Rudolph's JetStep System uses a single telecentric 2X dioptric form with one 45° fold mirror (Figure 4). The design permits large working distances—250mm for object space and 18mm for the image space. The long image working distance greatly reduces the risk of contamination and the need for maintenance, especially for resists that outgas heavily. The dioptric lens has a separated object and image space on a single axis, making it easier to provide a larger exposure field than the Wynne-Dyson form that reflects back on itself.

Compared to the 1X catadioptric system discussed above, the JetStep's 52 x 66mm exposure field is twice as large. (The circular optical system can also expose a 59.4 x 59.4mm square field.) The objective has less total optical path and uses materials with higher transmission over the ghi-line spectrum. The power density at the image plane typically measures more than 1100 mW/cm2 over the 66mm x 52mm exposure field. Thus the dioptric system prints a field twice the size but with half the power of the Wynne-Dyson system, resulting in a roughly equivalent total exposure time. However, the larger exposure field reduces the number of exposures per wafer and the total time spent stepping between exposures, ultimately yielding a significantly higher overall throughput.

Although the 2X dioptric form is more complex than the Wynne-Dyson form, it provides more degrees of freedom for correction of optical aberrations. Optical surfaces in the all refractive portion have much more relaxed tolerances for profiling the needed correction when compared to adjusting the internal folds of the two prisms in the Wynne-Dyson form. It is also a smaller overall package that is easier to mount into a stepper exposure unit (camera).

Careful attention to the materials for the camera design ensures the stability needed for high dose applications in a production environment. Because of the 2X reduction, the energy density at the reticle is four times less than at the image, greatly reducing the degrading effects of heating for opaque reticles. Similarly, lower power density and, only a single pass though larger refractive elements made of low absorption materials, reduces heating from gradient index absorption.

The non-symmetric 2X dioptric form has separate object and image spaces and is telecentric only on the image side, making it easy to adjust magnification over a range in excess of 100 ppm by independently moving the reticle and image positions. Automatic magnification corrections compensate for layer-to-layer thermal expansion or contraction of the substrate or mask. The reticle chuck mounts the reticle vertically to minimize sag effects. The 45° turning mirror allows the optical axis for the main objective body to remain vertical. The alignment system includes both visible and infrared capabilities to accommodate top and bottom surface alignment marks.

The last element of the lens system is used to provide a protective surface. The long working distance makes this element easy to access, and reduces the rate of deposition and the frequency with which replacement is needed.

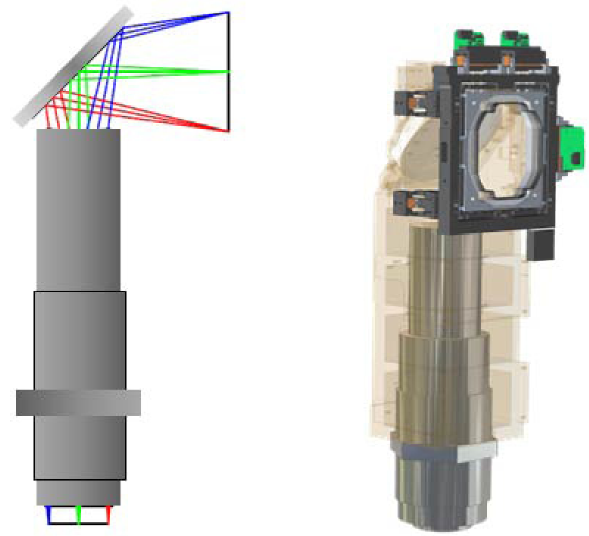

Figure 4. The JetStep System's 2X single telecentric dioptric form provides 18 mm of clearance between the optics and the wafer and permits automatic magnification adjustments by independently manipulating the positions of the mask and wafer.

TELECENTRIC LENSES

In a telecentric lens system magnification does not change with distance from the lens. For non-telecentric systems, magnification is different at different conjugates. The sense of perspective that we use to interpret out visual experience (objects appear smaller when observed at a greater distances) is due to the non-telecentric nature of the human eye. For instance, when you look through a tube of uniform diameter you expect the near end to appear larger, and to see the interior surface of the tube connecting the near end to the smaller distal end. In a telecentric system, you would see only the near end. The interior surface would be hidden and the distal opening would exactly fill the proximal opening. In machine vision and metrology applications telecentricity eliminates measurement errors associated with variations in the distance to the object. In a lithography system, telecentricity makes it difficult to adjust magnification to compensate for real changes in the substrate or reticle size.

