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FAILURE AND CAUSE ANALYSES

Chiplets and Advanced Packaging Changing System Test and Failure Analysis

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Abstract
The rapid evolution of semiconductor technology has given rise to novel paradigms in chip design and manufacturing. Such innovation is the concept of chiplets, which involves breaking down a complex integrated circuit into smaller, interconnected components, each designed to perform specific functions. This article delves into the world of chiplets and their intrinsic connection to material testing. Chiplets offer numerous advantages, including enhanced flexibility, scalability, and cost-effectiveness in semiconductor design. However, the successful implementation of chiplets hinges on rigorous material testing and characterization to ensure reliability and performance. In conclusion, chiplets represent a transformative approach to semiconductor design, offering unparalleled opportunities for innovation and customization. However, the realization of their full potential relies heavily on robust material testing and characterization processes. This abstract underscores the critical relationship between chiplets and material testing, highlighting the challenges and advancements in this dynamic field that pave the way for the next generation of electronic devices.

KEYWORDS

bond testing, shear test, pull test, chiplets, material test, fully integrated bond testers, strength of bonds, copper pillar shear testing, testers for push and bending testing, teamnology

1 Introduction

In the ever-evolving landscape of microelectronics, innovation is driving the development of new technologies that continue to push the boundaries of what is possible. That groundbreaking advance is the transition from monolithic chip design to the modular world of chiplets (FIGURE 1). This shift represents a fundamental departure from the traditional approach to microchip architecture and promises to revolutionize the way are designed, manfacture and use semiconductor devices. But the same is true in the world of material testing, which has shifted dramatically in recent years. Whereas in the past, more or less dedicated solutions were the goal, today we find complex and centrally arranged test laboratories. However, due to the quantities involved, these can no longer be operated manually, but must be converted to fully automated testing concepts, in which automatic assessment of the test points can also take place. However, this kind of technological turnaround raises the issue of efficient material testing before the completion of the chiplet. The challenge is essentially to be able to permanently monitor chiplets in the various phases of production, process this information, provide just-in-time feedback to the corresponding phase and intervening in the production process in good time if necessary.

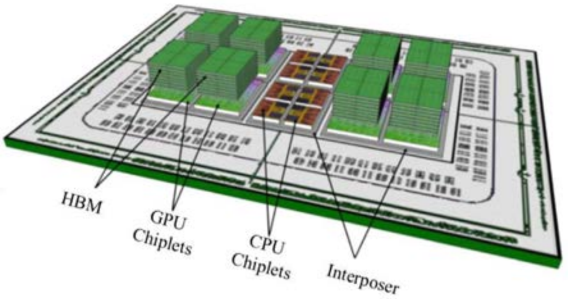


FIGURE 1: Chiplet System from Ref. [1]

As time and money are amongst the most important factors, test speed, high precision, and least possible product damage is always the desired goal.

1.1 Time for inline

As destructive testing destroys the product it cannot be done directly inline in most situations. It can though be done in a fully automatic parallel process via overhead transport systems, transport robots or multi-loader feeding a fully automated tester. On the other hand, non-destruct (ND) testing typically tests all the product and is/can be done directly in line. Testing all the product takes a lot of time typically limiting its use to safety critical applications. In this paper among other things we discuss ways to increase the throughput of the testing process. However, this can only be achieved if the device meets the quality requirements of the following three classifications:

1. alignment,
2. test Speed and
3. accuracy

2 Alignment

2.1 Stiffness of a machine

Stiffness generates accurate alignment of the tool and precise control of the test speed. These are the most important requirements for a bond tester. Both alignment and speed affect the test results, which includes the measured bond strength and failure mode. It is also important that these values are maintained during the test as the load increases. For this reason, a bond tester must be very stiff.

Like all machines the Condor Sigma is a compromise between incompatible and competing objectives. Its designed stiffness having to compete with its cost and, as a bench top machine, transportation and handling. Floor standing Sigma systems have been developed, where these objectives are optimized much more in favor of stiffness. However, no machine can be infinitely stiff, so there may be deviations in test results due to lack of stiffness. At least that used to be the case until xyztec recognized Active Stiffness as an essential component of a high-precision bond tester and added Active Stiffness as a software correction in addition to a great deal of hardware customization. The lack of overall stiffness causes the test speed to be lower than programmed and the tool orientation to be displaced

