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Development and Optimization of Automated Dry-Wafer Separation

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***Abstract*—**In a state-of-the-art industrial production line of photovoltaic products the handling and automation processes are of particular importance and implication. While processing a fully functional crystalline solar cell an as-cut photovoltaic wafer is subject to numerous repeated handling steps. With respect to stronger requirements in productivity and decreasing rejections due to defects the mechanical stress on the thin wafers has to be reduced to a minimum as the fragility increases by decreasing wafer thicknesses. In relation to the increasing wafer fragility, researches at the Fraunhofer Institutes IPA and CSP showed a negative correlation between multiple handling processes and the wafer integrity. Recent work therefore focused on the analysis and optimization of the dry wafer stack separation process with compressed air. The achievement of a wafer sensitive process capability and a high production throughput rate is the basic motivation in this research.

***Keywords*—**Automation, Photovoltaic Manufacturing, Thin Wafer, Material Handling

I. Introduction

STRICTER technological and economical requirements need improved and enhanced coordination and control of the production processes in the mass manufacturing of crystalline thin photovoltaic wafers [1]. Due to the commonly known reasons the thickness of photovoltaic wafers has decreased in dependence on the solar cell technology and the applied manufacturing method. The production quality and output highly depend on the level and excellence of the applied automation [2]. According to roadmaps of international experts the wafer thicknesses will drop to approx. 120 µm or will become even thinner within the next 10 years [3], which will highly increase the fragility and the sensibility of the wafers. Therefore, a gentle automated handling and transport of thin wafers without damage and contamination in combination with a high process capability are striven for in the mass manufacturing [4].

The Fraunhofer Institute for Manufacturing Engineering and Automation (IPA) has recently built up and expanded a test and demonstration platform for the operations involved in thin wafer handling and automation, [5]. With the platform, the researchers at Fraunhofer IPA investigate the implication on the wafers/cells which are caused by certain handling processes along the entire production line. Previous researches showed up the significance of thin wafer transportation and handling [6, 7]. This issue is especially important for one of the first process steps in a solar cell manufacturing line: the separation of dry photovoltaic 6”-squared wafers from a stack.

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II. Experimental Set-Up

A separation process working with compressed air is used to singularize dry wafers from a stack. This handling step is required for processing crystalline silicon wafers into solar cells. Within the IPA`s test and demonstration platform this separation method is implemented as a combination of a pre-separation module and a pick-and-place portal, (see Fig. 1). For enabling the picking process executed by a Bernoulli or vacuum gripper the adhesive forces between the thin silicon slices on the stack have to be reduced. Therefore the few topmost wafers of the stack in the pre-separation module are separated from each other by air flow supplying lateral nozzles.During test runs a higher breakage rate was observed within the separation process. Therefore the focus of the research is to investigate, analyze and optimize the separation process with the goal of a zero-breakage rate.

Starting with a simple pre-separation module a method for the evaluation of the process`s quality was systematically generated. By using high speed camera shots and distance sensors a characterization of the separation process before, during and after the gripping of the topmost wafer has been elaborated.

Fig. 1 Pre-Separation module prototype

III. Challenges Of The Separation Process

In order to establish a reliable and safe separation process the main challenges are to minimize vibrations with high amplitudes which occur during the pre-separation sequence, as well as to reduce or even to eliminate the lifting effect of successive wafers during a pick-up process caused by a suction force when the topmost wafer is being lifted (see Fig. 2).

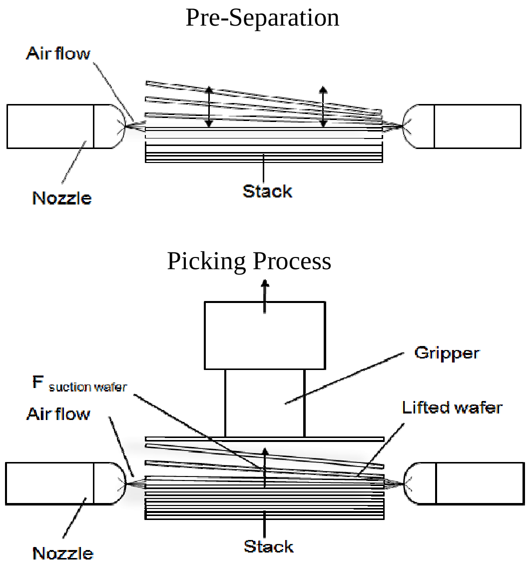

Fig. 2 Schematic sketch of the main challenges of the separation process

Therefore, the analysis was divided into two working packages:

1) A precise and continuous pre-separation with compressed air.
2) A safe and repeatable picking process.

