Stepper Training

Overview

A Wafer Stepper is a reduction projection exposure tool. An image formed in a chrome-on-glass photomask, called a Reticle, is reproduced on a wafer one “die” at a time by projecting the reticle image onto a wafer positioned below the reduction lens. The wafer, which is coated with a UV light-sensitive polymer film called Photoresist, is moved from one die position to the next by a motorized stage assembly. The reticle image size, up to 88mm x 88mm, is reduced 5 or 4 times by the projection lens making individual die exposures as large as 22mm x 22mm. The positioning of the wafer for exposure under the lens is computer controlled using a laser interferometer system for very high accuracy. Alignment for layer-to-layer overlay can be performed with similar precision. Placement, exposure, and focusing of each exposure is programmable with all operations performed automatically.

History

Steppers were created to address the problems limiting yield of working devices or “good die” in semiconductor wafer manufacturing. Before this Mask Aligners were exclusively used in photolithographic manufacturing processes. A mask aligner mounts a fixed photomask and has a movable wafer chuck that can bring the wafer and mask into tight contact. Alignment systems are used to view alignment marks on the wafer through the photomask. The photoresist coated wafer is then exposed in one action. However, contact mask aligners could not achieve adequate alignment across wafers as they had no ability to compensate for scaling and orthogonality changes caused by processing or introduced by mask making variations. They also suffered from low yield due to defects caused by physical contact between the mask and wafer, or by reduced resolution caused by proximity exposure methods. Additionally, operators performed most system functions by hand, causing even more variation and loss. In the early 1970’s Perkin Elmer developed the Micralign 1:1 scanning projection system to address some of these issues, and with great success compared to contact mask aligners, but across-wafer alignment and operator error rates were still problematic, and the entire wafer was still exposed as one fixed image.

The David W. Mann Company, precision machine tool makers, built early photo-repeaters which were used to print multiple copies of a single die across a photomask for use on a mask aligner. This reduced the final mask cost as only one high-precision copy of the die had to be made on a reticle, usually at a larger size, which would then be projection printed onto another photomask to form the final mask layout. The early tools were hand-operated and had limited precision compared to later versions. These evolved into programmable laser interferometer-controlled exposure systems for mask making, first by using a master reticle, and eventually using a programmable rotatable multiple blade system to print rectangles of varying size; this system was called a Pattern Generator. These rectangles were stitched together to make almost any shape on the mask, although no true curves were possible; these were approximated using many overlaid rotated edges.

In the mid-to-late 1970's in cooperation with IBM, the Mann Company, now owned by GCA, built and developed the first "Direct Step on Wafer" or DSW system consisting of the bottom stage motions of a pattern generator with a reduction lens incorporating a mount for a reticle, as well as Köhler illumination. The system used the same interferometer-controlled stage positioning system and automatic focusing for each exposure as the pattern generator and allowed precise alignment of the reticle to the lens and stage motions. Importantly, it also included an additional alignment system which allowed measurement of individual locations on the wafer for layer-to-layer registration. The automated form of this system could "map" the wafer die locations using the precision of the laser interferometer system and then apply an algorithm to the exposure map providing compensation for scaling and orthogonality, solving the alignment problems encountered with previous methods of optical lithography. These systems also operated in completely automated modes, eliminating operator error from most processes. Steppers quickly became the dominant method of lithography in semiconductor manufacturing and have remained so.

Current versions of these tools have the additional complexity of scanning the reticle across a slit at the top of the lens while simultaneously scanning the wafer die location in the opposite direction. They are known as Stepper-Scanners and currently perform the bulk of high-volume manufacturing. While this may seem to be a potential cause for errors, the results are superior in both resolution and alignment, with overlay specifications below ±6 nanometers at over 275 wafers per hour and a die size up to 25mm x 33mm. The highest resolution versions of these tools can achieve a half-pitch of 38nm by using water between the wafer and exposure lens, introducing many engineering challenges. Regardless, these tools are operating with high yields and over 97% uptime in constant usage around the world.