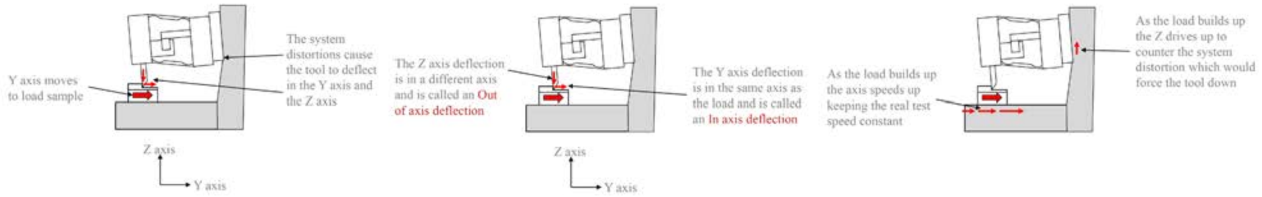


FIGURE 2: Active Stiffness on a Condor Sigma simplyfied

in one or all of the three X, Y and Z axes. In the 2D plots (FIGURE 2) a load is applied in the Y axis. The deflections in the frame are greatly magnified to show the effects. Consequently, deflections in the axis reduce the test speed, whereas out of axis deflections change the tool orientation. There is only one deflection in the axis, but there maybe 1 or 2 deflections out of the axis. Active stiffness uses the motorized X, Y, and Z axes to correct for the speed change and out of axis deflections. These adjustments happen in real time as the test is being performed. Within the margins of error, it makes the bond tester theoretically infinitely stiff.

2.2 Creep behavior

Creep behavior refers to the deformation of materials under load. After the initial rapid deformation, a smaller additional deformation takes place. This describes the creep behavior. When looked at the load cell of a bond tester, the deformation takes place in the form of bending (FIGURE 3). This is called positive creep because the deflection continues to increase. However, in the case of a strain gauge system, negative creep can occur where the deflection appears to decrease over time.

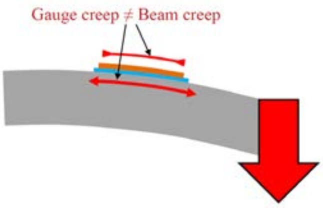


FIGURE 3: Schematic beam

To understand negative creep, we need to look at a strain gauge under load. If the creep of the beam is greater than the creep of the strain gauge, we get positive creep, if the creep of the strain gauge is greater than the creep of the beam, we get negative creep. When using a strain gauge, the type of gauge, the adhesive and its thickness are chosen so that the creep of the gauge is equal to that of the beam. This helps, but similar to correcting for temperature effects, the limitations of the hardware are greater than what can be achieved by digital correction. The two creep values are still very different in most cases, and some creep still remains.

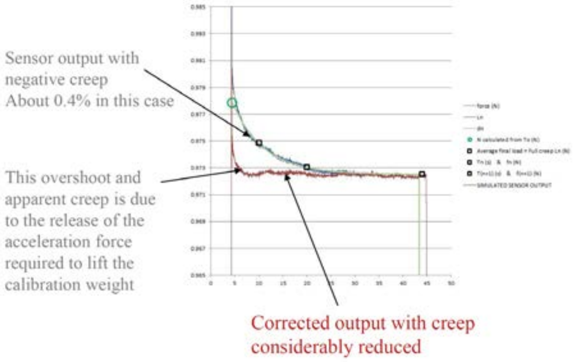


FIGURE 4: Creep calibration with a constant load application

Based on this knowledge, all sensors were provided with a creep correction (FIGURE 4), which takes the form of an adapted calibration based on the different creep behavior of the materials. In addition, new sensors were developed for chiplets applications so that even very low forces can be measured accurately and such material properties were eliminated as far as possible.

3 Sigma test speed

3.1 Pulse direction

In current Sigma systems, the communication to the drives is done using RS232 Serial communication and CAN. This communication protocol is the limiting factor in the sampling rate of the closed-loop motion controller and hence limiting its bandwidth. Changing the control mode to pulse-direction, where every pulse signals a step of the stepper motor, allowed to increase the sampling rate and hence the bandwidth. This change has halved the duration of a move done by the sigma due to improved rise and settling times. The top speed has also increased from 50mm/s to 60mm/s Table 1. Not only does pulse direction improve on move times and hence UPH, it also results in greater disturbance rejection and hence more accurate control. Similar as to the shearheight controller, the technique used to design the controller is loop-shaping (FIGURE 5).

Though the improved bandwidth is only 10Hz, fast references can still be tracked due to a feed-forward path implemented in parallel to the feedback path. Since the feedforward path is in open-loop with the plant, it cannot destabilize the system making it possible to track faster references than the closed-loop system would be able to do on its own.

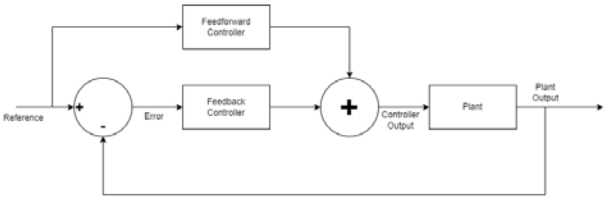


FIGURE 5: .Control scheme Pulse-Direction control

3.2 Robotic move

When moving within an automation, in an old system, three moves were carried out separately: Move the z-axis to safe height, move xy to target position, move back the z-axis to the target position. Though being the shortest path from point A to B, this is not the fastest path (similarly as to F1 cars not driving the shortest path through a corner).