IV. Analysis And Optimization Of The Pre-Separation Process

In the first step, the pre-separation process of the wafers was analyzed and optimized. To achieve the goal of a precise and continuous pre-separation the following method was applied.

A. Determination of suitable settings

Based on the general feasible settings of the pre-separation module (Fig. 1) the most influential control factors have been identified and determined through variation and experienced data. A table with all possible alternatives of the six control factors is depicted in Fig. 3. The six control factors are

1) Amount of nozzles
2) Nozzle position
3) Nozzle slot shape
4) Supplied pressure
5) Nozzle direction
6) Inclination of nozzles

Because of numerous unsuitable settings e.g. high vibrations, asymmetrical separation etc. during pretests the quantity of the feasible pre-separation settings can be reduced by applying a systematic design of experiments.

Control Factor	# Types	Specification				
#Nozzle	4	1	2	3	4	
Nozzle Position						
1 Nozzle	2	1.1	1.2			
2 Nozzles	6	2.1	2.2	2.3	2.4	
		2.5	2.6			
3 Nozzles	10	3.1	3.2	3.3	3.4	3.5
		3.6	3.7	3.8	3.9	3.10
4 Nozzles	12	4.1	4.2	4.2	4.4	
		4.5	4.6	4.7		
		4.8	4.9	4.10	4.11	4.12
Slot	4	|	—	+	×	
Pressure [bar]	3	≤0,7	1,0	≥1,3		
Nozzle direction	3	→	↗	↘		
Distance N-W	3	~0	5	10		

Fig. 3 Table of all possible pre-separation settings

B. Design of Experiments

Requiring more than 16000 tests for applying a full factorial design a screening design was developed. During the pretests four potential suitable quantitative and qualitative factors have been determined. In order to receive a balanced screening plan also four levels for each factor have been determined. Using a factorial screening plan for multi stage factors, called latin squares, a design of experiments with the resulting four factors with four stages (Fig. 4) was created.

Control Factor	Factor Level 1	2	3	4
Nozzle Position	1.1	1.2	4.1	4.5
Slot	|	—	+	×
Pressure [bar]	0,3	0,5	0,7	1,0
Nozzle Direction	0°	-5°	-10°	+5°

Fig. 4 Resulting quantitative and qualitative factors with four levels

C. Execution of Experiments

Following the screening design the experiment was carried out with wafers of 120 µm and 200 µm thicknesses for an analysis of a pre-separation of two different wafer thicknesses.

The vibrations of the topmost wafer during the floating phase were recorded in each corner of the wafer with four distance sensors with a given accuracy of up to 15 µm (see Fig. 5).

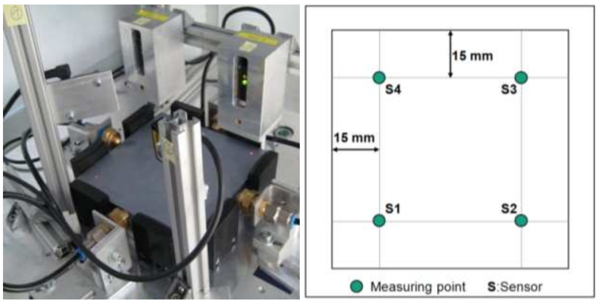

Fig. 5 Left: four sensor test set-up; Right: position of the four measuring points (S1-S4)

To provide a reasonable process capability each topmost wafer has to be separated precisely without high vibrations even after a series of picking processes. Therefore the chosen method was to measure the vibrations of the topmost wafer after ten picking processes. To avoid a systematic falsification the screening design was executed randomized and repeated three times. For further measurements of the separation and picking process only two distance sensors were use due to a limited work space (S1 and S2, as depicted in Fig. 8).

D.Evaluation of the experiments with ANOVA

Based on the recorded measurements of the wafer vibrations the significance of each factor was determined by applying the analysis of variance.

After the determination of the significance of each factor the suitable factor levels were finally determined (see Fig. 6).

