This paper first appeared in the ninth print edition of *Photovoltaics International* journal.

Separation of wet wafers after sawing

Kevin Reddig, Fraunhofer IPA, Stuttgart, Germany

ABSTRACT

"Handle with care" – this world-renowned warning sign is inherently printed on every wafer until it is safely wrapped into a finished module – and for good reason. Despite the declining price of silicon and the improved manufacturing methods, the raw wafer still has a major share in the overall cost of a module. If we assume an average wafer price of €2.70 for a 156mm multicrystalline wafer, the finished cell will cost about €4. Adding in the module manufacturing costs, a cell in a typical module will cost €5. Hence, the wafer accounts for more than 50% of the total manufacturing costs, and as such is key to optimizing the costs in the solar value chain for crystalline photovoltaic products. This paper offers some guidelines on the wet wafer separation process that are intended to aid in minimizing the cost associated with wafer breakage.

Wafer manufacturing is key to optimizing the costs incurred in crystalline photovoltaic product manufacturing. However, before a wafer first sees the light of day, it has to undergo numerous process steps that include mechanical cutting, heating and pressing of the wafer as well as several more stressful operations including wafer handling. So it is not surprising that wafer breakage is still a major concern in the process chain. The main manufacturing steps through which a wafer has to pass are wafer manufacturing (production of the raw wafer), cell manufacturing (the wafer is processed into a photovoltaic cell) and module manufacturing (the cells are interconnected in a larger module).

> "The tricky part is the separation of the sawn ingot into individual wafers."

Compared with the (usually) cleanroom-centric cell manufacturing process, the wafer manufacturing process is very dirty. Wafers are cut out of an ingot using a wire saw, and then an abrasive slurry (mainly based on glycol and silicon carbide) is applied. Before sawing the ingots, one or more such ingots are glued to a plate, the so-called 'beam' (usually made of glass), which in turn is glued to a re-usable dovetail-shaped carrier. This carrier is then clamped into the wire saw. After the wafers are cut out, they are still glued to the beam (see Fig. 2). The tricky part is the separation of the sawn ingot into individual wafers which are then cleaned, characterized and packaged.

Wafer separation at a glance

Though wafers might undergo separation several times during the whole manufacturing process, the only time they are wet and laden with residues is in the manufacturing of the wafers themselves. Dry and clean wafers can be separated by directing pressurized air between them, then gripping the topmost one with a vacuum or Bernoulli gripper. This principle can most definitely not be applied within the wafer manufacturing step because the wafers are wet and laden with remains from the slurry at this stage in the production.

In the past, wafers were separated by hand – an approach that is still used in some manufacturing facilities. The operator collects a number of wafers and carefully removes it from the beam. The wafers are then separated one by one from this package and sorted into a carrier or placed on a conveyor belt for the cleaning process. Because of the size of the average human hand-span, this manual separation was a lot easier with the former 125mm wafers than it is now with the current 156mm wafers. In terms of the throughput and the yield, automating this step is highly preferable, leading to considerable R&D investment and effort on the part of equipment and wafer manufacturers to ensure an automated wafer separation.

Figure 1. Wafers are prone to damage due to their fragile nature.