JETSTEP BENEFITS

Throughput

As described above, illuminating a field twice the size with half the power density results in roughly equal total exposure time. However, it also reduces the number of exposures required to cover the wafer or substrate surface, and, thus, the non-exposure time spent moving between exposure fields, by half. Other aspects of the JetStep System design further reduce non-exposure time. A reticle wheel holds four (4) reticles and serves as a queuing station for the robotic 30-reticle library, allowing reticle swaps in as little as six (6) seconds.

Aperture blades permit variable masking of portions of the reticle, hiding or exposing special purpose structures such as alignment targets, and reducing the number of reticle changes required and also the total number of reticles required. The impact of these factors on overall throughput and cost will vary depending on the details of the exposure process. One recent third-party analysis quoted throughput for the catadioptric system at 70wph and the JetStep System at 90wph, nearly a 30% increase.

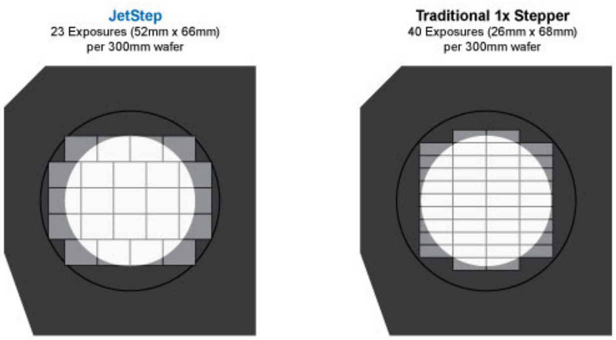

Figure 5. The JetStep System's large exposure field reduces the number of exposures required and, thus, the non-exposure time spent moving between exposures.

Thick Resists

Advanced packaging processes often use thick photoresist layers which can lead to high levels of outgassing during exposure. The JetStep System's numerical aperture provides the optimal combination of resolution and depth-of-focus required to control critical dimensions and sidewall profiles in thick layers (Figure 6). Its long working distance eliminates lens contamination by 1) increasing the distance outgassed contaminants must travel from the wafer to the lens, 2) accommodating a three stage purge design that circulates clean dry gas in separate paths across the bottom of the lens and up through the lens assembly and 3) allowing easy access to the final protective element of the lens for cleaning or exchange. The long working distance also provides room for a grazing-incidence autofocus capability that optimizes the Z position of the substrate before each exposure, compensating for die-to-die variations on reconstituted wafers and pitch and roll stage errors.

Figure 6. The JetStep System's optical system is specifically designed to provide the optimal combination of resolution and depth of focus required to expose the thick photoresist layers frequently used in advanced packaging processes.

Warped Wafers

Some advanced packaging processes, such as wafer level fan-out, can induce several millimeters of warp across the wafer surface. The wafers must be pulled flat before exposure. The JetStep System's wafer handling components, including the FOUP mapping sensor, robot end effector, prealigner, and vacuum chuck, have all been specifically designed to accommodate highly warped wafers. The autofocus system adjusts each exposure to accommodate any residual Z variation in the chucked wafer surface.

Substrate Handling

Advanced packaging substrates may be round or rectangular, arbitrarily sized, and composed of silicon, glass, polymer or other materials. The JetStep system stage is capable of handling 200mm, 300mm, 330mm and 450mm diameter wafers or rectangular substrates and is readily scalable to much larger sizes. The importance of scalable technology is rapidly increasing and advanced packaging facilities are transitioning to large panels to improve their cost of ownership and increase productivity. Traditional technologies have been limited to standard wafer sizes, however, companies adopting fan-out packaging on panels are no longer limited to operating within the constraints of a round wafer. The JetStep Panel Lithography System offers the same optical performance as the JetStep System, but with a larger exposure field that accommodates up to Gen 3.5 substrates (630mm x 720mm).

The JetStep System uses Rudolph's established XPort™ wafer handler. More than 1,000 XPort handlers are in the field today on various Rudolph inspection and metrology tools. Custom designed, application specific chucks are available for a variety of substrates. Programmable (0.5mm to 5.0mm) wafer edge protection capability is mounted in the wafer handler.

Process Control

The JetStep Total Lithography Solution tightly integrates the JetStep lithography system with Rudolph's inspection and metrology tools and process optimization software.

NSX® 320 defect inspection and metrology system monitors the major parameters that affect stepper yield: CD, overlay, and contamination/variation.