Control Factor	Factor Level 1	2	3	4
Nozzle Position	1.1	1.2	4.1	4.5
Slot	|	–	+	×
Pressure [bar]	0,3[1]	0,5[2]	0,7	1,0
Nozzle Direction	0°	-5°	10°	+5°

[1] 120 µm; [2] 200 µm

Fig. 6 Suitable factor settings for the pre-separation

V. Analysis Of The Picking Process

In a second phase after the establishment of a suitable pre-separation the analysis and optimization of the picking process was carried out.First test runs showed a critical lifting of the underlying wafers during the picking of the topmost wafer (see Fig. 7). The uncontrolled behavior of the lifted wafers not only disturbs or minimizes the process control moreover it increases the damage potential and the breakage rate.


Fig. 7 Wafer lifting during picking process

A. Characterization of lifting behavior

The lifting effect of the wafers which is caused by the suction force during the picking of the topmost wafer can be seen in Fig. 8. Two distance sensors measured the altitudes of the wafers surface before, during and after a picking process.

The picking process can be classified in 5 phases: 1) continuous pre-separation; 2) gripper picks topmost wafer; 3) waiting time; 4) vertical transport of topmost wafer and 5) lifting of second topmost wafer.

Phase 5 in Fig. 8 shows the unintended lifting of the second topmost wafer. Due to the suction force the wafer is pulled up beyond the sensor`s measuring range at around 12 mm. Afterwards the wafer drops down between the sidewalls of the module and is pre-separated until the next picking process starts again.

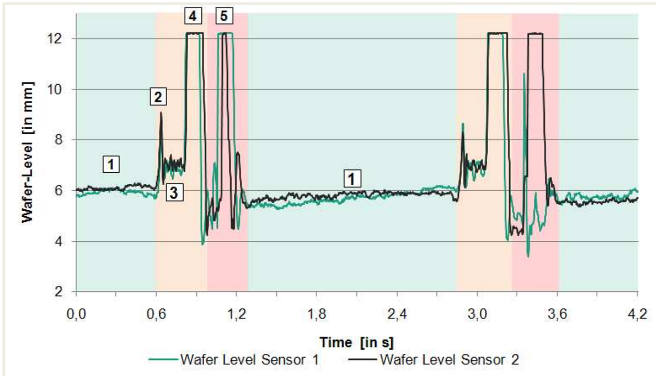

Fig. 8 Wafer altitudes during two separation and picking processes (two sensors on wafer surface)

B. Determination of the „Suction force"

However, for the minimization or even the elimination of the subsequent wafer lifting during and after a picking process the significance of the suction force which is generated by the take off of the topmost wafer and the corresponding influence was analyzed.

First investigations demonstrated an increase in the lifting effect with rising speed and acceleration of the gripper. In order to analyze the influencing factors and for determining the intensity of the suction force a load bending beam was used. Therefore several picking processes were carried out, whilst the second topmost wafer was stiff attached to the load bending beam which measured and recorded the forces acting on the attached wafer.

Investigations about the influence of speed and acceleration in the picking processes were carried out with varying speeds (0,5–3 m/s) and accelerations (5–25 m/s^2). Furthermore, regarding the effect of different wafer thicknesses, the research was carried out with 120 µm and 200 µm wafers.

The measured suction forces are shown in Fig. 9. The force paths with respect to the sequences are similar among the two wafer types. One difference appears in higher amplitudes for the 120 µm wafers.

The suction forces are of high relevance for a safe and reliable picking process. For 200 µm wafers the suction force can result in up to 10 times the weight of one wafer (ca. 11-12 grams). For 120 µm wafers the resulting suction force can reach 20 times the weight of one wafer (5-7 grams).

A significant growth in suction force is registered between the acceleration value of 5 and 10 m/s^2.

Responsible for the intensity of the suction effect therefore is the acceleration whereas the velocity is of less implication.