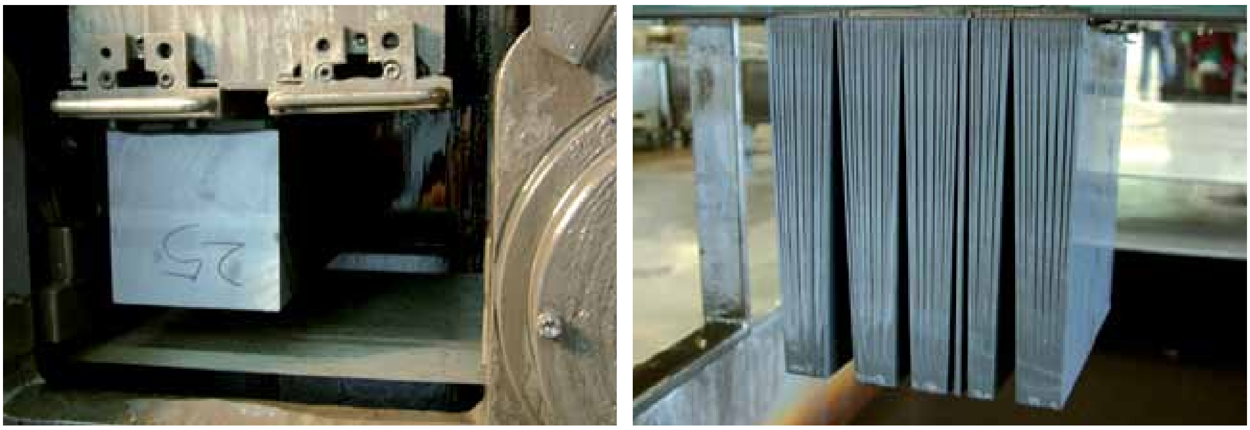

Figure 2. Wafers in a wire saw (left). After sawing, the wafers are clustered into packages (right).

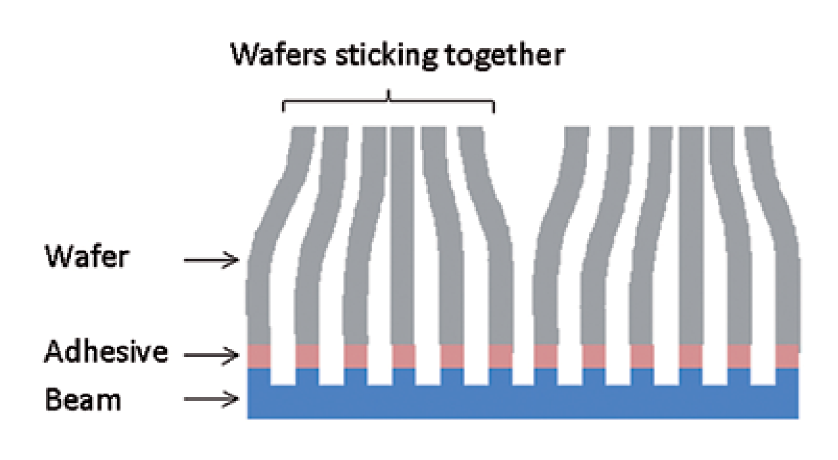

Figure 3. Unproportional schematic sketch of wafers after sawing (bow of wafers is exaggerated).

Due to the fact that companies usually do not wish to divulge too many details of their hard-earned knowledge, scientific and technical publications on wafer separation are quite hard to find. Nevertheless, a good overview on both proposed and implemented solutions can be gained by analyzing existing patents describing automated separation techniques. About 12 relevant patents have been analyzed that give a good picture of possible solutions. One viable option is to separate the wafers directly from the beam while the wafers are still adhered to it. A further option is to unglue the whole sawn ingot and collect the wafers in a special carrier or in packages for further processing steps.

Both approaches have advantages and disadvantages: if the wafers are separated directly from the beam (option 1) they are in a defined position and usually do not need any additional support. Ideally, each wafer stands on a thin bar of glue as the saw also cuts the beam (see Fig. 3). However, in a manufacturing environment some wafers might already be dissolved from the glue, and thus can form an obstacle to the separation. Additionally, the adhesive force of the glue can vary widely, which can require larger mechanical forces to dissolve the wafers.

The other approach (option 2) requires the dissolving of the entire wafer stack from the beam as well as the collection of the wafers for the separation process. The dissolving can be achieved by using warm water or a chemical solvent, depending on the type of glue. As soon as the wafers are collected, they are arranged in a defined and secure manner. This transfer requires an extra handling step in which the wafers are gripped or clamped at the edges. Even though this is an additional hazard to the material integrity, the advantages of this latter approach seem to outweigh the disadvantages as most known solutions offered on the market have chosen this approach. One reason for this decision is that it better suits the typical manufacturing environment scenario.

Typical characteristics of a sawn ingot

The decision as to whether the wafers should be separated directly from the beam or dissolved and collected in a stack is fundamental. Therefore, numerous experiments have been conducted in a manufacturing environment to determine the adhesive force of the adhesive bar which connects the wafer with the beam.

In these experiments, the ingots were processed using a set of different process parameters. After the sawing of these ingots, the wafers are drawn from the ingot by means of experimental equipment that features a vacuum pad. This equipment grips the wafer on the entire surface and records the force that is needed to dissolve the wafer from the beam with a load cell. Several experiments were performed by testing a number of silicon ingots with different manufacturing parameters. These parameters include the adhesive type, the duration of placement in a cleaning solvent and the angle of the vacuum pad. Three different types of two-component epoxy adhesives were used. Ingots were placed in a hygroscopic cleaning solvent that consists of an aliphatic compound, which usually has a disintegrating effect on the epoxy adhesive.