ProcessWORKS® run-to-run control software analyzes the results of each run and adjusts process parameters to improve the results of the next run. The die placement controller analyzes placement offsets for pick-and-place embedded die in fan-out wafer level processes, the overlay controller adjusts overlay offsets and the CD controller calculates exposure dose for the next lot.

ARTIST® fault detection and classification software tracks JetStep System calibration parameters, sensor data, error logs, machine logs, measurement data and model data to predict faults and classify parameter issues.

Discover Lithography™ yield management software analyzes process data to identify sources of yield loss and optimize system uptime. For example, a topographic map of the wafer surface based on autofocus data may be correlated with defects or parametric variations using spatial pattern recognition. Or the optimum time for light source maintenance may be predicted from an analysis of throughput and lamp intensity measurements.

RESULTS

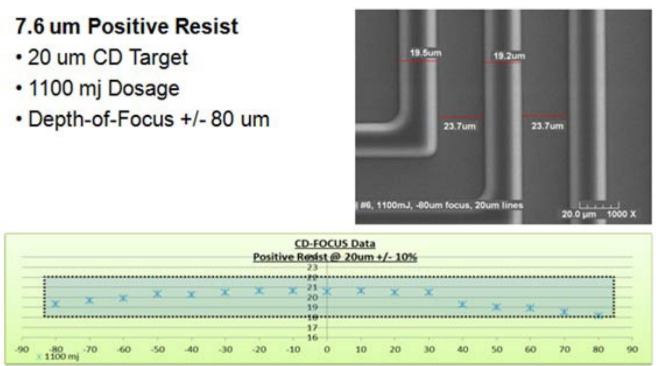

Figure 7. Positive resist lines with a 20µm target CD. Line widths remain within 10% of target as focus is varied over a +/- 80µm range

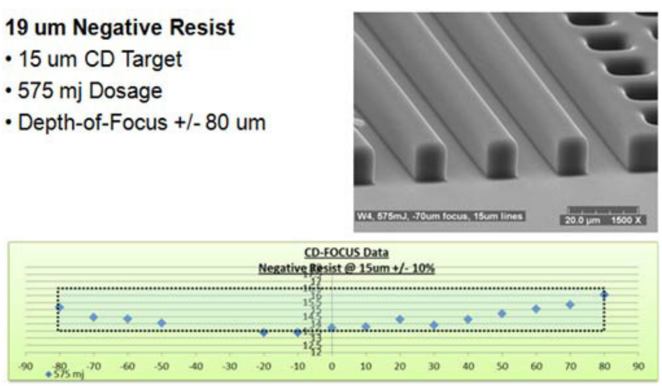

Figure 8. Negative resist lines with a 15µm target CD. Line widths remain within 10% of target value as focus is varied over a +/- 80µm range.

CoO ANALYSIS

3 Layer – Bumping – 4 New Products/Month – 350mj		
	Traditional 1x Stepper	JetStep
System Price	$4,100,000	$4,100,000
Lamp/Bulb Pricing	$5,953	$3,200
Pricing/each 6" mask	$1,400	$1,200
# Mask per Product (# Layers)	3	3
# of New Products/Month	4	4
Throughput (wph)	66	83
Depreciation in Months	60	60
Ops/Maintenance Cost/Month (est.)	$10,000	$9,000
Lamp Cost/Month	$4,345	$2,336
Depreciation/Month	$68,333	$68,333
Mask Costs/Month	$16,800	$14,400
Total Cost/Month	$99,479	$94,069
Layers Exposed/Month	43,362	54,531
Cost per Layer Exposed	**$2.29**	**$1.73**
	COO Advantage	**25%**

Figure 9. Cost of Ownership analysis demonstrates a 25% reduction with the JetStep System.

SUMMARY

The JetStep Lithography System's large exposure field improves throughput by reducing the number of exposures required per wafer. Its optimized resolution/depth of focus ensures tight control of CDs and sidewalls for thick photoresist layers. Its long working distance eliminates lens contamination from outgassing resists. 2X demagnification reduces the effects of reticle heating and the printability of small mask defects and contaminants. The reticle wheel and library reduce reticle exchange time. Programmable aperture blades reduce the number of reticle changes and the number of reticles required. Each of these contributes to reduced costs or increased throughput, and ultimately to reduced cost of ownership. The JetStep System is the only lithography system specifically designed to address the unique challenges of advanced packaging applications at the lowest available cost of ownership.