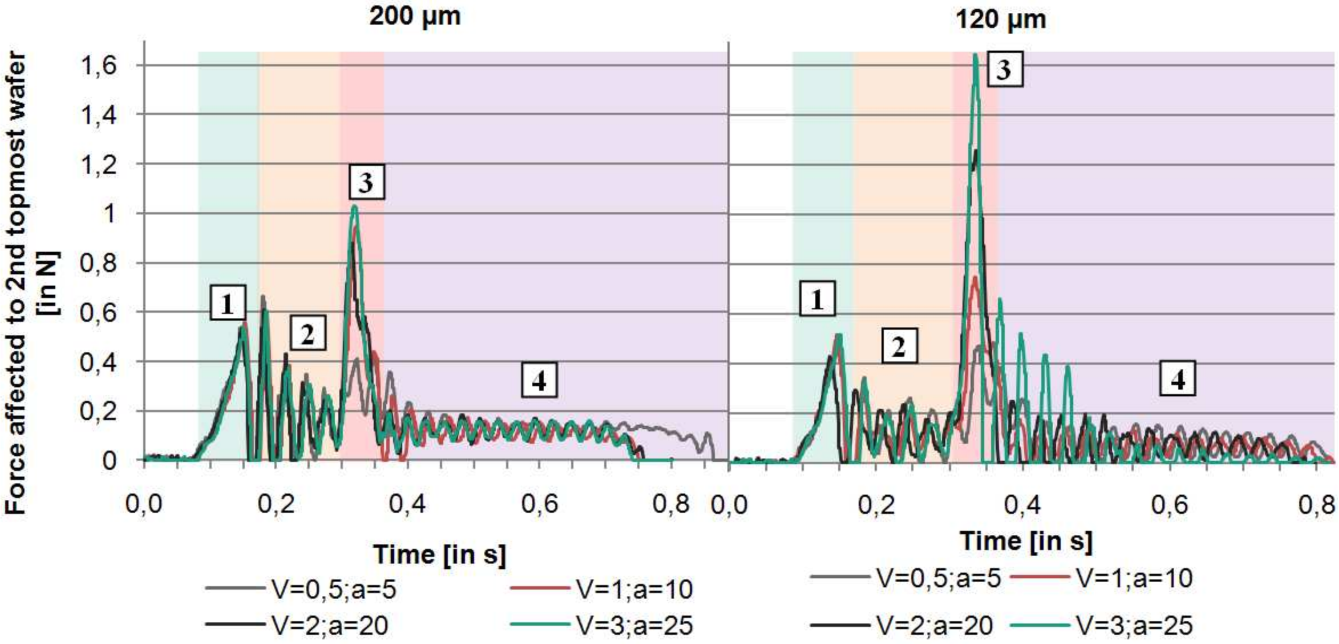

Fig. 9 Suction forces affected to the second topmost wafer during picking processes, depending on the wafer thickness. Phases: 1) gripper picks topmost wafer; 2) waiting time; 3) vertical transport of topmost wafer; 4) continuing suction force after the transport of topmost wafer

Using maximal parameter settings (v = 3 m/s, a = 25 m/s²) for the vertically departing gripper the suction force for 120 µm wafers are about 1,5 times higher than for 200 µm wafers. The increase of the suction force signifies a degradation regarding the behavior of the second topmost wafer. The lighter weight of 120 µm wafers and a higher acceleration results in a smaller inertia of masses comparatively to 200 µm wafers. In addition, on high speed camera videos a high reversible deformation of the wafer edges can be recognized which abruptly accelerate in height and therefore increase the suction force at a certain point.

In a second series of experiments the effect of speed and acceleration was focused. As in Fig. 9 depicted, the suction force increases abruptly at a certain level of velocities. Therefore the picking processes were carried out with constant low acceleration (5 m/s^2) at first and with increasing speeds (1, 2, 3 m/s) and vice versa with constant low speeds (0,5 m/s) and increasing accelerations (5, 10, 25 m/s^2).

The evaluation of the test data showed significant differences in the measured values. With constant low acceleration only a small suction force was measured for all speeds but on the other hand with increasing accelerations and a constant speed a high increase in suction force was recorded.

VI. Optimization Of The Picking Process

After the characterization of the suction force and the determination of the acceleration as main influencing factor a solution for reducing the suction force and enabling a safe and reliable process was developed.

A variety of optimization approaches have been developed, tested and elaborated with the goal to enable a safe picking process with maximal velocity (v_{max} = 3 m/s) and acceleration (a_{max} = 25 m/s^2) parameters values.