The robotic move is a optimization problem to determine the time optimal trajectory from any start position to any target position while adhering to constraints on maximum velocity and bounds on the position. This optimization problem is given by”Calculation basis (a-i)”.

Where T is a vector containing the duration of every section that the sigma machine should be accelerating, cruising or decelerating.

$$
\begin{array}{ll}
\arg_T \min & \sum T \\
\text{a) s.t.} & 0 \le p(t) \le P_{\max}(p) \quad \forall t \in T, \quad \forall p \in (x,y,z) \\
b) & -V_{\max}(p) \le v(t,p) \le V_{\max}(p) \quad \forall t \in T, \quad \forall p \in (x,y,z) \\
c) & z(t) \le Z_{\text{safe}} \quad \forall t \in [t_3, t_4, t_5] \\
d) & p(t) = p_0 \quad \forall t \in [t_0, t_1, t_2], \quad \forall p \in (x,y) \\
e) & p(t) = p_t \quad \forall t \in [t_6, t_7, t_8], \quad \forall p \in (x,y) \\
f) & p(t_0) = p_0 \quad \forall p \in (x,y,z) \\
g) & p(t_f) = p_t \quad \forall p \in (x,y,z) \\
h) & v(t_0,p) = 0 \quad \forall p \in (x,y,z) \\
i) & v(t_f,p) = 0 \quad \forall p \in (x,y,z)
\end{array}
$$

Calculation basis

Summing these durations then gives the total time required for the move. The first two constraints are general bounds on the system axis positions and velocities. Durations t3, t4 and t5, should be above safe height which is represented by the third constraint (note that z=0 is defined as the top position). Before and after these timings, both the x and y stage are not allowed to move which is captured in constraints four and five. The final four constraints make sure the start and end position are the specified initial and target position and that when the Sigma is there, its velocity is zero.

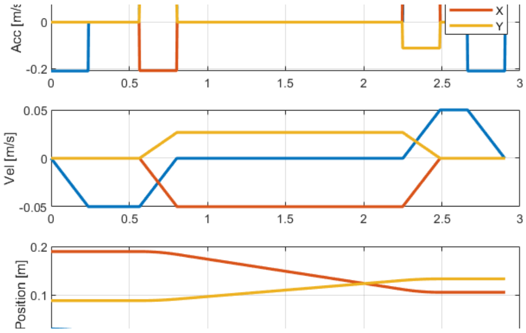


FIGURE 6: Example solution for the x, y and z axis

Move Distance	Speed Control [s] 50mm/s, No controllable acc	PID + FF [s] 50mm/s, 500mm/s^2	Pulse Direction [s] 60mm/s, 500mm/s^2
10µm	0,322	0,344	0,163
100µm	0,466	0,423	0,178
1000µm	0,647	0,576	0,242
10000µm	0,833	0,775	0,494

TABLE 1: *Comparison in move times between the old control modes (speed control and PID) and the new control mode (pulse direction).*

Though still only moving xy above the set safe height, it now is one smooth motion taking the minimum amount of time to reach the target position. FIGURE 7 gives an example of the robotic move.

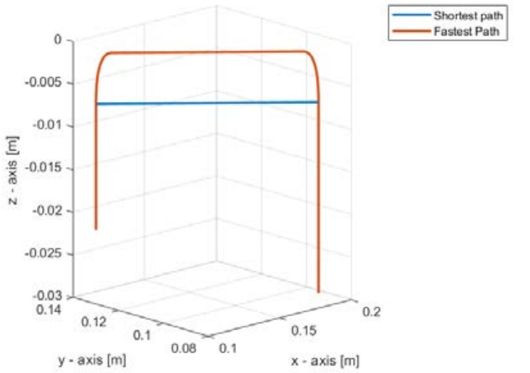


FIGURE 7: Shortest and faster route comparison in spatial coordinates

4 Accuracy

4.1 Shear height accuracy

The new Sigma nano- stepper/shear sensor has a local, closed-loop controlled, z-axis. The local z-axis is actuated using a actuator FIGURE 9 and measures its relative position with nano-meter accuracy using a capacitive sensor.

The complexity of the total system makes it very difficult to use classical PID control. Hence loop shaping techniques are used to design the motion controller such that it is robust enough to handle the hybrid nature of the dynamical system during a sheartest whilst rejecting disturbances. It is a hybrid system since the dynamics change severely during contact with the bond (change in resonance frequency, steady state gain, etc.).

