Overview of challenges in ultrathin substrate handling

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ABSTRACT

The positive expectations for the global PV market are driven by state-of-the-art PV products which have become economically attractive because of technical optimization. Nonetheless, scientists and engineers face the next generation of wafer-based PV technologies in terms of processing recipes and automation techniques. In this paper, motivations, challenges and advances relating to the handling of ultrathin PV substrates are identified for future application. A brief look out of the PV box at neighbouring disciplines in high-tech sectors will also be taken. The differences and advances in the automated handling of ultrathin substrates will be highlighted as well as the difficulties for transportation. The advanced production challenges of a gripper-based substrate movement will be accompanied by increased cleanliness requirements, as test results from the Fraunhofer IPA automation lab show.

Motivation of the PV industry for technology development

If we were to examine the path of the PV industry in relation to Gartner's Hype Cycle we could find ourselves somewhere after the 'trough of disillusionment' and on the 'slope of enlightenment'. Enlightenment? Yes, the global PV market seems to be on its way to stabilizing and recovering from the sector's self-made crisis. Regardless of the damaged confidence and the weak stability, the PV industry is being reanimated by market growth in Asia. For 2014, analysts expect the markets in China, Japan and the USA (with a new capacity between 8 and 12GW) to play the most important role. Europe is about to install up to 8GW, while new markets in South America, Southeast Asia and Oceania may contribute to further growth of the global market [1]. The positive developments in the PV markets will also have positive effects on the research and development of new crystalline PV technologies. As a consequence, the technological progress of PV products is reclaiming attraction. Initiatives for crystalline PV technology development and improvement will inevitably start to decrease the wafer thickness again: the silicon wafer still represents one-third of the cell's manufacturing costs [2].

Although the silicon bulk price is at a low level, the use of thin and ultrathin wafers is becoming more and more interesting. The material-saving argument is no longer the dominant research driver, as there are promising benefits expected from ultrathin substrates. The integration of PV cells on thinner substrates reduces the weight and broadens the area of their application. The reported increased versatility of ultrathin crystalline silicon substrates [3] facilitates a higher grade of customizability and may, for example, enable aesthetic issues with PV product designs to be addressed. Further opportunities for application are accompanied by the quest for increased cell efficiencies.

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Overview of ultrathin cell technologies

Kerr et al. [4] reported a theoretical maximum efficiency of 29% for single-junction silicon PV cells in relation to the substrate thickness; a substrate thickness in the range 55–90µm was calculated, depending on the dopant density and type as well as the silicon quality. Sakata et al. [5] realized a conversion efficiency of 22.8% with a 98µm-thick HIT cell; according to those authors the fabrication of a 58µm-thick HIT cell will become more lucrative when the I_{sc} transmission losses can be reduced by the cell's design. Kray & McIntosh [6] demonstrated constant high cell efficiencies for 75µm float-zone substrates with a PERC structure. The motivation for further reductions in cell thickness is also reported in the International Technology Roadmap for Photovoltaic [7].

While wire-sawing technology is limited to the wafering of certain thicknesses, new approaches to fabricating an ultrathin silicon substrate are being researched. Brendel et al. [8] provide an overview of recent progress in kerf-less wafering techniques and differentiate the wafering from liquid, solid and gaseous silicon. R&D pursuits in the fabrication of ultrathin wafers entail the conversion of the solid substrate from discs into foils and finally into silicon layers.

Returning now to industrial reality, while the state-of-the-art PV production of crystalline PV cells has the know-how to benefit from continuous optimization processes, the emerging wafer-based technologies have yet to enter this process, although the market entry already begins at a higher point on the PV manufacturing learning curve. This will be significantly assisted by appropriate automation solutions for processes and transportation.

Challenges for the handling of ultrathin wafers

The manufacture of cells from ultrathin substrates is somewhat challenging, both for the handling during processes and for the transportation between processes. The success of a handling or transportation method for thin wafers is directly linked to the mechanical strength of the substrate. Maintaining the mechanical integrity of the wafer at the required standard is one of the most important issues that must be considered in the development of automated handling [9].

The challenges for wafer handling in terms of the mechanical strength of silicon wafers have been widely researched, and have been reported by Brun et al. [10] and Koeppge et al. [11], among others. The results of Popovich [12] demonstrate that a certain surface roughness has an enormous effect on