A. Evaluation method

The evaluation of the process capability took place on a quantitative and a qualitative basis. For the quantitative evaluation the amount of picking errors during an experiment of 60 cycles was recorded. A picking error was defined as an unwanted event when a wafer remained on the sidewalls of the separation module or if a wafer had to be manipulated manually on the stack again after a finished handling cycle. The qualitative evaluation is based on subjective observations.

The tests were carried out with 200 µm multicrystalline as-cut, 180 µm monocrystalline as-cut and 120 µm multicrystalline textured wafers.

B. Air jet suppression

One optimization approach foresaw an additional force applied from top-down on the wafers to avoid the lifting effect. The counterforce was applied through compressed air which was directed through nozzles in order to push down the lifted wafers. The applied force on the wafers depends on the angle, the gap between wafer and nozzle and the operating pressure of the compressed air. An applied low force didn't succeed in a damping effect vice versa if the applied force was too high. The picking process was not possible because the damping air flow held down the topmost wafer. Suitable settings for an improved separation process have been determined with a distance of 15-20 mm, an angle of 30-40° and pressures between 0,4 and 0,5 bar. The applied forces have been measured with around 0,16 N (see Fig. 10).

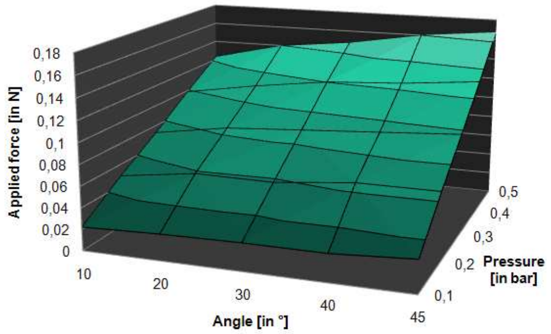

Fig. 10 Applied forces depending on the angle and pressure

Applying these settings an improvement in the separation process was achieved (see Table I). However, errors during the picking process could not be prevented especially not for thin 120 µm wafers. Furthermore, additional forces are applied to the wafers.

C. Stack Lowering

In order to avoid applying an extra force to the wafers the approach of the "stack lowering" prosecutes the idea of eliminating the air cushion between the wafers, during the pre-separation. If the air cushion is eliminated, the formerly separated wafers stick together again. Due to the increased adhesive forces between the wafers, the suction force is not sufficient for lifting any wafers.

For eliminating the air cushion, the level of the whole wafer stack is lowered, until the wafers have left the field of the separation airflow, directly after the gripper took the topmost wafer.Implementing the stack lowering approach the picking errors decreased in numbers (see Table I). Since the air cushion was not eliminated fast enough, still picking errors occurred often. In order to obtain short cycle times another solution had to be developed.

D. Pulsation of the separation airflow

An alternative to the "Stack Lowering" principle of eliminating the air cushion is to interrupt the pre-separation airflow directly after the picking process/before vertical transport and activating it again after the topmost wafer is out of range.

The implementation of the test runs with interrupting the air-flow by a control valve showed a significant improvement compared to the "Stack Lowering" due to the faster elimination of the air cushion which goes along with an increase in adhesive forces (see Table I).

Nevertheless during the separation of the 120 µm wafers still a not acceptable high picking error rate of 10% occurred.

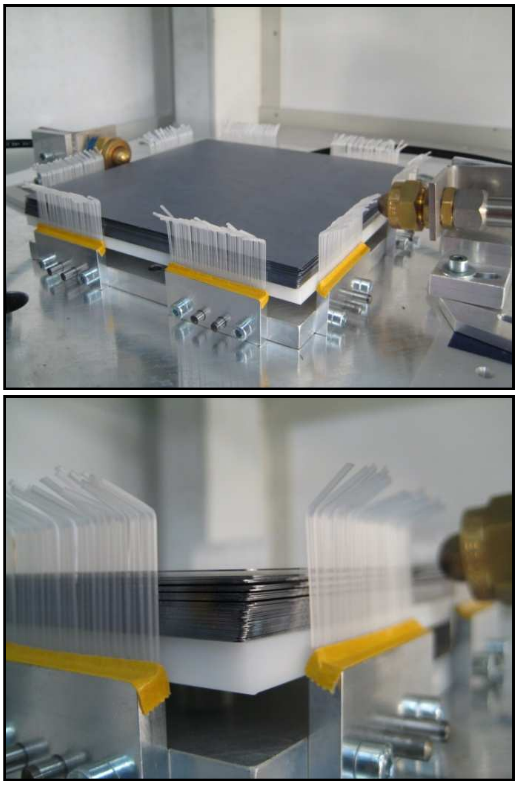

Fig. 11 Flexible bristles with funnel function

E. Closed side wall design

A new approach to improve the separation process was the variation of the sidewalls. The idea was to create a closed cage in order to receive improvements for the pre-separation process and to investigate the results on the picking process. Therefore the wafer stack was surrounded by a closed wall with openings only for the pre-separation nozzles.

