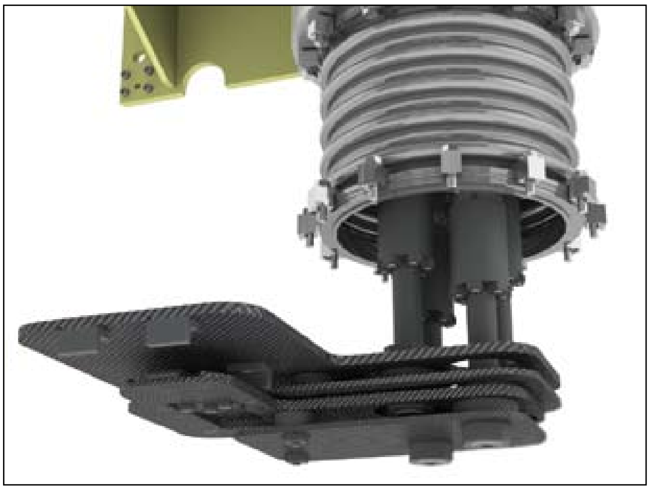
Handling units for

Technobis Mechatronics has developed and manufactured three mechatronic handling units for harsh environments. These units are part of breakthrough technological development operated by RGS Development, a company founded by Dutch energy research centre ECN, Deutsche Solar and Sunergy Investco, to come to a direct silicon wafer casting process (called Ribbon-Growth-on-Substrate (RGS) wafer casting). As part of this process development a prototype/test machine had to be developed and built in co-operation with technology partners, to find solutions to the challenges that had to be overcome in the translation of the RGS process from the batch-type laboratory-scale towards continuous operation. On the downstream side of the process, Technobis Mechatronics contributed its expertise on high-accuracy, high-speed mechatronics solutions that can be applied in harsh environments.

• *Ruud Bons and Alex de Leth* •

In general, silicon wafers are used as starting product for the production of solar modules. The wafer manufacturing today contributes to about 50% of the module production costs. By the RGS casting process the manufacturing costs can be reduced by 50% due to higher silicon material yield and more efficient high-speed production of the wafers. However, to enable this technology, a proven laboratory-scale process had to be translated into a continuously operating production process. To enable this, new solutions for silicon supply towards the casting process and wafer and tool handling after the casting process had to be developed. Technobis Mechatronics developed the handling units that are used to take the cast wafers out of the process environment, and to exchange worn or damaged cassettes on which the wafers are cast. The unit responsible for collecting the wafers is called the Wafer Outfeed (WO), and the units that exchange the cassettes are called the Cassette Infeed & Cassette Outfeed (CICO); see Figure 1.



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harsh environments

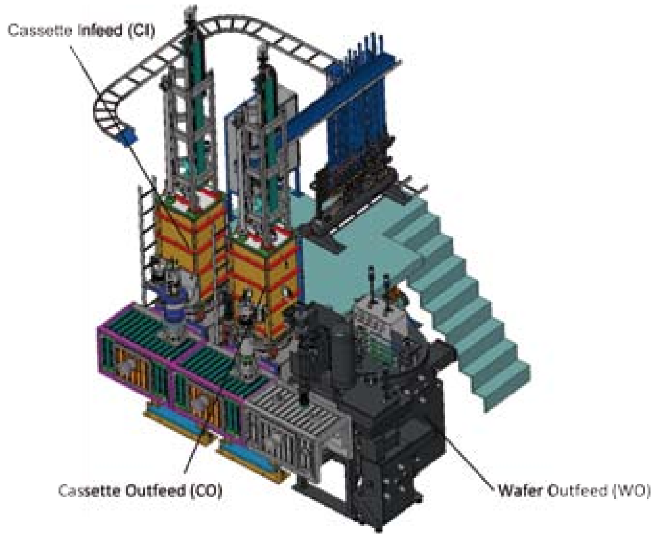


Figure 1. Three handling units attached to the RGS production line.

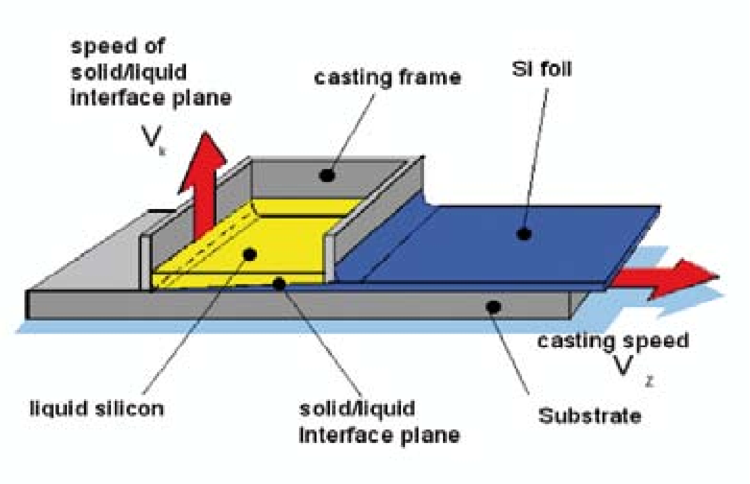


Figure 2. The Ribbon-Growth-on-Substrate (RGS) process.