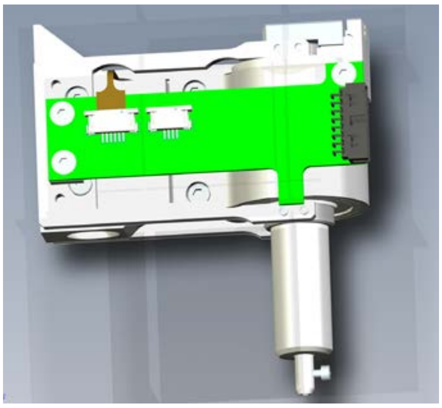


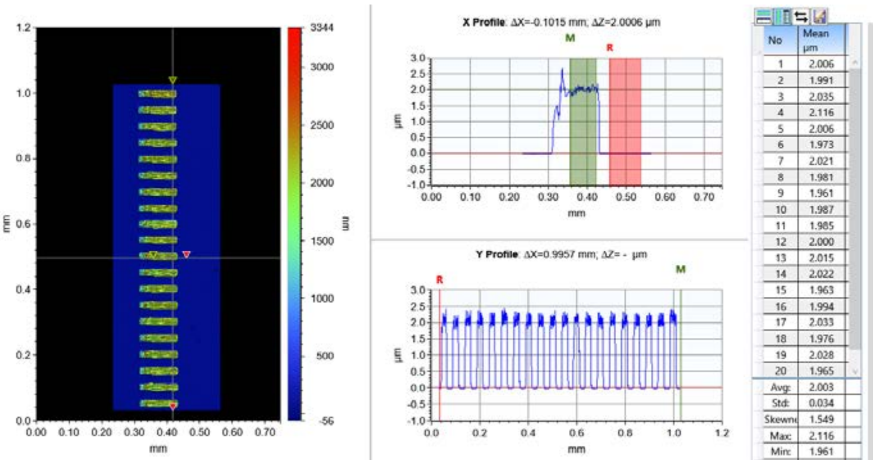
FIGURE 9: Sigma Nano control shear sensor

The use of this closed-loop feedback control system also allows to minimize the landing force to as little as 1.5gf .

This is done in two-fold:

First, the VCA is used to actively dampen any oscillation inside the system, which prevents false touchdowns and hence lowering the detectable force.

Secondly, when a touchdown is made, the VCA applies a force in the opposite direction of the landing force resulting in less force being applied to the sample.



X Profile: ΔX=-0.1015 mm; ΔZ=2.0006 µm

Y Profile: ΔX=0.9957 mm; ΔZ= - µm

No	Mean µm
1	2.006
2	1.991
3	2.035
4	2.116
5	2.006
6	1.973
7	2.021
8	1.981
9	1.961
10	1.987
11	1.985
12	2.000
13	2.015
14	2.022
15	1.963
16	1.994
17	2.033
18	1.976
19	2.028
20	1.965
Avg:	2.003
Std:	0.034
Skewn	1.549
Max:	2.116
Min:	1.961

FIGURE 8: Measurement of 20 sheared gold pads. Set shear height was 2μm

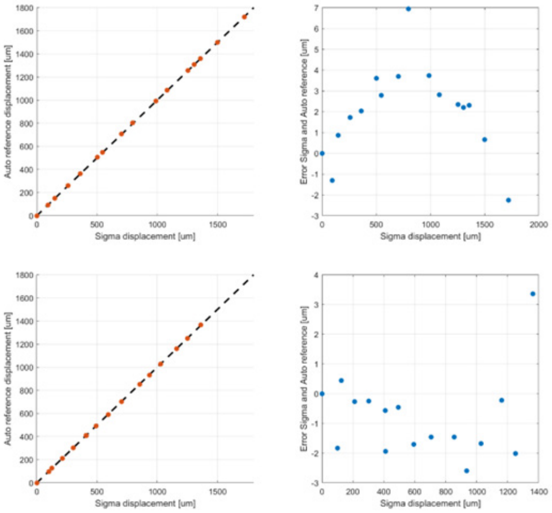


FIGURE 10: Validation of auto reference position measurement using the Sigma encoders (y-axis up, x-axis down). Note the black dotted line is the ideal result, the red dots are the measured results.

4.2 Dynamic measurement

Most bond testers simply output the force on the sensor and do not take into account the characteristics of the system itself. The Sigma uses an algorith to calculate the true force on the bond and thereby gives more meaningful results to take into consideration for the engineer.

Where the dots above the displacement represent the first (one dot) and second (two dots) derivative with respect to time (e.g., the velocity and acceleration respectively (FIGURE 11)).