In the experiments, no correlation could be observed between the variegated parameters. Instead, the adhesive forces were seen to vary significantly. In some experiments, all wafers were dissolved from the beam by the cleaning agent, whereas other experiments showed no influence of the cleaning agent on the adhesive forces. The adhesive forces, however, do not only differ within experiments but also from ingot to ingot. A typical graph of such an experiment is depicted in Fig. 4. In this experiment, the wafers were drawn orthogonally from the beam; some wafers were already dissolved (force = 0) while others were still attached tightly to the beam, requiring a force exceeding 100N for separation in some cases.

In order to reduce the high adhesion forces required in this step, a subsequent series of experiments involved tilting the wafers by 10°, after which the wafers were gripped and drawn by the vacuum pad. This has a tremendous effect on the stability of the adhesive bar, reducing those adhering forces not exceeding 40N by an average of 20N. A separation system treating adhered wafers should therefore always grip tilted wafers.

Nevertheless, the tilting of the wafers cannot be achieved without increasing the mechanical stress, especially in the region close to the glue bar, and does not solve the problem of wafers that are already dissolved within the ingot. These wafers cannot be separated easily from their respective neighbours. Moreover, such wafers could shift and lead to breakage because the gripping mechanism would obstruct a continuous and reliable processing. Therefore, all known solutions on the market work with a completely dissolved stack of wafers.

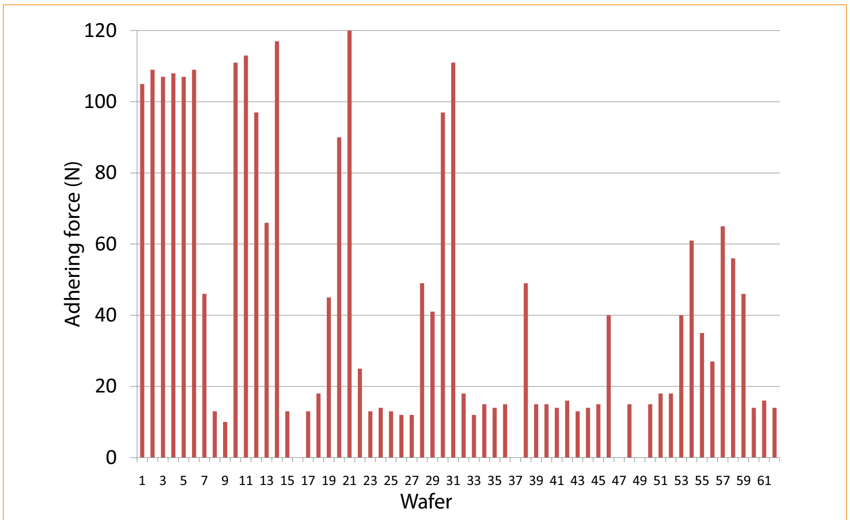

Figure 4. Typical adhesion forces of wafers to the beam.

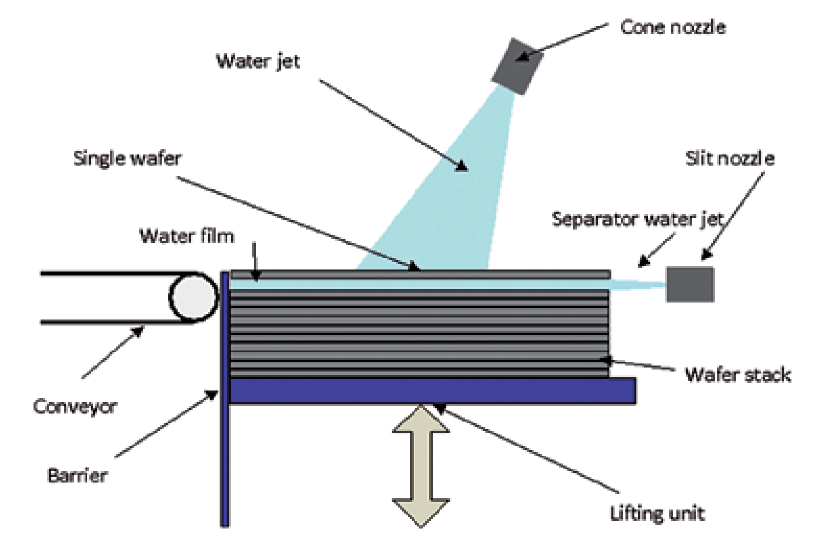

Figure 5. Fluid jet wafer separation principle.

