Wafer Placement Repeatibility and Robot Speed Improvements for Bonded Wafer Pairs Used in 3D Integration

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Abstract— **Robotic wafer handling of bonded wafer pairs (BWP) brings new challenges in placement repeatability and robot speed. Current standard SEMI M1.15 [1] does not contemplate wafer pairs >775 microns thick. Varying wafer thickness of 800-microns (top wafer thinned to 25-microns bonded to a 775 micron carrier wafer) to 1550 microns thick (two full thickness 775 micron wafers bonded together) creates additional mass and thus additional momentum during wafer movement. Without a corresponding increase in holding force, wafer sliding on the end effector is likely. One solution is to reduce robot velocity, but this can lead to tool throughput reductions. In this paper we explore wafer handling issues for BWP and the application of a new end effector technology, called Gravity Edge Hold (GEH). Wafer sliding issues will be described in terms of substrate momentum, lateral holding force, and robot acceleration. It will further describe the wafer placement repeatability issues encountered and the corresponding decrease in robot speeds implemented to counteract this problem. Laboratory experiments were conducted to compare the performance of traditional end effectors used in current 300mm tools to that of the GEH end effector. An evaluation based on lateral holding force is included.**

Keywords: 3D, 3D interconnect, robot end effector

I. Introduction

SEMI® M1.15 defines many wafer parameters for 300mm crystalline silicon used in semiconductor manufacturing. Bonded wafer pairs (BWP) will not comply with many of these SEMI®-specified wafer parameters (e.g. thickness, diameter, edge bevel, notch and bow), and will compromise wafer handling requirements that expect wafers comply with single silicon wafer specifications. An additional consideration is that the mass of bonded wafer pairs will represent new challenges for traditional robot end effectors used to move silicon substrates within process tools (TABLE I). Accurate placement of wafers within tool process modules and safely returning them to wafer carriers on tool load ports is absolutely essential from a process stability and safe wafer handling perspective.

TABLE I. SEMI® M1.15 Comparison for Bonded Wafer Pairs

Parameter	Single Wafer	Bonded Wafer Pair
Thickness	775 microns	1550 microns (bonded) 785– 850 microns (bonded/thinned)
Diameter	300 mm	300 mm (bottom wafer) 294 – 300 mm (top wafer/edge bevel trimmed)
Edge Bevel	T/3, T/4 in M1.15	Modified by edge bevel trim
Notch	Figure 7 in M1.15	Overlay/edge trim modified
Bow/warp	100 microns	30 – 2000 microns observed
Mass - grams	126 g (not specified)	140 – 286 grams

Traditional robot end effectors have successfully handled single silicon wafers for more than 15 years of 300mm wafer processing. End effector contact on the back of the wafer (either through a grooved channel or three points of contact) will seal against the wafer backside when process vacuum is applied. Process vacuum is typically supplied to a tool in the range of 15 - 26 inches of mercury. This resultant holding force allows a wafer to be removed out of a wafer carrier, cycled within a process tool and returned to the wafer carrier with placement precision that enables the process while maintaining safe wafer handing.

Certain process tools are location sensitive, and the process repeatability will suffer if wafer placement repeatability within a process module is compromised (e.g. not centered on a spinning wafer chuck in a photolithography coat and develop module). Safe wafer handling and damage losses are avoided when robot end defectors deliver wafers to locations that avoid potential wafer breakage (e.g. etch chamber door closure) or defect contribution (e.g. scraping wafer carrier sidewalls).

During the start-up of the SEMATECH 3D interconnect toolset in Albany, NY, one lesson learned [2] was the need to slow down wafer handling speed when placing wafers in various process modules. Wafer slippage was observed on robot end effectors, and handling errors (wafer collision with wafer carrier sidewalls) occurred when using default robot setups designed for single wafers. Root cause for the slippage errors was determined to be the increased mass (and subsequently theorized to be associated with thickness) and momentum of the bonded wafer pair that exceeded safe handling speeds. A reduction in BWP handling speed was implemented as a workaround, empirically derived by observations on the velocity changes that minimized wafer slippage.