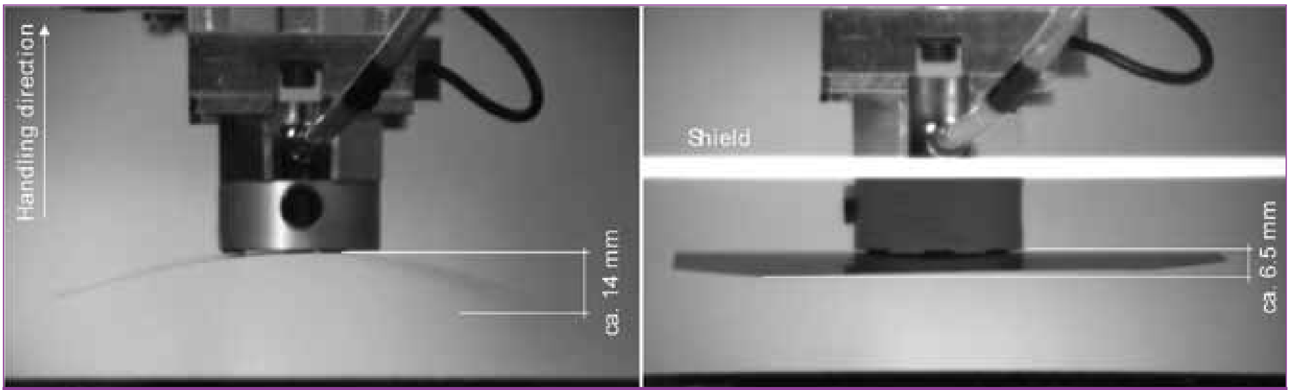

Figure 1. Deformation of thinned 125mm × 125mm ultrathin wafers during high-speed handling with a Bernoulli gripper (vertical acceleration 25m/s^2, travel velocity 3m/s). Aerodynamic issues become a more important factor in meeting future production throughput requirements.

the bending strength of 200μm silicon substrates. The strength of textured and polished samples is significantly higher than that of as-sawn samples. The same characteristic may be assumed for wafers with a reduced thickness. As reported in Schoenfelder et al. [13], a reduction in the substrate thickness leads to an enhancement in strength of small-area substrates: the fracture stress increases considerably in the 50–100μm thickness range. However, the increased fracture stress detected in multiple lab tests with homogeneous loads can not be directly assumed for the actual challenges in an industrial production environment where inhomogeneous loads frequently occur. Here, the reduced stability and stiffness of ultrathin substrates, paired with demands for a high production throughput [7], are facing yet-unresolved challenges.

Some of the automation solutions developed for thin PV wafers [14] may be directly adaptable to ultrathin wafer handling. Since temporary bonding techniques are not likely to be economically attractive to PV producers, an adaptation of pick-and-place methods from thin to ultrathin handling objects may be feasible. However, a general statement cannot be given, as investigations in automated handling have identified significant differences in the behaviour of large-format ultrathin (~50μm) PV wafers and thin (~160μm) PV wafers [15].

The potential benefits offered by ultrathin cells do not yet outweigh the production advantages of standard cells. But the usual technology life cycle is most likely not making an exception for PV products. Even if producers decide to leapfrog certain cell technologies, the appropriate automation concepts need to be identified more quickly than in the past in order to shorten the time taken to put the next-generation PV on the market. The big quest for competitiveness for new PV technologies based on ultrathin cells is enabling a fast improvable production by using capable equipment. By projecting this picture onto the handling automation, the gripper-based transportation of ultrathin substrates will fade in the spotlight.

In general, the goal of modern industrial production is to develop manufacturing methods which keep the working piece always positioned and in contact with a carrying device; the latter acts as a targeted permanent access for the collection of evolutionary data regarding the working piece.

In any case, relocation by pick-and-place operations will remain a necessary handling step in the manufacturing and processing of next-generation PV cells. Carrying devices such as the temporary carrier used in ultrathin semiconductor production are currently not suitable for PV throughputs. The pick-and-place of ultrathin PV wafers can be achieved by appropriate gripping methods, though the specified cycle times remain challenging. The handling and transportation of ultrathin wafers by using established gripping principles has revealed some differences in comparison with state-of-the-art wafers. Three types of gripper have recently been investigated in the Test and Demonstration Center of Fraunhofer IPA: these pneumatic end-effectors can be grouped into Bernoulli grippers, vacuum cup grippers and area vacuum grippers. A repeatable breakage-free transportation of thinned (50–70μm) 125mm × 125mm CZ wafers is possible if attention is paid to some interactions.

The gripping of flat ultrathin wafers by vacuum suction cups evokes selective stresses and strains, accompanied by relatively strong vibrations in the crystalline substrate. The detected vibrations not only result from the transportation/movement but also originate from an ordinary asynchronous compression of the activated suction cups. Such uncontrollable movements are typical for a vacuum cup application on flexible substrates. A certain amount of time is necessary to identify the suitable parameter settings for a workable pick-and-place application while not punching holes in the substrate. The employment of vacuum gripping for a high-volume wafer handling requires a more detailed study, especially for precise assembly tasks. It is therefore doubtful that vacuum cup-based handling has a future in ultrathin wafer handling automation.

> “Tests demonstrated that the direct handling of flat and ultrathin wafers by standard Bernoulli grippers causes strong deformations during pick-up and placement.”