CNF Steppers

At CNF we have three wafer steppers, each from different manufacturing eras and utilizing different exposure wavelengths. The **GCA 6300 DSW 5X g-line Wafer Stepper** is a mid-1980's tool using 436nm (g-line) light from a 350W Mercury (Hg) arc lamp source. It has a 5X reduction lens but has no automated functions; all automated systems were removed long ago due to unreliable performance and difficulty obtaining repair parts. It is operated in manual mode. It can accommodate substrates ranging from 150mm wafers to small pieces, with maximum thicknesses up to 1.5mm. The **GCA AutoStep 200 DSW i-line Wafer Stepper** is an early-1990's era stepper using 365nm (i-line) light from a 1000W Hg arc lamp. It also has a 5X reduction lens but is nearly fully automated; the automated optical alignment system has been disabled but automated mapping functions are still available. It can also be operated in manual mode. It can accommodate substrates ranging from 200mm to small pieces, with maximum thicknesses of 1.5mm. Automatic wafer handling is available for 100mm silicon wafers only. The **ASML PAS 5500/300C DUV Wafer Stepper** is a late-1990's tool using light from a 10W Krypton-Fluoride (KrF) excimer laser source. It has a 4X reduction lens with variable Numerical Aperture (N.A.) and a programmable light source shaping system called AERIAL. The system is fully automated and, unlike the two GCA tools, can only be operated in fully automatic mode. Additionally, it has the 3D-Align system which allows very accurate back-side wafer alignment for 100mm and 150mm wafers. The system can accommodate wafers ranging from 200mm to 3" and is nominally configured for 100mm wafers. Other wafer sizes require several hours of changeover and calibration which must be scheduled well in advance of use.

	GCA 5X	**GCA AS200**	**ASML /300C**
Field Size	15 mm	15 mm	22 mm
Wavelength	436 nm	365 nm	248 nm
N.A.	0.30	0.45	0.63 - 0.40
Resolution $k_1 = 0.8$ $k_1 = 0.6$	 1.16 µm 0.87 µm	 0.65 µm 0.49 µm	 0.25 µm* 0.15 µm*
Depth of Focus	± 2.420 µm	± 0.870 µm	± 0.250 µm
Alignment	± 0.250 µm	± 0.120 µm	± 0.045 µm

*k1 values different for DUV photoresists

Choosing a Stepper

Deciding which stepper to use for your process requires evaluation of several factors. Most of the important attributes for each system can be found in the chart above.

You should first determine which capability is most important for success of your process, for example alignment accuracy or resolution. Continue through a process of elimination with each attribute until you can choose one tool with reasonable certainty. Keep in mind the types of substrates you can use on each tool as this is important but not contained in the chart. Also consider the Depth of Focus associated with each tool. DOF varies with feature size, so the stated values are measured when printing the minimum feature size but become larger as the feature size increases. Even so, DOF can be an important limiter in your process depending on your substrate flatness, resist thickness, etc. Photolithography Staff can assist you with these decisions.

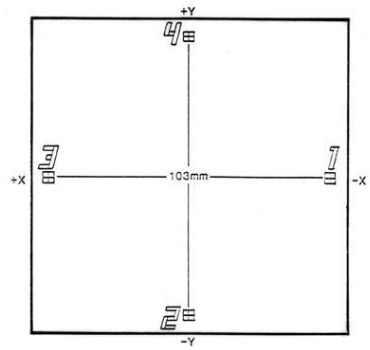
Another important choice is the photoresist you will use. You must select a photoresist which is designed to work with the particular exposure wavelength used by your selected tool. Mismatched resist can result in poor sidewall slope or poor performance. Note in particular that DUV photoresists cannot be used with i-line or g-line exposure tools, nor can i-line or g-line resist be used at 248nm. DUV resists also require higher bake temperatures and Post-exposure Baking which may affect your substrate.

Reticles

Each one of the steppers requires a different set of Fiducial Marks which are used to align the reticle to the stepper. The reticle is aligned to marks built into the Platen, which is the plate mounted at the top of the reduction lens. The platen is a precision device calibrated to allow correct demagnification and distortion as well as alignment with the stage motions. Masks made at CNF using the **Heidelberg DWL 2000** should contain the fiducial marks needed for the stepper you choose if you follow the instructions provided and select the correct Frame data. Note that the GCA steppers both use a 5” reticle while the ASML uses a 6” reticle; sizes cannot be interchanged. All stepper reticles sold by CNF are made of fused silica material.

GCA 5X Fidicual Marks

(not to scale)



Design of your pattern in CAD should always be done at wafer level, meaning you should design at the final size of the features on the device. Do not consider the lens reduction as this will be taken care of during the mask making process. This allows you to use your design on any tool, from contact aligner to direct write or on any stepper. It also prevents you from making all-too-common errors in design. You should only consider the field size and resolution limits of the exposure tool.