Wafers are often held in place on an atmospheric robotic end effector by a vacuum holding force. The total vacuum holding force is a product of the process vacuum that is applied to the open area of the end effector contacting the wafer surface, minus vacuum leakage and delivery line losses. Vacuum holding force can increase or decrease based on the size, shape and materials of the portion of the end effector that comes in contact with the wafer. Process vacuum levels in fabs can vary, further impacting this holding force and causing problems for end effectors that do not have significant design margins. Additional consideration should be given to surface roughness of the wafer backside in contact with the robot end effector, as this can induce vacuum leakage, producing reductions in vacuum holding force.

Equation (1) shows that the momentum (P) of a moving wafer is equal to its mass (m) times its velocity (v)

$$P=mv \tag{1}$$

In the case of bonded wafer pairs, the mass can increase to more than double that of a single wafer. If wafer handling robot velocities for a BWP are held constant (i.e. not reduced versus velocities used with single wafers), the BWP momentum will double. This increased momentum will significantly increase the need for an end effector that can firmly hold the BWP in place. When momentum exceeds the vacuum holding force for the robotic end effector, wafer slippage occurs. If the end effector design did not anticipate the increased mass associated with bonded wafer pairs, the BWP handling velocity will likely need to be reduced to insure safe wafer handling and repeatable wafer placement. The lateral force on a wafer in motion is its acceleration (g's) times it mass, so it's actually the acceleration (and deceleration) of the bonded wafer pair that creates the force which overcomes an end effector's lateral holding force.

Many atmospheric end effector designs cause a visible wafer "dimpling" when engaged with the wafer. In this experiment the traditional robot end effector was observed to create a dimple measuring 19 microns deep [3]. This may be a concern with regard to device structures (stress) and wafer backside contamination, but in the case of bonded wafer pairs, it is predicted to reduce vacuum holding force. The stiffness of a BWP is greater than that of a single wafer, and the dimpling effect is correspondingly reduced. When the BWP is gripped with the traditional robot end effector, the dimple was not observed. The dimpling is a result of the wafer shape conforming to the applied vacuum holding force. For a bonded wafer pair, the additional stiffness reduces the ability of the BWP to conform to the end effector when vacuum is applied. This can reduce an atmospheric robot end effector's holding force. The BWP is less likely to mold to the end effector's shape, allowing vacuum leakage and reduced vacuum holding force.

II. METHODOLOGY

To make comparisons between robot end effectors and their ability to hold a 300mm wafer without sliding, a metric and test methodology was developed. The test metric is termed lateral holding force, and is defined as the lateral force required to overcome the static friction between a wafer and a robot end effector. Lateral holding force is exceeded when a wafer begins to slide.

A test apparatus was developed to measure this lateral holding force, as shown in Figure 1. An end effector is mounted rigidly and level, with a wafer or bonded wafer pair placed on the robotic end effector. A digital force meter with peak hold measurement capability is mounted on a linear rail on the same plane as the end effector. This force meter is then moved laterally by a low speed electric motor, to drive the meter into the wafer edge until wafer movement occurs. The peak force is read, recorded and averaged for multiple runs on the same wafer or bonded wafer pair being tested. A variety of robotic end effector designs can be evaluated on the test apparatus, including atmospheric and non-atmospheric styles. Wafer movement indicates that the lateral holding force has been exceeded for the robot end effector design.