Tests performed with a variety of settings demonstrated that the direct handling of such flat and ultrathin wafers by standard Bernoulli grippers causes strong deformations during pick-up and placement of the handled object. The implications of strong yet smooth deformations are unknown, as are universally valid absolute numbers for the limit of mechanical loads on wafers in general. The results of previous investigations were inconclusive. Deviations in the integrity of standard wafers have been found to be somehow gripper dependent: the investigation by Koeppge et al. [11] stated that an effect of handling by grippers can be characterized by deviations in the wafer's mechanical strength. The fact that the wafer oscillations were responsible for a change in wafer strength could not be confirmed.

At any rate, Bernoulli grippers are suitable for ultrathin wafer-handling operations, although the implications on throughput have to be considered. An increased throughput requires faster handling cycles, whereas the effect of air drag on the unstable substrates is considerable. The abilities of Bernoulli grippers in combination with optimized parameter tuning are convincing – it is possible to achieve precise positioning of substrates where necessary and fast handling where required. In the high-speed handling of ultrathin substrates a wind shield assists even more (see Fig. 1).

In a third test batch the area gripping of flat thin wafers produced acceptable results in all categories. Area grippers comprise a substrate-covering gripper body and model-dependent gripping-force activation. Bearing in mind that certain ultrathin substrates sporadically tend to form a bow, the limitation of the handling capability is reached when it comes to manipulating ultrathin handling objects with uneven or non-plate-like surfaces. For high-speed PV handling, the potential slip of tensioned wafers is contrary to the requirement of reliable positioning accuracy.

A large area support of the substrate offers handling benefits: deformations during the gripping phase are kept to a minimum, even in comparison with a shielded Bernoulli gripper. The full-area gripping of light pieces, however, also has a certain side effect. Waiting times for the wafer placement after handling may prolong the cycle time (up to 600ms) because of a sticking effect of the light and smooth substrate. An irritation of the ultrathin wafer during the release can result in breakage, chipped edges or other losses in quality of the working pieces when being blown off onto carriers, ring belts or rollers. Electrostatic gripping may offer an acceptable alternative, although the risk of polarization of the thin substrate requires slightly more complex solutions for multiple repetitive grippings of the same substrate. Most electrostatic gripping solutions make use of a full-area contact for ultrathin wafer support and blow-off functions, so the same side effects as for pneumatic area gripping will have to be taken into account in terms of particulate contamination on substrate and gripper surfaces.

Contamination challenges of gripping processes for cleanliness-critical products

Another point that should be addressed is the implication of the contact area. For example, area grippers distribute the gripping force on larger surfaces by using large contact areas between the gripper material and the wafer. While Bernoulli grippers are designed for so-called contactless handling, a vacuum suction gripper will patently 'print' the suction cup material on the substrate, as found in the laboratory investigation presented here (see Fig. 2). This is contrary to the trend whereby PV producers and equipment designers strive for a minimum of contact between devices and substrates.

For the investigation, different kinds of suction cup with a diameter of 9mm were tested for stain production on standard CZ wafers. First, all suction cups were run in by performing more than 2000 handling cycles. In a second step, the untouched as-cut wafers were gripped and released 20 times. Subsequently, the handled wafers (not pretreated) were slowly passed through an alkaline solution to evoke visible cup imprints.

As the results demonstrate in Fig. 2, the different contact materials have different implications for the surface condition. All wafer charges of silicone (SIT) cups and nitrile butadiene rubber (NBR) cups left significant imprints. The suction cup with a polyether ether ketone (PEEK) inlet, however, produced very slight imprints on one wafer, while other wafers in the PEEK batch had no marks.

It is assumed that a certain material deposition on the wafer's surface is caused by the abrasive contact during suction cup contraction in the vacuum gripping phase. As a consequence, the cup material at the contact point causes a different wettability of the solution in comparison to the untouched silicon surface. As producers have stated, there is no implication for the cell's electrical quality and only the aesthetic drawback remains, apart from the fact that an unknown and uncontrollable