Separation from a stack of wafers

Several approaches to the separation of wafers from a stack are in use or are described in patents. The main difference between the methods is the orientation of the stack. Some solutions clamp the wafers vertically into the stack in order to be able to process all wafers on the beam in one run; other solutions use horizontally stacked wafers. As a consequence, these stacks are limited in height because the tolerable weight on the lowermost wafers is limited. Again, both approaches have their advantages and disadvantages. The clamping mechanism for the vertical presentation of wafers is more complex and requires precautions in order to avoid harming the wafers. The horizontal stacking of wafers allows the use of comparatively simple cassettes but limits the amount of wafers in such a cassette and therefore requires a constant re-loading of the separation unit.

The known separation methods comprise different approaches. A well-known solution from other industries is the placement of a stack of wafers on synchronously powered rolls which separate a wafer by conveying it beneath a separator. Other solutions use grippers or conveyor belts to transport separated wafers from a vertically-aligned stack. In such solutions, water jets are sometimes used to support the separation of the wafers.

Wafer separation with fluid jets

At the Fraunhofer IPA, a method for separating wafers on the basis of fluid jets has been developed and analyzed. With this method, fluid jets are directed to move the separated wafer over a barrier. A stack of wafers is placed on a platform which can be traversed vertically. The wafer at the top of the stack is moved into the fluid jet, which separates it from the rest and moves it over a barrier. A conveyor belt transports the wafers to further processing stages, usually to an inline cleaning tool or an indexer that collects the wafers in a carrier. The principle behind this separation is depicted in Fig. 5.

> "The wafer at the top of the stack is moved into the fluid jet, which separates it from the rest and moves it over a barrier."

The procedure was developed with the intention to minimize the mechanical stress on the wafer. However, the force of the water jets can also reach a level that might harm the wafers. Additionally, the quality of the separation process is dependent on other parameters such as the location and the angle of the water jets. Therefore, an experimental set-up was constructed in which the top wafer is separated but not carried away. Instead, the elevation of the wafer is constantly monitored by a special configuration of four laser distance sensors, which allows the measurement and recording of the influence of the water jets on the elevation, the tilt and the vibration of the wafer. By means of this set-up, several experiments were executed and an optimal range of the parameter values was determined, which was in turn applied and adapted to a prototype. The advantage of this approach is that it provides an opportunity to study the effects of the adjustment of the changing parameters, which is not possible if the wafers are carried away.

Set-up for the experiments

Separation is achieved by using slit nozzles aligned at the rear, opposite to the barrier. About four or five nozzles are evenly spaced along the length of the wafer, tilted at an angle of -25° and +25° to the wafer. The upper nozzle emits a cone-shaped jet and can be tilted to add an additional momentum to the wafer. The main purpose of the upper nozzle is the generation of a force that partially neutralizes the vertical momentum of the wafer, which otherwise might be thrown in an undefined position by the separation effect of the rear nozzles. This also suppresses the vibrations, and without this upper nozzle, the wafer could flap uncontrollably, likely leading to wafer damage.

Nowadays, deionized water (DI-water) is used in manufacturing processes for cleaning or as a medium for the interim storage of wafers, so it makes sense to employ the same medium for the separation process. The water is collected in a basin underneath the separation unit and pumped with a multi-stage rotary pump to the nozzles. The pressure for each nozzle unit can be adjusted to a maximum pressure of 10 bar, whereas the separation process is accomplished with much lower pressure rates.

Distance sensors based on laser LEDs are used for measurement of the wafers' elevation and vibration. The sensors have a theoretical resolution of 2µm, but realistically, about 10µm can be achieved. Without any precautions, the water jets would render the optical distance measurement useless as the water droplets and spray would block the signal path. Furthermore, droplets would accumulate at the sensor and in this way blur the laser beam. Therefore, a special housing was constructed of acryl glass tubes to shield the signal path. In order to prevent the spray from entering the tubes, they are constantly charged with compressed air (see Fig. 6). Four sensors were used to determine both the elevation of the wafer and the roll and pitch angles.