Layers in CAD are often assigned to the making of different reticles of the same device in a process. All layers in device CAD should share the same coordinate space in the same cell; do not make separate cells for different layers of the same device. When the CAD data is exported as a GDSII file any layer names will be lost, so be certain that you know which GDS layer numbers correspond to each reticle you want to make. Also make certain that you know the name of the top-level cell, the cell containing all the child cells used in your CAD. Keep cell names short and use only letters and numbers.

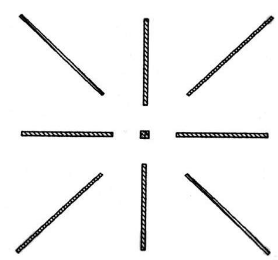
The Origin of the cell, point (0, 0), will become the center of your reticles. Be certain that the origin is the point that you want to be in the center of the reticles. You can move the origin in CAD before exporting to GDSII. Also be certain of the locations of any alignment marks with respect to the origin.

Alignment

Registration, or alignment, of layers on steppers may not seem intuitive. The operator does not align marks on the reticle to marks on the wafer; instead, the reticle is aligned to marks on the platen and the wafer is aligned to marks in the separate wafer alignment system. Calibrations are performed periodically to ensure that the final alignment is correct. There are specific marks used for reticle alignment and wafer alignment. Each one of the steppers uses a different set of alignment marks. Be certain to design your alignment strategy well in advance of making any reticles to avoid having to duplicate your efforts.

Both GCA steppers utilize the <u>GCA Key</u> for optical alignment. The GCA key is available in GDS format and can be downloaded from the stepper web pages in either the GCA_KEY.zip or AS200.zip file. Both GCA tools have two optical alignment microscopes placed <u>63.5mm</u> apart. Two GCA keys should ideally be placed on the wafer 63.5mm apart to allow viewing both marks at the same time; this makes manual optical alignment somewhat easier. This is not possible when using pieces, but alignment can still be performed. The operator must alternate between the two marks until alignment is achieved. In any alignment procedure it is recommended that rotation be determined first using both marks, and then X and Y alignment be adjusted using <u>only</u> the right-side mark. The systems <u>only</u> use the alignment information from the right-side key. The left-side microscope can only be calibrated for wafer rotation and <u>not</u> for X alignment.

GCA Key

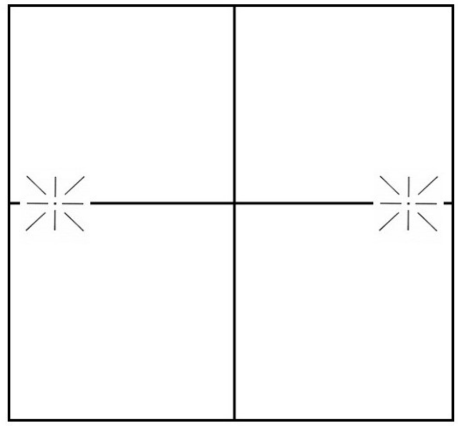


GCA Keys must be printed <u>first</u> to allow alignment of subsequent layers. They can be included in the first device layer if the first layer process will yield highly visible marks; the keys will be viewed in the optical alignment microscope so high contrast is desired. If the marks will be covered or damaged in processing, new marks should be made at that time. Therefore, it is best to design patterns that protect the marks when possible.