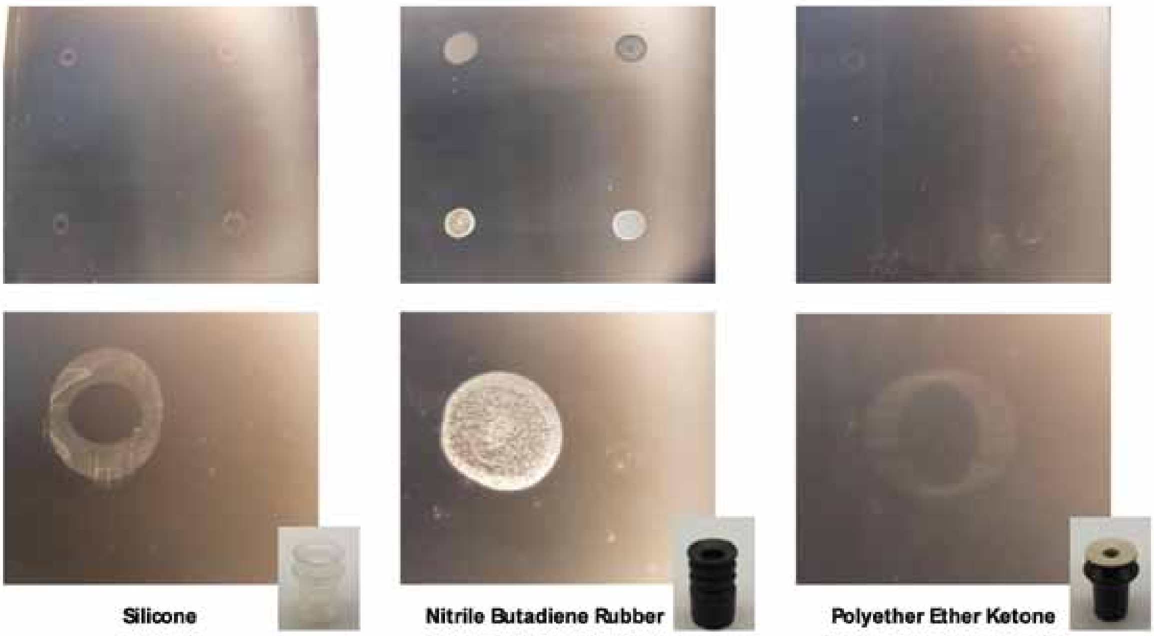

Figure 2. Visible imprints of different suction cup materials produced on as-cut wafers.

event occurs in the production chain. This appearance is negligible for thick wafers but may become an issue for ultrathin wafers: for the latter, surface homogeneity may be an even more important requirement, such as for new light-trapping techniques. Without a doubt, contact materials do have an increasing significance for the handling of thin substrates and have therefore been investigated in another experiment.

As substrates and functional layers become thinner, contact materials become more critical. Particles in the size range of a few microns may be generated from a touched material because of contact. In general, different contamination scenarios of a substrate are possible:

- Generated particles caused by friction between the gripper and the handled substrate.
- Particles transferred from the gripper to the substrate.
- Particles transferred from supply media, such as compressed dry air.

To avoid, or at least diminish, these contamination factors, some counteractive measures are possible. Since friction between the gripper and the substrate is possible during gripping processes, it is important to consider more precisely the effect of frictional processes as a critical source of particles. In order to reduce particle generation to a minimum, it makes sense to take this aspect into consideration when selecting suitable materials. To do this, the emission of particles from tribologically stressed materials can be determined: airborne particles generated by the frictional process are detected by a particle counter and correlated with air cleanliness classifications in accordance with ISO 14644-1 (1999). This enables material pairings tested under the same stress parameters to be compared with one another, and the results obtained to be used to select the most suitable material combinations for the gripper system (see Fig. 3).

(a) (b)

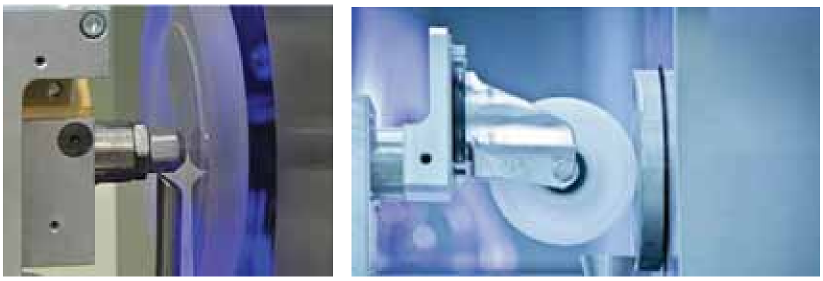

Figure 3. (a) Ball-disk test to simulate sliding friction; (b) roll-disk test to simulate rolling friction.

It is unlikely that contact between the gripper and the substrate can be avoided during a gripping process (even for so-called 'non-contact grippers'), so it is important to consider the *cleanability* of materials, as a contaminated gripper material could lead to contact transfer contamination. Cleanability describes the extent to which various forms of contamination (particulate, filmy, etc.) can be removed from a material surface under defined general test conditions (cleaning procedures, contamination quantities, roughness, etc.). Such a test ascertains the amount of contamination present on the surface before and after cleaning. In conjunction with the chemical resistance that determines the compatibility of materials with certain cleaning agents, the cleanability of