The test results showed neither improvements regarding to the saving of air for the pre-separation process nor a better pre-separation height of wafers. Furthermore during the picking process the sidewalls prevent the surrounding air to fill the space under the picked wafer. Due to the absence of sufficient air supply from the outer ambient air a vacuum effect is created and the topmost wafer cannot be picked. The approach of a closed side wall design is therefore not suitable.

F. Free floating wafers with absorption bristles

Within the framework of gentle wafer handling the closed side walls are replaced with bristles manufactured of a flexible plastic material. The bristles enable gentle shock absorption and the lightly and airy design reduces the occurrence of a vacuum effect and minimizes the suction force.

In addition to guarantee a safe and gentle guidance back on the stack, in case a subsequent wafer should be lifted, the top ends of the bristles are shaped to form a funnel function (see

Fig. 11). Test runs verified the theory of an improved behavior of the wafers during the picking process. The wafer lifting effect during picking processes was reduced and in case a wafer was lifted the funnel function enabled a gentle slide back on the stack. To provide a safe and reliable picking process especially for thinner wafers a combination of the bristles with the pulsation of the separation airflow was applied. A visualization of an overall successful separation process is presented in Fig. 12 using the bristle sidewall design in combination with the pulsation. According to Fig. 8 the wafer-level, depending on the separation phase, of the topmost wafer is measured by a distance sensor.

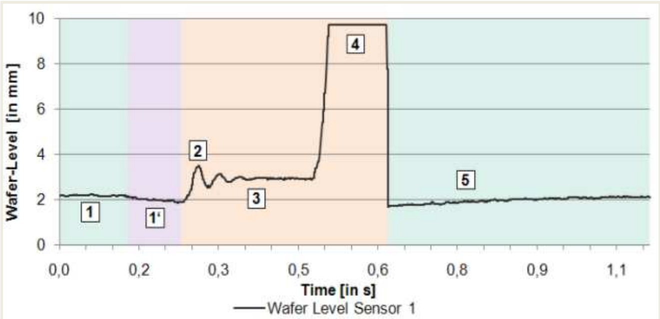

Fig. 12 Wafer behavior during perfect picking process with bristles in combination with pulsation

The process can be divided into 6 sections: in section 1 a precise and continuous pre-separation without significant vibrations of the topmost wafer is measured. In section 1' an anomaly in the constant pre-separation appears which is caused by the approaching gripper who exerts a force to the pre-separated wafers and pushes the wafers a bit down. Section 2 shows the vibrations of the wafer after the gripper has picked the topmost wafer continuous with the lifting onto the waiting position in section 3. In section 4 the gripper vertically departs the picked wafer out of the measuring range and subsequently transports it horizontally. After the picked wafer was moved out of the measuring point the sensor measures again the level of the new topmost wafer, shown in section 5. Without any major vibrations this wafer was pre-separated again and no impact of the previous picking process (suction force) to the other wafers could be detected. To enable a new picking process the stack is moved incrementally upwards by a stepper motor.

G. Data of average picking errors depending on approach

Applying the test and evaluation method described in VI.*A.* for each optimization approach the following data in Table I was noted.

TABLE I
AVERAGE PICKING ERROR (IN %) IN DEPENDANCE ON THE WAFER THICKNESS

	200 µm	180 µm	120 µm
Initial state	15	20	26
Damping (0,4-0,5 bar)	0	6	11
Stack Lowering	1	7	13
Pulsation	0	0	10
Only Bristles	2	7	18
Bristles + Stack Lowering	0	1,6	11
Bristles + Pulsation	0	0	1,6

In Table I and Fig. 13 a continuous improvement regarding the picking errors can be seen. Using 200 and 180 µm wafers an error free process can be reached. The whole experiments were carried out using a gripper with suboptimal and extreme parameters. Using a newer and optimized gripper also the error rate of 1,6 % using 120 µm wafers can be reduced to 0%.