Experimental results

This section presents the principal results of the experiments conducted. Most of the experiments were designed using the ceteris paribus principle. The pressure at one of the nozzle units was varied during one experiment; other parameters included the angle of the rear nozzle unit, the location and the angle of the upper nozzle as well as the usage of nozzles at the side of the wafers.

The first run of experiments investigated the influence of the upper nozzle. The graph in Fig. 7 represents a typical result of such an experiment, showing how the average relative elevation of a wafer changes with the increase in pressure on the upper nozzle. The fluctuation of the wafer elevation (vibration) diminishes as the general elevation of the wafer itself is decreased. The subsequent carry-off of the wafer should ensure a clear separation in order to guarantee a minimum elevation. The reduction of the vibration is necessary to reduce the potential damage of the wafer. Therefore, a good setting for the upper nozzle is around 3 bar. The experiments on the rear nozzle unit concentrated on the angle in relation to the wafer plane and the pressure on the nozzles. The angle is categorized into three ranges as depicted in Fig. 8.

Suboptimal results in terms of the separation quality were achieved by applying a positive angle, although the initial assumption suggested a good separation effect with the water jet detaining the following wafer. A neutral angle showed the same drawback as the width of the water jet expanded and seized the next wafer as well. The best separation result is achieved by a negative angle as the water jet can be adjusted in such a way that only the top wafer is affected and separated from the rest of the stack.

The pressure of the rear nozzles was varied in a range of 1 to 7 bar. Depending on the angle of the rear nozzle unit, a pressure of 3-4 bar was sufficient for a good separation. In all experiments, the vibrations of the wafer increased with rising pressure, a factor that must be closely monitored because of the potential harm to the wafer. Fig. 9 shows a close-up of the resulting vibration. The frequency of the wafer elevation was 10Hz, which fluctuates at a frequency of roughly one second with a peak-to-peak amplitude of about 1mm. Such a scenario is a typical result of application of pressure of more than 4 bar on the rear wafer nozzles.

The presentation of the wafer stack in relation to the separation unit has a large influence on the separation process itself; to prevent lateral dislocation, the wafers are guided at the sides. Alternatively, a cassette can be used with which the wafer stack is inserted into the separation unit. The usage of a cassette proved not only to be advantageous because of a simplified loading, but also served as a method of optimizing the separation procedure. By enclosing the wafer stack, the liquid volume underneath the separated wafer is enlarged and stabilized, thus facilitating the separation and the transport of the wafer.

Figure 6. Compressed air is used to clear the signal path of the distance sensors.

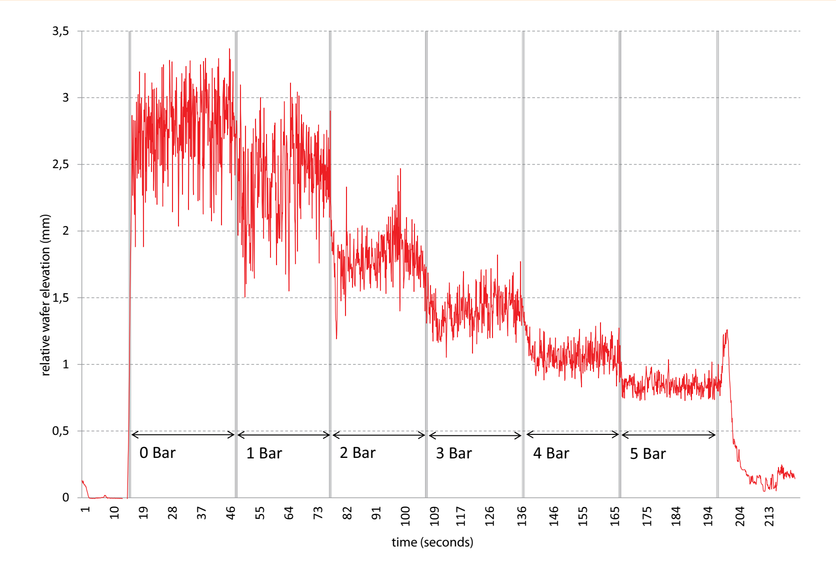

Figure 7. Average elevation of the wafer at increasing upper nozzle pressure.