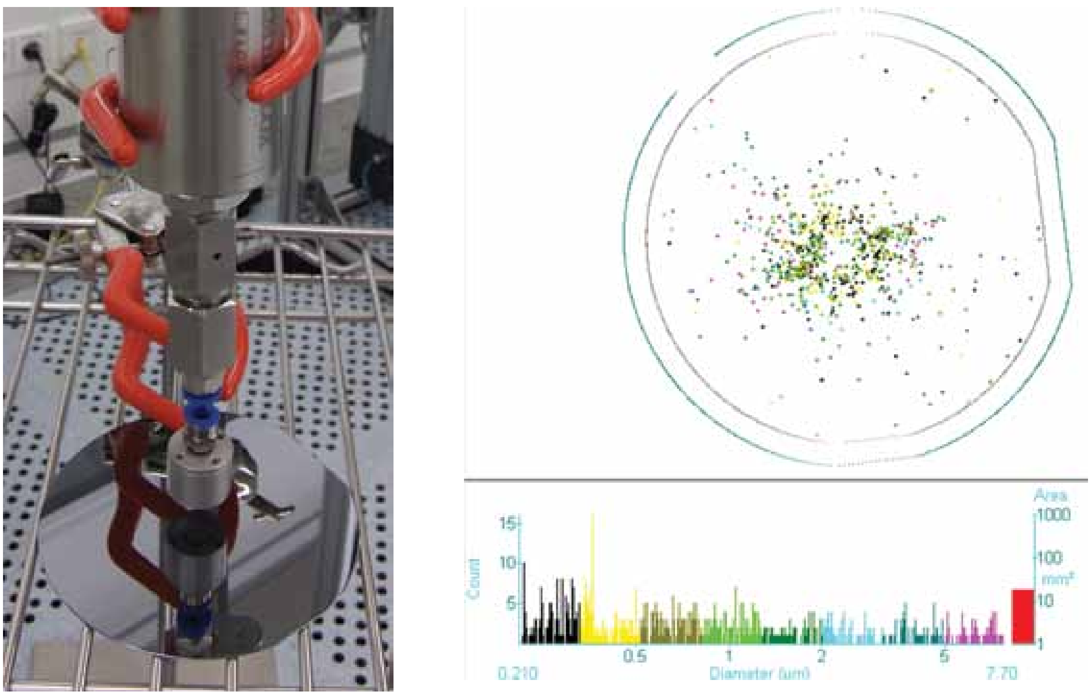

Figure 4. (a) Set-up of the ISO class 1 cleanroom handling experiment with a Bernoulli gripper above a clean and polished 4" silicon wafer. (b) Surface inspection result of one handled wafer after seven gripping cycles – 1.5 bar supply pressure, 7-sec activated gripping each cycle. Gain value 0.21–7.7µm: twenty times more particles.

a material may become an important assessment and selection criterion for a gripper system. Even if wafers are handled with a minimum of direct material contact, such as during Bernoulli gripping, a contamination of the substrate is possible.

> "The cleanability of a material may become an important assessment and selection criterion for a gripper system."

Fig. 4(a) shows the handling of a polished 4" wafer with a Bernoulli gripper; Fig. 4(b) shows the contamination assessment performed using a surface scanner (type: KLA Tencor Surfscan 6200) after Bernoulli handling of the previously clean substrate. Bearing in mind the general advantages of the minimum contact points of Bernoulli grippers, the implication of an activated Bernoulli gripper for the substrate's surface cleanliness was not clear. The necessity of using filtered compressed air for pneumatic grippers was investigated in a cleanroom experiment.

The test demonstrated the potential implications of automated handling using a Bernoulli gripper. In order to obtain a visible result, the test set-up was designed as a worst-case scenario, in which the wafer had to clear a gap of 5mm during picking up. Consequently, the wafer impacted on the gripper's end-stops, with parameter values being used that were not optimized but were realistic in relation to industrial applications. This material contact, along with the contamination of the compressed dry air (CDA) used, provoked the detected contamination shown in Fig. 4(b). To reduce this contamination factor, the additional use of filtration for receiving ultra-high purity CDA, as well as the use of abrasion-resistant contact materials, could be helpful. Moreover, all surfaces in direct contact with the CDA, for example pipes, have to be clean with regard to the considered critical contaminants. This will apply in particular to PV substrates when new cell technologies become more sensitive to contamination.

Challenges and solutions in other sectors

It is not just the PV industry that is steering towards thinner and contamination-sensitive substrates. The EC-funded project SMARTLAM aims at building complex three-dimensional components from stacks of structured and functionalized polymer films for microelectronics. Different additive and subtractive technologies are combined to cover a wide range of applications. Furthermore, polymer films with functional properties, such as anisotropic conductive properties, are applied (see Fig. 5). An overview of the technological approach has been recently published [16].

Besides the individual processing technologies, the handling of polymer films is an important aspect of the technological approach. Flexible materials are manipulated not only in industrial applications in the field of electronics, but also in, for example, the textile and automotive industries [17]. In particular the mechanical flexibility of the applied films and the sensitivity of the films pose numerous, as yet unresolved, challenges.