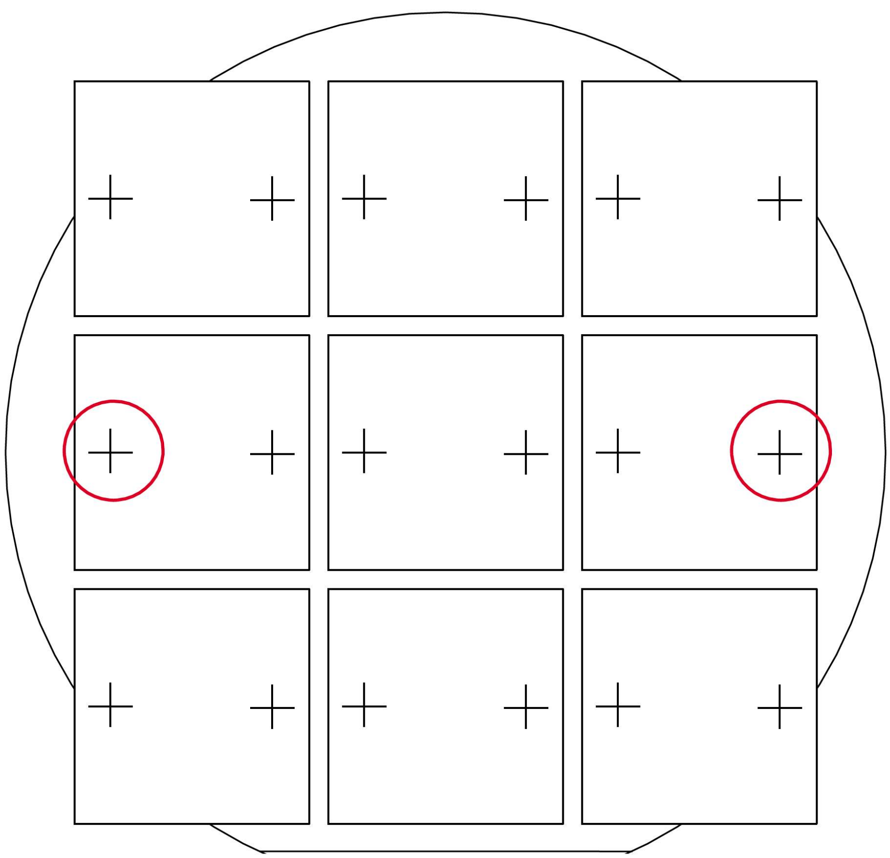
The recommended beginning methodology is to place two keys in each die, both on the X-axis, and both at equal but opposite distances from the center. This prevents some issues: there will be no confusion regarding mark locations due to inverted coordinate systems on the steppers, there will always be multiple marks available if the substrate should break, and an additional exposure level may be eliminated as there could be no Zero layer required; this would be true if the first layer process did yield acceptable mark visibility. Ideally, in combination with the wafer layout it should be possible to position two of the marks 63.5mm apart on the wafer. This is called <u>Standard Keys</u> in the software. Note that once the operator gains experience with the coordinate systems involved the marks can be placed anywhere in the die or around the wafer.

Viewing the wafer resting on the stage, a key on the ***left*** side of the die has a ***negative*** X <u>Key Offset</u> value, while a key on the ***right*** side of the die has a ***positive*** X key offset.

Recommended GCA Key Layout



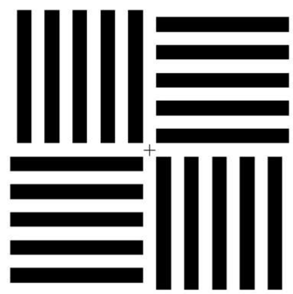
Δ -X should equal Δ +X
Y should equal Zero



3 X 3 array	n=3	s=22 mm
Standard Keys:	R2C1	R2C3
Key Offset:	X=9.75	Y=0

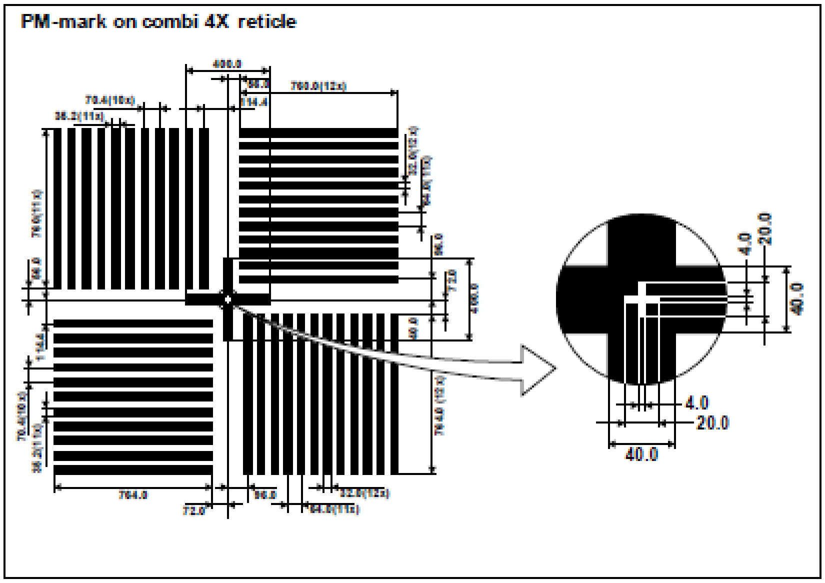
The **AS200** can additionally perform automated alignment utilizing the µDFAS system. This system uses a dark-field illumination strategy and is mounted off-axis at the bottom of the exposure lens. The DFAS marks are available in GDS format and can be downloaded from the AS200 web page in the AS200.zip file. The MASK_BLANK cell in the file can be disregarded as this data is provided in the Frame data at the mask writer. The DFAS_SOLID_POS mark is typically used with good success as long as the marks have sharp vertical edges. Dry etching to a depth of at least a few hundred nanometers is recommended. Deposited marks can also work, but the edge height and reflectivity are important to generating good signal levels.