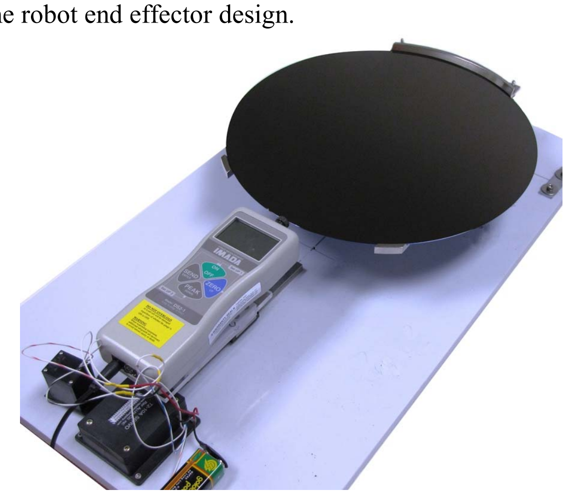


Figure 1. Test apparatus for measuring lateral holding force

The semiconductor industry is constantly working to reduce defectivity. Excessive contact areas with the wafer backside and wafer sliding on end effectors are known causes of particles [4]. Proper end effector design requires minimal wafer contact area, zero wafer sliding, and adequate lateral holding forces applied to the wafer backside and edges. Ideally, the end effector will enable the robot to perform at high speeds, so that tool throughput is not compromised, regardless of wafer mass, bow, warp, stiffness or backside surface texture. Wafer rubbing or collisions on tool parts and carriers can be considered another source for particles. Wafer placement repeatability is necessary to avoid this contamination source, as wafer slippage can cause particles to be generated when wafers collide.

Five versions of robot end effector styles were tested and compared for lateral holding force including single wafers, bonded and thinned wafer pairs, and double thickness bonded wafer pairs. Test results for lateral holding force are summarized in Table 2.

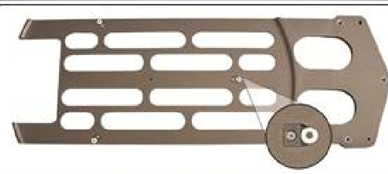
A. Metallic pocketed end effector

Typically used in vacuum chambers, wafers are held in place by gravity and friction with the metal end effector. There is no external process vacuum applied to add a vacuum holding force, and as expected, this design style demonstrated the lowest lateral holding force.

B. Pocketed end effector with embedded o-rings

Many robot end effectors utilize perfluoro-elastomer or similar materials in pad or o-ring shapes to minimize wafer contact and to provide a higher coefficient of friction with the wafer. When designed properly, the lateral holding force of this method is impressive considering there is no additional vacuum holding force. This style end effector can greatly reduce wafer backside contact area and sliding, improving particle performance. Typically, this style end effector is also used in vacuum chambers.

TABLE II. END EFFECTOR LATERAL HOLDING FORCE

End Effector		Single Wafer Mass = 0.126 Kg	BWP, Thinned Mass = 0.134 Kg	BWP, Full Mass = 0.281 Kg
1. Metallic Pocketed End Effector – No Holding Mechanism		0.19 N	0.19 N	0.36 N
2. Pocketed End Effector with Embedded O-Rings Holding Mechanism		2.92 N	3.22 N	3.89 N
3. OEM/ Traditional Atmospheric End Effector – Vacuum Holding Mechanism		8.82 N	9.00 N	8.82 N
4. Atmospheric End Effector With O-Rings And Vacuum Holding Mechanisms		42.23 N	42.63 N	42.29 N
5. Gravity Edge Hold™ End Effector		>100 N	>100 N	>100 N

C. OEM/Traditional atmospheric end effector

Machined ceramic, stainless steel or aluminum materials are typically used. Lateral holding force is primarily controlled by a process vacuum holding force created by the end effector's vacuum groove area in contact with the wafer backside. A variation on this type of end effector will use three points of contact with the backside of the wafer, and might include some elastomeric materials to help provide a more conformal grip.

This style of end effector required a reduction in robot speed to control wafer slippage during wafer handling on the 300mm tools used to process bonded wafer pairs. Wafer momentum exceeded the lateral holding force of the end effector, and the wafer slipped during acceleration and deceleration of the end effector during wafer placement within the tool.

The data in TABLE II suggests that the dimpling of the wafer is not significant in reducing lateral holding force for this style end effector. The observed wafer slippage is being attributed to the momentum of the wafer during acceleration or deceleration of the robot.