The size of the applied sheets is 150mm × 150mm with thicknesses down to 100µm. Different polymer materials (e.g. PI, PMMA, COC and PE) are applied, partly with structured or functionalized surfaces.

In contrast to rigid parts, the application of stresses leads to a change in the shape of thin, flexible parts. The influence of stresses caused by physical, thermal or chemical interaction therefore needs to be reduced to a minimum. Additionally, the manufacturing of the sheets leaves them with internal stresses, which causes them to bend without any further external influences. Generally the internal stresses need to be reduced beforehand, in order to decrease this bending effect. Furthermore, any deformation of a flexible part needs to be counteracted by the handling process itself.

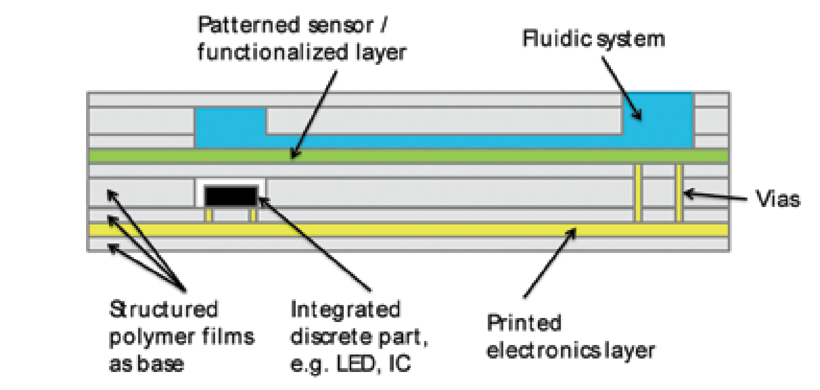

Figure 5. Example of a complex layer-based component.

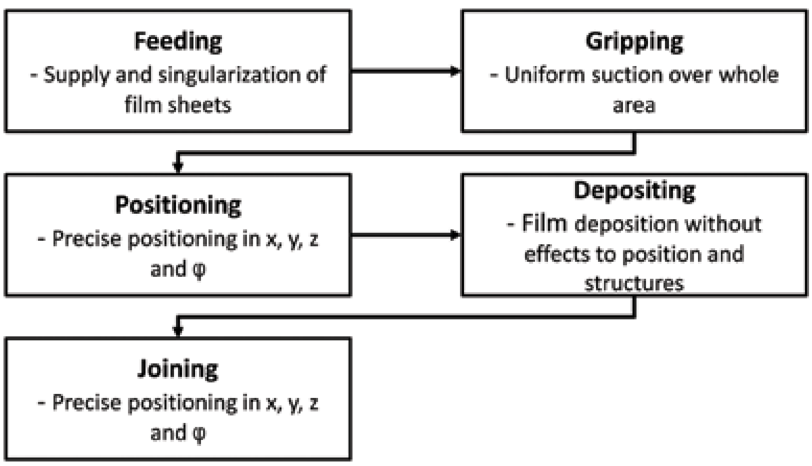

Figure 6. Handling steps for SMARTLAM foil handling.

> "Any deformation of a flexible part needs to be counteracted by the handling process itself."

The overall handling process in SMARTLAM has been subdivided into feeding, gripping, positioning, depositing and joining, as depicted in Fig. 6. Single film sheets in an approximate known position and orientation are provided in the first step – the feeding step. The flexibility of the sheets is an important factor that needs to be taken into account: to flatten and to clamp the sheets for the following processing steps in a standardized way, a work-piece carrier is therefore provided (see Fig. 7). This is equipped, on the one hand, with a removable porous vacuum chuck for a uniform gripping action with clamping forces that are only perpendicular to the sheet surface so as to avoid deformation by, for example, stretching. On the other hand, the carrier has an additional mechanical clamping means for transport purposes or for processes requiring an aperture. Sheet distortion is reduced by vertical clamping after the sheet is flattened on the vacuum chuck.

The next step in the handling sequence is the gripping of the sheet. During this process the work-piece carrier suction must still be activated to avoid deformation of the sheet. In this state a gripping device should pick it up, again without deforming the sheet. In addition, the sensitivity of the structures, particularly the additive ones, has to be considered. A flat gripper based on porous material and providing a uniform vacuum over the whole surface, similar to the work-piece carrier, is proposed for this task. The structures on the sheets require precise relative positioning and orientation of the sheet relative to the substrate: the required positioning accuracy is less than 10µm. The specific approach to achieving the alignment is based on fiducial markers on each sheet and the work-piece carrier, which are measured by a highly precise vision system. As in the case of the gripping process, the deposition should again avoid any sheet deformation or loss of position. Here an appropriate deposition strategy is required which does not affect the position or shape of the sheet during or after the deposition as a prerequisite for the joining process.