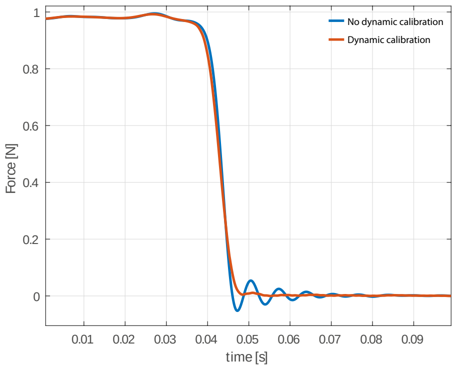


FIGURE 11: Result of dynamic calibration at the end of a test

5 Game-changing full automation

5.1 Integration transforms

Robotic handling ensures safe load and unload of applications and avoids handling error and damage. Particularly in the chiplet sector, the handling and removal of the unfinished chiplet at various points in the production process represents a major challenge. It plays an important role whether the systems are integrated (FIGURE 12) or operated independently as stand-alone solutions.

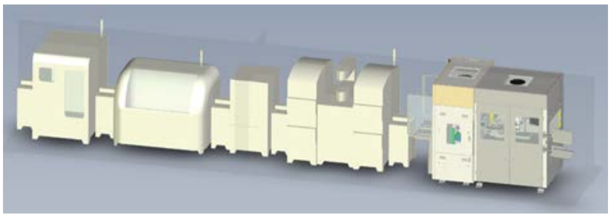


FIGURE 12: Machine integreated

FIGURE 13: Machine with loader (front view)

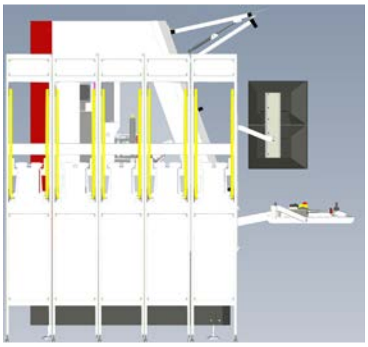


FIGURE 14: Machine with loader (side view)

Based on this fact, the machine development was adapted in such a way that it is possible to test different production stages (FIGURE 15) with corresponding traceability via several loaders (FIGURE 13, FIGURE 14). Due to the different production stages and the associated different architectures to the final chiplet, corresponding workholders have to be developed.

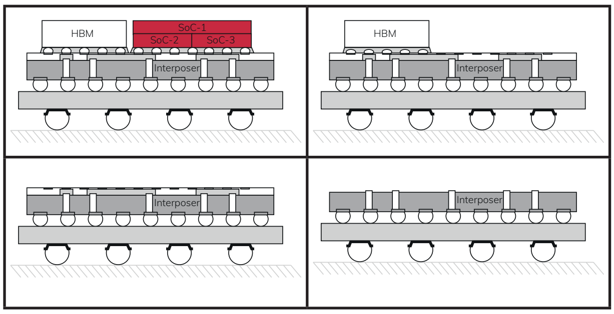


FIGURE 15: Chiplet production variance

5.2 Automatic loading

A load port is the perfect basis for complete line integration if the subsequent steps meet optimized requirements. In addition to the necessary If/ Then security queries, at least one tracibility check should be performed by a barcode reader in the sequence of the automation process. Ideally, a data matrix code or an OCR recognition (FIGURE 16) is used. Bound to the code, a bidirectional data

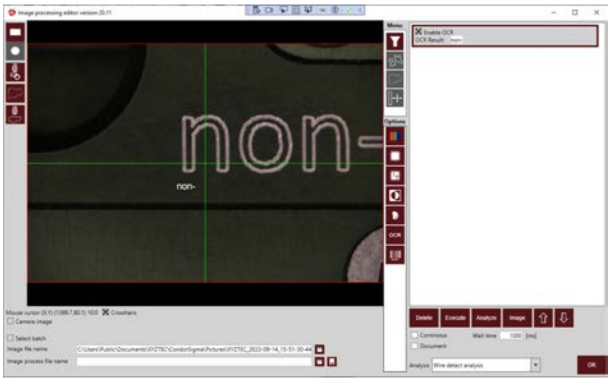


FIGURE 16: OCR recognition

communication (FIGURE 17) can be used to select the correct test method,

FIGURE 17: Bidirectional communication

adjust the indexer (FIGURE 18) to the appropriate application, select preconfigured workholder (FIGURE 19),

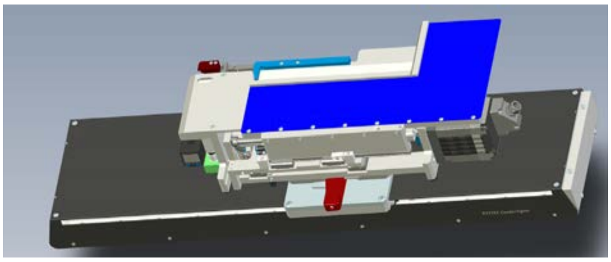


FIGURE 18: Adjustable indexer

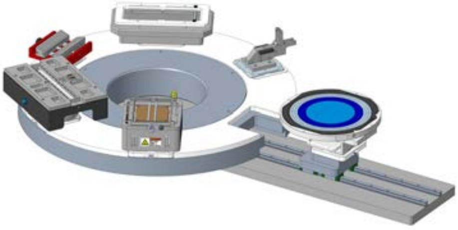


FIGURE 19: Workhloder carousel

turn the RMU to preconfigured tool and open the mapping file (FIGURE 25). After appropriate positioning and optimal clamping, the bond tester is able to perform a fiducial check for final clamping control before image acquisition prior to testing, followed by testing.