Implementation of results in a prototype

The results garnered from the experiments were transferred and implemented into the prototype depicted in Fig. 10. Additional adaptations to the previous settings were made to optimize the separation and the transport of the wafer. The pressure on the nozzles can be decreased without impairing the quality of the separation. However, the transport of the wafers still needed additional attention. Directing the water jets of the rear nozzle from slightly underneath the wafer plane reduced the initial velocity required of the wafer to pass the barrier. It is therefore advantageous to somewhat split the responsibility for the separation and the initial transport by introducing a special nozzle that is solely responsible for vertical movement. The nozzle adds some velocity to the wafer after separation and starts the wafer on its way past the barrier. Wafers with thicknesses of 210µm and 180µm were used in these experiments; thinner wafers will also be tested in the future.

Conclusion

The separation of wafers from a stack by means of water jets proved to be a feasible approach. Future work will focus on increasing the speed of the process as well as on further researching the effects of separation on the mechanical stability. During the separation process no immediate wafer breakage could be

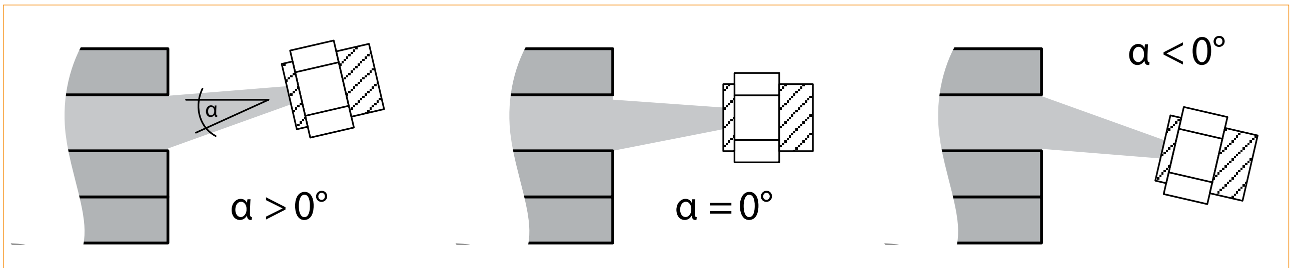

Figure 8. Angle ranges of the rear nozzle unit.

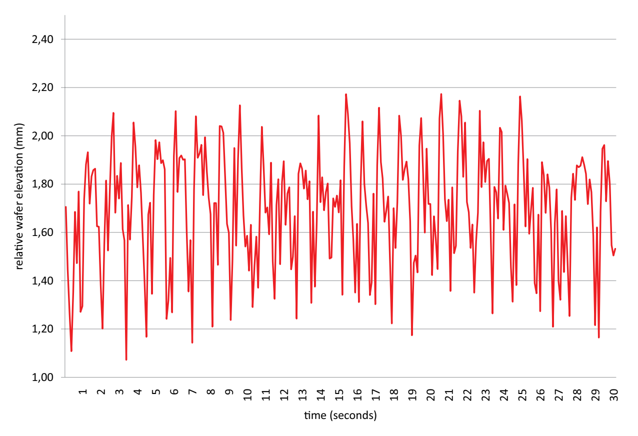

Figure 9. Details of vibration caused by the separating water jets.

Figure 10. Prototype of the separation unit.

observed; however, the reuse of the same wafers in the separation unit increases the danger of wafer breakage. Therefore, wafer breakage can either be caused by manual handling and the insertion of the wafer stack or by micro-cracks in the wafer which can arise during the separation process, a result of vibrations or edge damages, for example. The next step in addressing this issue should be a more detailed characterization of wafers prior to separation by detecting possible micro-cracks and by using a subsequent cycle of repeated separations and qualifications of the same wafers in several runs.

About the Author

Kevin Reddig is a team leader at the Fraunhofer Institute for Manufacturing Engineering and Automation (IPA) which he joined in 2002. He received an M.S. degree in industrial engineering at the University of Karlsruhe (TH), and works in the field of factory planning and automation including equipment automation, material flow solutions and data modelling and processing. Kevin has experience in both hardware and software automation projects in both the photovoltaic and semiconductor industries.

Enquiries

Kevin Reddig
Fraunhofer IPA
Nobelstrasse 12
70569 Stuttgart
Germany
Email: reddig@ipa.fraunhofer.de
Tel: + 49 711 970 1232