During the whole handling process, particle contamination is to be controlled and aggressively avoided. Appropriate cleaning procedures for the equipment involved between process steps are therefore called for. Furthermore, in-process inspection steps of each layer are being considered in order to detect potential sources of failure as early as possible. A number of preliminary tests of the handling process have been made with promising results. A modular automated manufacturing system is currently being set up as a basis for further development of the process chain and detailed investigations.

As well as the development of polymer film handling, along with other applications, the semiconductor industry has been reducing the thickness of semiconductor dies for many years now. As is widely known, the trend for compact and portable electronic devices drives the semiconductor industry towards thinner substrates, which enable the packaging of integrated circuits on a smaller footprint. The gain in flexibility of ultrathin silicon substrates is being increasingly taken advantage of in new applications. Various techniques for manufacturing ultrathin chips for solid-state devices have been researched and solutions published [18,19].

Advances in ultrathin substrate handling

In PV the challenge of transporting ultrathin wafers with considerably larger areas than those of the dies of integrated circuits, while aiming to achieve anticipated PV wafer throughputs, still remains. One particular advance in PV manufacturing is module-level processing [20]. Here, a certain number of pre-processed ultrathin wafers are bonded on a glass superstrate, which allows a more rigid handling object to be transported between processes. The monolithic back-side processing of back-contact cells is performed at the module level and could be performed on thinner wafers. Rationalizing effects are further gained by an integrated cell and module metallization of back-contacted cells. This requires a very sensitive and accurate assembly of the wafers on the common glass substrate.

An automated prototype for the placement of front-side processed ultrathin wafers on a glass substrate

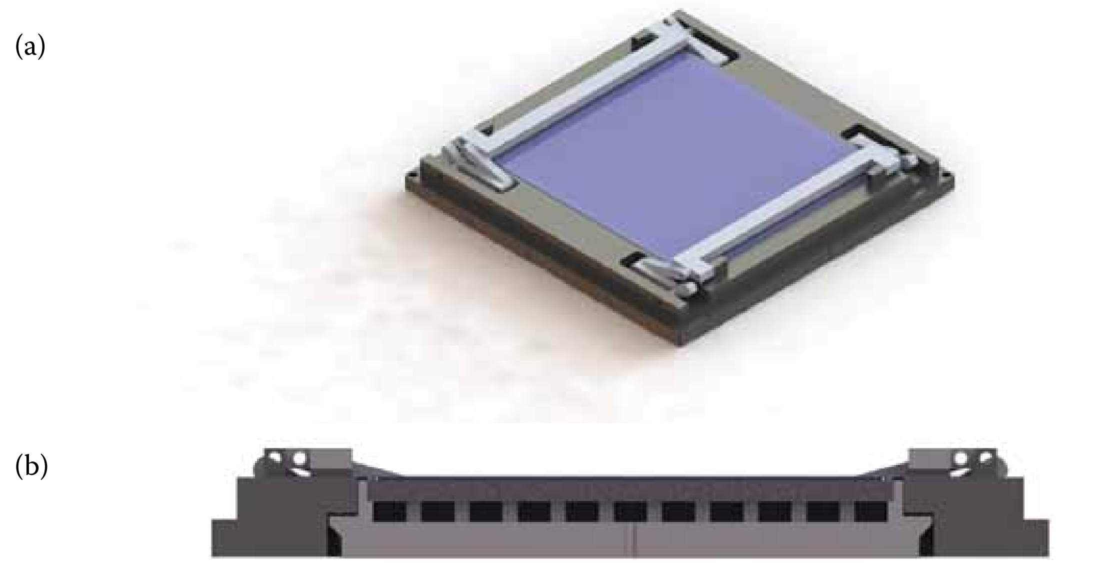

Figure 7. (a) Work-piece carrier solution for 100µm polymer film handling; (b) section view of the work-piece carrier.