5.3 Automatic testing

The destructive pull test is a commonly used mechanical testing method. The wire jumper is stressed until it breaks off using a hook and applying a continually rising pull force. It is essential that reproducible constant conditions are used (for example comparable wire jumper geometry and test conditions) to ensure reference can be made to other tests or specified standards. Attention must always be paid to the influence of the wire diameter, the distance between the two bonds with each wire jumper, the angle of ascent and the application of the hook. The hook should be L-shaped and its flat surface should have a diameter 2-3 times that of the wire. 0.2 to 0.6 mm/s are recommended for the pull speed of the pull tester. The ideal loop geometry is shown in FIGURE 20.

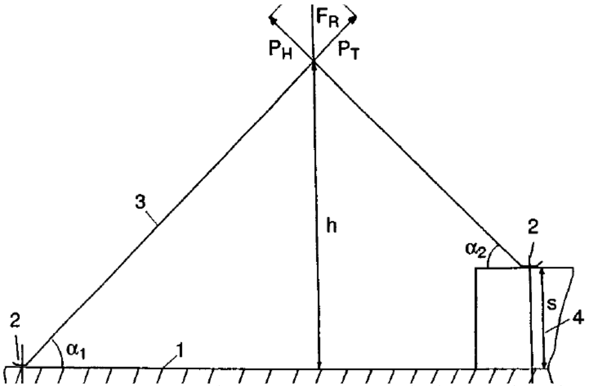


FIGURE 20: Example arrangement with the two bonds of each wire jumper at different heights (1Substrate material; 2 Bonds; 3 Bonding wire; 4 Chip; FR Pull-off force; PH, PT Forces in direction ofwire; <xv a2 Pull-off angle; h Wire jumper height; I Distance of bonds; s Chip height). from Ref. [2]

In addition to the destruction of the product, which is positive for the quality evaluation, the destructive test also results in a restriction of the test speed, since the test is usually performed with 250μm. This means that a limitation of the test quantity is inevitable. When processing cost-intensive semi-manufactured products or manufacturing for sensitive areas (military and aerospace technology, medical electronics), the non-destructive pull-test may be used to test a large quantity of wire jumpers (up to 100%). Wire jumpers or bonds must not be damaged beforehand with this test though no sufficient explanation exists regarding the matter of prior damage. Furthermore, care must be taken during the non-destructive test as the wire jumper geometry may be changed due to bonding, which can be disadvantageous. Considering these points, it is possible to increase the test speed in such a way that the non- destrucvtive tests can be carried out in a very short time and thus an inline test can be carried out, not in production but very close to it. With the non-destructive test, the characteristic values (minimum pull forces in cN) stated in TX should be 100% attained for the wire jumpers (ASTM standard).

Coditions directly after bonding	Min. pull-off force for wire diameter in μm				
	17,5	25	32	38	50
MIL-STD 883C, Method 2023					
Al- wire	1,2	2,0	2,5	3,0	4,2
Au- wire	1,6	2,4	3,2	4,0	5,6
Labratory/ manufacturing[1]					
Al and Au wire	2,4	3,0	5,0	6,4	9,0

TABLE 2: Minimum pull forces for different wire diameters. From Ref.[2]

Final statements on the test and throughput speed cannot be made at the moment, as these parameters are still in a test study that can be expanded.

5.4 Automatic grading

5.4.1 Deep learning autograding

Autograding of sheared bonds can be seen as a Semantic Segmentation problem. This means that every pixel in an image is given a classification (e.g., Ductile, Brittle, Gold, etc.). This can be done fully automatically using a Deep Learning network with the power of Convolutional Neural Networks (CNNs). The proposed architecture for this specif-

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[1] The values shown are based on experience in a wide range of application areas and have been proposed by the working group as guideline values preferably to be used. Exceptions may be necessary with special applications for example.

ic task is the U-Net architecture (FIGURE 21), which was developed for biomedical image analysis of cells. This also works well for bonds (FIGURE 22) since both cases use images made from microscopes and have irregular but distinct shapes and textures.

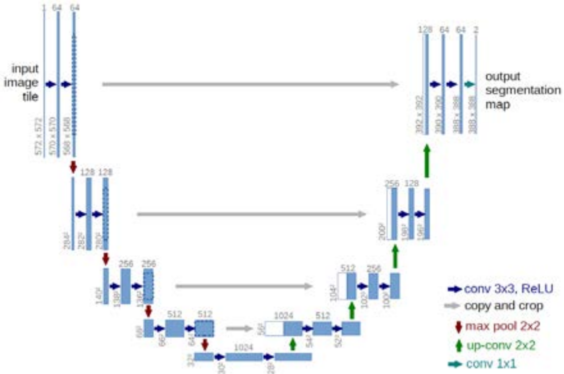


FIGURE 21: U-net architecture.