DFAS Solid



Placement of DFAS marks is very flexible. Any location within or around the die is acceptable as long as there is an exclusion area of at least a few hundred microns around the mark. One recommended strategy is to place one of each of the four mark variations in every die, each at the same XY vectors but with varying signs; i.e. (+5.7,+5.7), (+5.7,-5.7), (-5.7,+5.7), (-5.7,-5.7). This allows easy switching between marks to find which version yields the best signal.

ASML PM Mark



PM-mark on combi 4X reticle

The alignment system used on the **ASML** stepper is somewhat different than that on the GCA tools. One interesting difference is that the user does not need to include wafer marks in their pattern design. The ASML can print the PM Marks at locations specified by the user. The advantages are both that the user has less to consider during design, and that the mark locations can be selected independently of any pattern or wafer layout parameters. The etched depth of the PM marks is important and should be as close to 120nm deep as possible (or odd multiples of 120) as the system uses a phase-contrast detection system. Note that some transparent layer marks may cause issues; consult the Photolith staff.

The alignment marks are typically printed in a Zero layer so that the etch depth can be well controlled. Marks should not be printed in a device layer unless the process for that layer is known to yield good marks. Marks can be placed individually or automatically distributed by the software. Scribe lane alignment marks are also available. Back-side PM marks can only be located at ±26.8mm and ±30.6mm and need to target a 160nm depth. All alignments are performed automatically without user intervention unless errors halt the process.

Operational Notes

Resolution

The resolution achievable in any photolithographic process depends upon multiple factors including resist thickness, substrate film stack, and feature geometries and placement. Typical aspect ratios of height (thickness) to width (Critical Dimension) in photoresist are limited to 3:1. Higher ratios can result in line collapse or unacceptable sidewall slope. Reflectivity of any film stack should be considered, particularly if there is surface roughness. There will be significant impact on the exposure dose, and if there are different film stacks in different locations on the wafer the local dose required can change dramatically. This may be mitigated by introducing Mask Bias, where the mask features are adjusted in size to compensate for these and other optical effects. Printed feature sizes are strongly affected by not only reflectivity but by proximity effects, where the placement of features on the mask relative to open spaces or unexposed areas can alter the final results in unforeseen ways. Often the only way to determine these effects is to experiment and measure various combinations of features and placement before making the final mask. Modelling the process using PROLITH by KLA-Tencor software, available on several CNF workstations, can be very useful in these situations. Focus and dose ranges can be varied in the simulation to determine process latitude under proposed process conditions, allowing the operator to find which choices offer the easiest path.

Focus Issues

Steppers focus on the wafer surface using a light beam directed across the die location at an angle of grazing incidence, typically around 6 degrees. The wavelengths of light used are varied and can include laser sources, but fine focusing usually incorporates broad-band light to minimize interactions with the film stack. Even so, there is some interaction and different films can result in different best focus values. Focus testing should always be performed when using the **AS200** or the **ASML**; the **5X** generally does not require these tests as the DOF is so large.

The GCA steppers have a limited focusing range and can only process substrates with thicknesses within ±100µm of nominal height. Both GCA steppers have multiple interchangeable wafer chucks to accommodate substrates of various sizes and thicknesses. You must select a chuck designed for use with thicknesses as close as possible to your substrate thickness. If you cannot find a chuck designed for thicknesses within 100µm of your substrate you will need to work with staff to find a solution. It is recommended that you verify that a useable chuck is available for your substrate before committing resources and effort. The ASML is not limited except in regard to maximum and minimum wafer thicknesses of 1.1mm and 250µm, respectively.

The **GCA 5X g-line** focus system has an additional limitation in that transparent substrates are problematic. The monochromatic focus beam can create a secondary reflection, confusing the system and causing focusing errors. There is a hardware switch on the panel below the operator keyboard marked "Transparent" and "Opaque" which should always be verified for position before operation. In transparent mode the secondary reflections are reduced, but the nominal system focus is changed from 0 to +77 in software, a 7.7µm shift. It is recommended that transparent mode only be used if there is a transparent layer more than 2µm thick, or if the substrate itself is transparent.