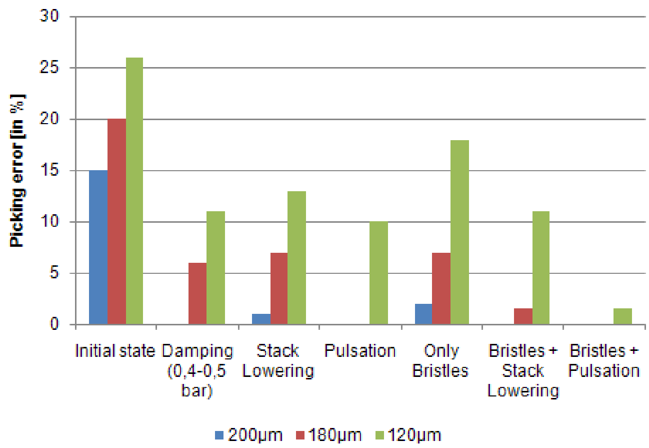

Fig. 13 Average picking error (in %) depending on wafer thickness and optimization approach

VII. CONCLUSION

The paper describes the analysis and optimization of the overall dry wafer separation process. In the first optimization step a suitable pre-separation of the wafers using compressed air was determined applying ANOVA. The optimized pre-separation provides a precise and continuous pre-separation setting for a variety of different wafers with thicknesses of down to 120 µm.In the second step the suction force as main reason for picking and separation errors was identified and characterized. Subsequently optimization approaches for establishing a safe and reliable picking process have been developed. The found solutions of a wafer module with flexible bristles in combination with a pulsation of the pre-separation airflow guarantee a safe, gentle, repeatable and a fast wafer separation process. In the laboratory at the Fraunhofer IPA industrial scaled cycle times of less than one second have been reached for the dry wafer separation process.

REFERENCES

[1] EPIA-European Photovoltaic Industry Association, *PhotoVoltaic-Technology Platform:* "Solar Europe Industry Initiative, Implementation Plan 2010-2012", May 2010.

[2] K. Reddig, “Overview of automation in the photovoltaic industry”. In *Photovoltaics International*, no. 4, pp. 18-29, 2009.
[3] CTM Group (Crystalline Cell Technology and Manufacturing): CTM Group: ”PV Roadmap for Crystalline Silicon”. March, 2010.
[4] P. A.Wang, “Industrial challenges for thin wafer manufacturing” in: *Fourth World Conference on Photovoltaic Energy Conversion (1)*, vol. 1, pp. 1179–1182, 2006.
[5] C. Fischmann et al., “Analysis and Evaluation of Thin-Wafer Handling Methods“ in: *Proceedings of the 24th European Photovoltaic Solar Energy Conference 2009*, pp. 1352 – 1355.
[6] X. F Brun, “Analysis of stresses and breakage of crystalline silicon wafers during handling and transport.” In: *Solar Energy Materials & Solar Cells*, pp. 1238–1247, 2009.
[7] R. Koepge, S. Schoenfelder, T. Giesen, C. Fischmann, A. Verl and J. Bagdahn, “The Influence of Transport Operations on the Wafer Strength and Breakage Rate“, in *Proceedings of the 26th European Photovoltaic Solar Energy Conference 2011,* submitted for publication.

Tim Giesen graduated in 2008 from the University of Applied Sciences Kaiserlautern/Germany in industrial engineering with a focus on manufacturing engineering. Subsequently he joined the Fraunhofer-Institute for Manufacturing Engineering and Automation in Stuttgart/Germany. His field of expertise lies in the area of customized automation solutions for handling and material flow systems in the photovoltaic industry in which he has broad experience through industrial and research projects.He is project manager for the EU-funded project SUGAR with work package leadership for the handling automation of ultra-thin wafers. As project engineer he supervised the technical work within the EU-funded project HighSol which coped with the issues in high volume manufacturing of photovoltaic wafers and cells. Furthermore he led the designing and realization of photovoltaic module prototypes with integrated sun tracking mechanisms in the EU-ASPIS project. Besides he has international experience in the engineering consultancy for handling automation in the photovoltaic industry.