Autograding of pulled wires is a classification problem where an entire image needs to be classified. This is proposed to be done using a (pre-trained) ResNet architecture.

Both networks need to be trained before they can be used. Depending on the quality of the image and annotation, the required amount of training data varies from 50 to 500 images for robust results

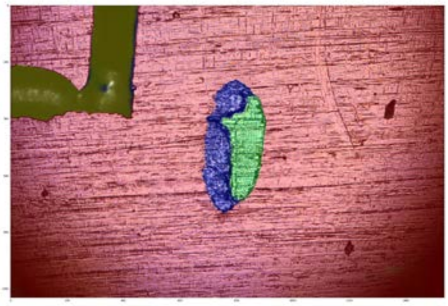


FIGURE 22: Image graded by trained U-Net[2] . Red: Background, Green: Ductile, Blue: Brittle, Yellow: Debris.

5.4.2 Automatic image measurement

Image measurement is an additional function that is intended for further scientific approaches or which is used for early detection. However, studies are currently taking place in which images are compared with measured (FIGURE 24) values in order to be able to recognize trends at an early stage and to be able to implement corresponding early warning systems for chiplets. The goal is to minimize errors within the entire production chain.

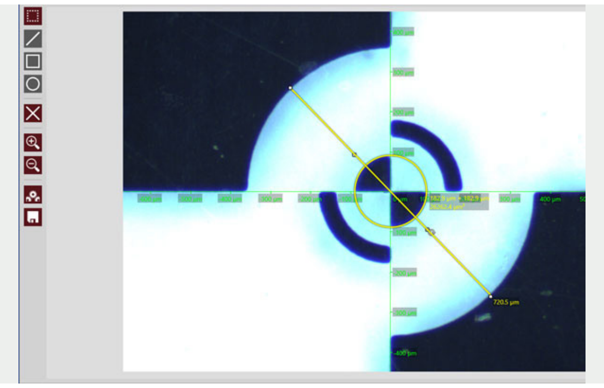
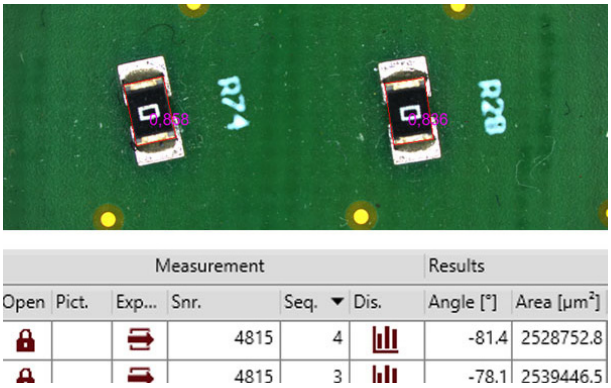


FIGURE 23: Calibration tool for image measurement



Measurement						Results	
Open	Pict.	Exp...	Snr.	Seq.	Dis.	Angle [°]	Area [µm²]
🔒		⇄	4815	4	▮▮▮	-81.4	2528752.8
🔒		⇄	4815	3	▮▮▮	-78.1	2539446.5

FIGURE 24: Image recognition with measurement

5.4.3 Wafer mapping

For all further processes, the marking of all tests performed and the error-free transfer of the data is provided. For this purpose, the corresponding wafer format files (FIGURE 25) are updated and all tested sectors are marked with a „V“. All data transfers and tests are monitored by a corresponding data communication concept.

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[2] Sample: Thin wire shear (aluminium on aluminium) Melaka.

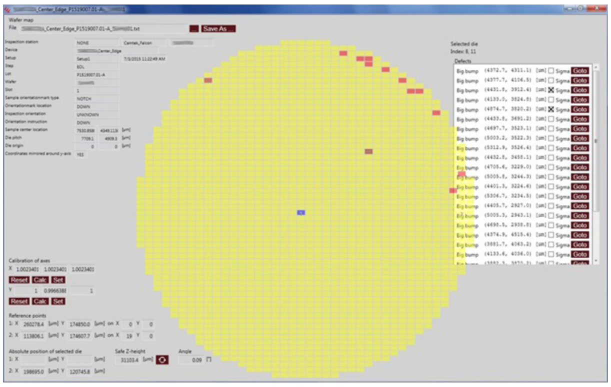

FIGURE 25: Wafer maping with V marker

5.4.4 Data communication SECS GEM / GEM300

SECS/GEM is a collection of communication standards specified by Semiconductor Equipment and Materials International (SEMI), an international organization, together with industry. SECS is an abbreviation for SEMI Equipment Communication Standard. GEM stands for Generic Equipment Model and refers to the E30 SEMI connectivity standard. The protocol family defines a generic model for communication and control of production equipment. In the complex manufacturing process, many process steps are carried out that can only be optimally completed and checked with the support of IT systems. SECS/GEM based networks enable remote control of production equipment and automated operation with the support of MES. Structured data collection also offers the opportunity to further improve quality and availability. In SECS/GEM, functional models represent the material flow from loading to processing specifications, execution and unloading. For this to be done in a structured way, communication and various settings must be configured first. As a result reports on events, alarms and process values are available.