D. Atmospheric end effector with o-rings

The atmospheric end effector combines perfluoro-elastomer o-rings with a vacuum gripping mechanism, drawing on the best of both wafer holding techniques. Because of the softer o-ring material, this method seals well against rough wafer backsides. Wafer backside contact is minimized, and due to the larger sealing area the dimpling effect on the wafer is also reduced. Significantly higher lateral holding forces were observed. This style end effector is shown to be quite suitable to handling a BWP at normal and even slightly elevated robot accelerations.

E. Gravity Edge Hold™ (GEH) End Effector

When a wafer or bonded wafer pair is lowered onto a GEH end effector, its weight engages four cams. The wafer keeps the cams engaged, eliminating wafer sliding regardless of wafer mass. Wafers are re-centered by this technique. Wafer contact is minimal; end effector contact is only made between the wafer backside and a small bump on the cam bottom, and lightly between the wafer edge and a perfluoro-elastomer post mounted in the cam upright. Overall performance is not sensitive to wafer bow, warp or thickness. The GEH style end effector demonstrated the highest lateral holding forces, and will enable wafer transfers at top robot speeds and accelerations

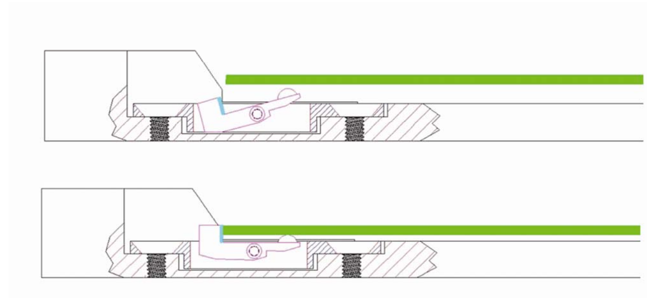


Figure 2. GEH end effector showing cam engagement mechanism on wafer. Wafer weight moves cam to contact wafer edge to hold it in place.

Note that the GEH end effector style is applicable to both vacuum and atmospheric environments.

F. Robot velocity and acceleration

While robot accelerations will vary by manufacturer, typical maximum robot acceleration is 200 inches per second^2 [5]. Based on this acceleration, the lateral wafer force on a single wafer, a thinned BWP, and a full thickness BWP are plotted in Figure 3. These wafer forces can now be compared against the lateral holding force of various end effectors. If the end effector design does not accommodate this increased mass, the acceleration (velocity) of the robot will need to be reduced to insure safe wafer handling.

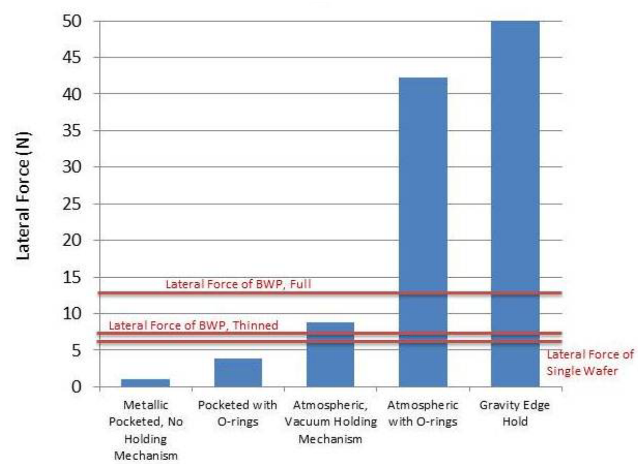


Figure 3. Lateral force on wafer (red line) compared to lateral holding force on end effector (blue bar).

III. Conclusions

Bonded wafer pairs do not comply with many of the parameters specified in SEMI M1.15, including wafer thickness, diameter, edge bevel, notch and bow. BWPs contain additional mass that can create lateral forces which exceed the lateral holding force on robot end effectors. The result is wafer slippage and placement errors on 300mm tools.

Robot end effectors used to process bonded wafer pairs on SEMATECH's 3D interconnect toolset in Albany, NY required a decrease in wafer handling speed to prevent wafer slippage, resulting in safe, repeatable wafer placements.

SEMI standards need to be updated to reflect the specific handling requirements for bonded wafer pairs, including wafer mass as a new concern. Tool design and robot end effectors must reflect the new BWP parameters.

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