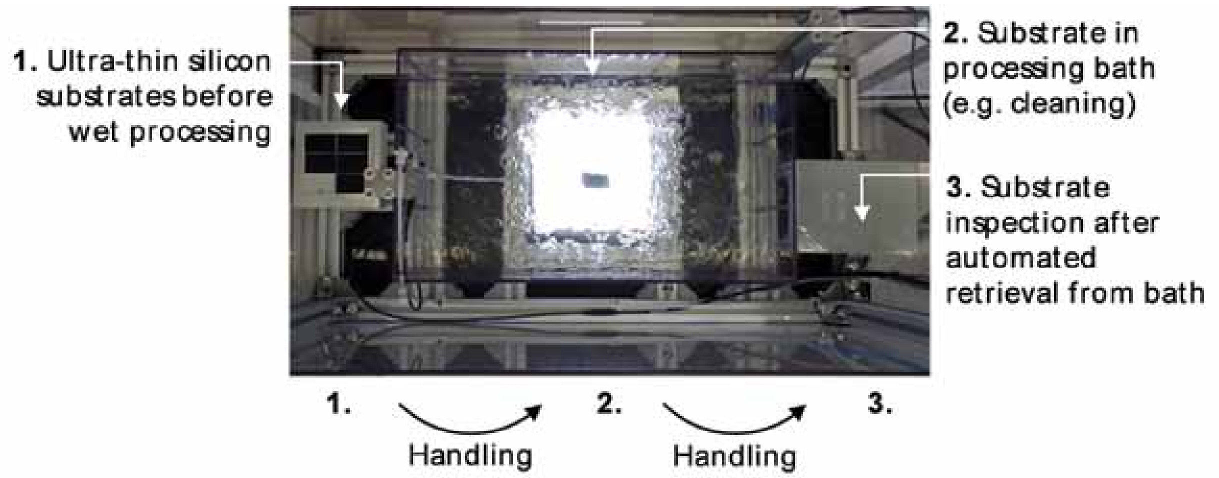

Figure 8. Top view of the test equipment for the automated handling of ultrathin substrates within wet processes. The correlation is determined between the achievable accuracy of substrate detection and a reliable, gentle gripping for retrieving the ultrathin substrate from the cleaning bath.

for the bonding-on-glass step has been developed and is presented in Mayer et al. [21]. The requirements for the accuracy of the ultrathin wafer placement are in the range ±50µm, defined by the module-level processing conditions. Because of the silicone-coated glass, only one attempt for the wafer placement is possible, as adjustments after placement are impracticable. Extensive investigation of the handling characteristics of different grippers has led to a feasible automated process for the bonding-on-glass method. The appropriate gripper settings are essential for thinner wafers, because wafer deformations due to gripping (e.g. strong suction) will cause deviations in the position accuracy during the placing procedure. The in-house team at IPA has demonstrated repeatable results for automated handling and assembly of ultrathin wafers, and the procedures are ready for industrial exploitation and scale-up.

Furthermore, when the manufacture of products from ultrathin wafers is envisaged there will also appear new challenges for processes that are already under full control in a state-of-the-art cell production. For example, the batch processing of ultrathin substrates may limit the current capabilities of carrier solutions, as the unstable substrates will tend to sag in carrier slots. As a consequence, the breakage rate, which has been stringently reduced in PV productions by optimization efforts in the past, will once again become critical.

The primary handling methods for thin substrates will have to be reviewed for their use with ultrathin substrates. Some state-of-the-art solutions may be adaptable, but some uncertainties are obvious. A higher risk of crashes among the substrates because of their vibrations in the carrier slots caused by the carrier movement, or because of the interacting forces in processes such as the dipping in wet benches, may occur. In addition, inline processing will need to address the interaction of substrate edges with lateral guides during roller transportation, as well as the accurate and sensitive substrate hold-down mechanisms during forwarding in wet processes. Critical edge loads have already been minimized in previous automation approaches because of the crucial disadvantages of contact between transporting device and silicon substrate. There is also an increase in equipment component wear as the substrates get thinner and the edges sharper [22].

One advance for ultrathin substrate handling is the gripping-in-liquid method, which consists of ultrathin substrate handling in different liquid environments for cleaning purposes (see Fig. 8). Beyond the point at which a batch or an inline processing capability is stretched to its limits, the gripping-in-liquid process provides an addition to the available capacities and manufacturing skills. Thus, with the implementation of the process feed-through of ultrathin substrates in cleaning solutions or rinsing baths, the gripping-in-liquid method allows flexible interaction within dry and wet environments where other approaches risk partial damage or breakage and therefore process interruptions. The gripping-in-liquid method facilitates the processing of substrates which undergo a geometrical transformation, such as a substrate that is bowed before liquid (e.g. a solution) contact and flat after retrieval from the liquid – or conversely. Such geometric transformations can be caused by intrinsic tensions in ultrathin substrates, by deposited material on ultrathin wafers, or by future surface structuring for light trapping. As a result of an applied advanced process control method and the accessibility of multiple sensor data, the new handling process is adequately prepared for the requirements of the factory of the future.

“The use of smart equipment will optimize interdependencies of processing and automation.”

Conclusion

In general, developers face new challenges for the manufacturing of ultrathin silicon or other versatile substrates for high-volume production. However, modern production methods – such as the implementation of smart equipment for PV – can assist in reducing the obstacles to the accelerated manufacturing of new PV cell concepts. Such smart equipment may be represented in several ways. For example, a control for the wear and tear of drives and the determined placement inaccuracies in the handling of wafers or cells will help to plan maintenance intervals and reduce equipment downtimes. The use of smart equipment will lead to even more transparent production steps and will optimize interdependencies of processing and automation and the corresponding implication for the product’s quality. Smart equipment in production will allow a faster optimization and therefore a faster profitability of processing for the production of the next PV technology developments. But there may be many ways leading to a 'plateau of productivity'.

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