The SECS protocol architecture consists of several layers. The first SECS layer is based on the RS232 interface (SEMI E4) and the TCP socket (SEMI E37) respectively. The SECS I and HSMS layers above are primarily responsible for connection management between host and equipment. The SECS II (SEMI E5) and GEM (SEMI E30) protocols for data exchange via standardized messages are located on the hierarchy levels above. This layer model enables the plant to provide the host with information such as status and data variables, events as well as alarms. The factory management system (MES) can use this information to monitor production, adjust parameters as needed, and provide useful information to management via monitoring (FIGURE 26)

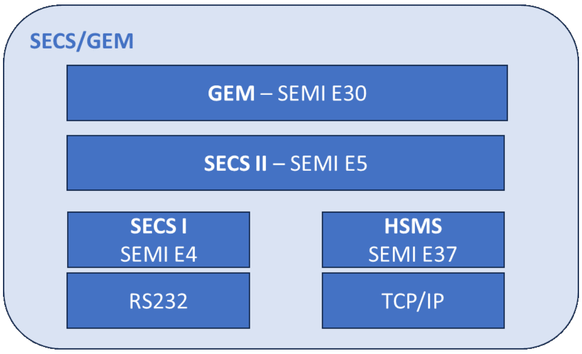

FIGURE 26: SECS GEM Organisation Ref. [3]

GEM300

While the SECS/GEM standards are used for factories with a low level of automation, high-end production with, among other things, automated material transport within the factory (e.g. AGV or OHT) requires further standardizations according to the GEM300 standards. These build on the SECS/GEM standards and serve, for example, the detailed tracking and release of carriers and individual substrates (SEMI E87) or the differentiation of control jobs (SEMI E94) and process jobs (SEMI E40), whereby the control jobs perform an assignment of individual substrates to process jobs that contain different recipes. The individual substrates are tracked in detail within the system (SEMI E90). In addition, detailed performance monitoring of the plant with all its modules is possible (SEMI E116). This ensures full control over production at all times (FIGURE 27)

FIGURE 27: Communication interface from Ref. [3]

Interface A (EDA)

- E120 Common Equipment Model
- E125 Equipment Self Description
- E128 Specification for XML Message Structures
- E132 Authentication and Authorization
- E134 Data Collection Management
- E138 Semiconductor Common Components
- E145 Classification for Measurement Unit Symbols in XML

6 Discussion and conclusion

The ideal future bond tester should be designed to meet the evolving needs and challenges of various industries, such as electronics manufacturing, aerospace, automotive, and materials science. Here are some key features and characteristics that an ideal future bond tester might have:

1. Versatility: The bond tester should be versatile and capable of testing various types of bonds, such as wire bonds, die bonds, and flip-chip bonds. It should also be adaptable to different materials and bond sizes to meet the versatilitys, new finepitch extensions are currently under development and in an extended feasibility trial. Within these trials, new sensor types are tested and camera systems are adapted for customer needs. Extremely important is the aspect of optimal illumination.
2. Reliability and durability: Finally, the bond tester should be highly reliable and durable, able to operate consistently in demanding industrial environments.
3. Safety features: Safety should be a top priority, with built-in safety mechanisms to protect operators and prevent accidents during testing.
4. Integration with Industry 4.0 technologies: To align with the trends of Industry 4.0, the bond tester should be capable of integrating with other smart manufacturing systems, enabling seamless communication and data sharing across the production line.
5. High throughput: Efficiency and speed are critical, especially in high-volume manufacturing environments. An ideal bond tester should have a high throughput capability to keep up with production demands.
6. Cost-effective: While offering advanced features, the bond tester should also be cost-effective, providing value for the investment.
7. Upgradability and maintenance: The bond tester should be designed for easy maintenance and should allow for hardware and software upgrades to stay current with evolving industry standards and requirements.

Keep in mind that the specific requirements for an ideal bond tester may vary depending on the industry and application. Therefore, customization and flexibility in the design and configuration of bond testers may be essential to meet diverse needs. Additionally, continuous innovation and adaptation to emerging technologies and industry trends are key to ensuring the bond tester remains „ideal“ in the future.

Conflict of interests

The authors declare the absence of any conflicts of interest.

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