Photoresist

In selecting photoresist, the thickness needed for processing will be an important consideration as well as the exposure wavelength. It should also be noted that, because steppers use single wavelength light, standing waves will form within the material during exposure. This phenomenon can cause swings of 40% or more in absorbed energy due to constructive and destructive interference effects. The thicknesses at which these effects occur can be determined in advance, and a thickness that causes a controllable effect should be targeted; this is usually at the peak of a swing on the graph. Swing Curve graphs are provided in the manufacturer's data sheets, but typically are only useful for bare silicon substrates. More complex film stacks can be modeled to find applicable swing curves using PROLITH. Resist thickness should be monitored for all runs in order to achieve consistent results.

Characterization

Characterization is critical for repeatable success of photolithographic processing. Every combination of substrate, pattern, tool, and resist is unique, and any change to any one of these requires additional characterization. It is important to establish the resist process first before any testing is performed as any process change would also require recharacterization.

Steppers themselves only have two controllable parameters: focus and dose. Focus, once established for a particular film stack, should be stable as long as no significant layer thickness changes occur. However, dose will need to be tested for every reticle of every layer individually to achieve consistent results. Proximity effects are predictable through modelling, and PROLITH is very useful for this, but empirical testing is still required. It is recommended that at least two test wafers be prepared for any new process, one for Focus/Dose Matrix testing, and a second for fine Exposure Array tests. If the operator makes incorrect choices for range values more wafers will be required.

<u>IMPORTANT</u>: the substrates used for testing <u>MUST</u> be the same as the product substrates: the film stack and resist processing must reflect the actual device process to be valid. For a Focus/Dose Matrix test a resolution target reticle is typically used to make interpretation of focus results easier. For Exposure Array testing the actual reticle to be used for the layer being tested is required for valid results.

Below is an example Focus/Dose Matrix layout of 5 rows and 5 columns:

Dose

		Dose				
		0.8	**0.9**	**1.0**	**1.1**	**1.2**
	+10	A1	A2	A3	A4	A5
	+5	B1	B2	B3	B4	B5
Focus	**0**	C1	C2	C3	C4	C5
	-5	D1	D2	D3	D4	D5
	-10	E1	E2	E3	E4	E5

Example: for B2 the values are Focus = +5, Dose = 0.9

The numbers shown and the size of the matrix are not realistic, only an example of the procedure. In the diagram each row of exposures has a focus value (letter) assigned, and each column has a dose value (number) assigned. The result is a progressive matrix of values which should be evaluated for optimum results. The ranges should ideally be large enough that focus can be seen to deteriorate at both the top and bottom of the columns, and both over- and under-exposure can be seen across rows. This requires both a large enough matrix design and large enough values selected by the operator to achieve. The result should be that the centers of both value ranges are clearly seen, although the dose steps will likely be too large to determine the final values and would be invalid anyway if a resolution target reticle were used.

A second test of exposure dose <u>only</u> using small steps in dose and fixed at the selected focus should determine the final dose values.

Below is an example of an Exposure Array:

Dose

0.85	0.86	0.87	0.88	0.89
0.94	0.93	0.92	0.91	0.90
0.95	0.96	0.97	0.98	0.99
1.04	1.03	1.02	1.01	1.00
1.05	1.06	1.07	1.08	1.09

Again, the test size and numbers shown are not realistic but only an example of the procedure. The goal of this test is to find <u>multiple</u> exposures which meet the operator's process criteria, and to then use the center value in processing. If only one or two values meet the criteria the test should be run again using smaller steps in value. Note that in this test the values increment linearly across the row, and then continue in the opposite direction in the next row. This is called Boustrophedonic motion and is how all steppers move their stages for efficiency. In the Focus/Dose test they still move in this way but form the matrix as determined by software. In a <u>Focus Array</u> test the layout is the same as in the exposure array, but each exposure has a different focus value while all die have the same dose value. Note that the arrays shown follow the GCA protocol, while the ASML software works somewhat differently. Check the manual for the tool you use to determine the final exposed array layout.

<u>Final Words</u>

Successful stepper processing requires practice. It is recommended that operators begin use with assistance from an experienced CNF User or group member. Tool operation is usually not much of a problem, even for beginners, but evaluating results and making corrections to the process can be. Consistent resist processing must be done to control any photolithographic results. Proper use of metrology is very important and includes the use of optical microscopes, while for DUV processing the use of SEM inspection is required. These skills will be important, and operators should devote effort to improving them. It must be stressed that proper characterization is critical to repeatable success. Shortcuts will not lead to long-term success, and in many cases will cause wasted time and effort. Staff is always available for consultation regarding these issues and can often save operators time and effort.