RGS process

The casting of RGS wafers is a continuous process; see Figure 2. Silicon is melted in a casting frame. As bottom of the casting frame a relatively cold substrate band is used that extracts the crystallisation heat from the melt. During the pass of the substrate underneath the casting frame, the silicon wafer (Si foil) is grown. After the casting process, the wafer can be removed from the substrate and the substrates are re-used in the process; see Figure 3.

Challenges

Due to the special properties of silicon (melt temperature at about 1,410 °C, sensible to oxygen and metal contaminations), the wafers are cast in a vacuum/argon environment at temperatures far above 1,000 °C, which immediately states the challenges of this project. All three handling units are partially exposed to temperatures of around 1,000 °C, and have to operate in a vacuum environment without contaminating the process by e.g. metal evaporation. The handled wafers and substrates will have to be brought to an atmospheric environment without compromising the vacuum/argon environment by loadlocking units. Allowing oxygen to enter the process chamber, would result in the contamination of the silicon wafers and the oxidation of constructive elements (graphite burning).

Requirements

The requirements for the handling units can be divided in functional and environmental requirements. Functional requirements have reference to the handling of the products, such as picking up wafers or substrates without damaging the products, the sequence of functions which will have to be performed by the handling units, and the interface with the transport unit which moves the substrates in the vacuum furnace to create an "endless" flow of substrates to cast on.

Figure 3. RGS wafers (156 mm x 156 mm), substrate side on the left, and free crystallising top surface on the right.

The main environmental challenges for the handling systems are:

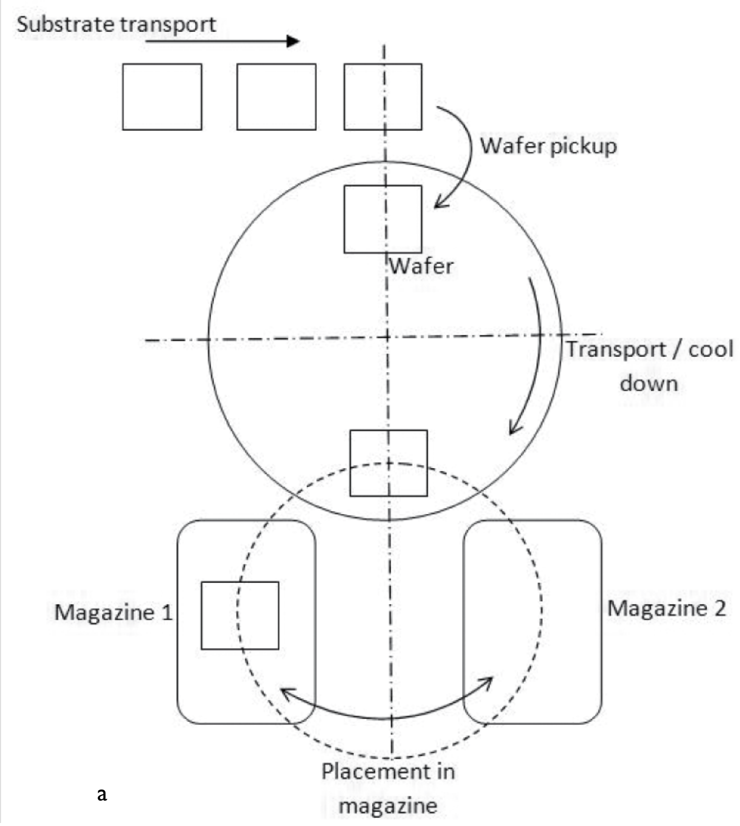
- The systems will have to be able to operate under vacuum conditions as well as ambient conditions while meeting the requirements for handling accuracy.
- The systems will have to operate in a high-temperature (> 1,000 °C) environment.
- The systems will have to handle products which have temperatures of more than 1,000 °C.
- The systems may not contaminate the shielded environment (metal outgassing, leakage, oxidation).
- The systems may not contaminate the handled silicon wafers and substrates (contact contamination).

Design and implementation

Wafer Outfeed

The design of the Wafer Outfeed consists of a large vacuum housing in which the functions pick-up, transport/cooling, inspection and placement in storage are carried out; see Figure 4. The Wafer Outfeed vacuum housing is connected to the vacuum furnace, which contains the transport for substrates.

After the wafer is taken out of the transport line, it is rapidly cooled down to almost room temperature. At that point the wafer is picked up by a second handler, which places it in one of the storage bins. When one storage bin is full, it is closed with a custom-made loadlock valve. After pressurising the storage bin, an operator can take out the wafers. Meanwhile the handling unit fills the other storage bin, enabling the Wafer Outfeed to have a continuous work cycle. When an operator has emptied the storage bin, all oxygen needs to be removed, before opening the loadlock valve. This is done by evacuating the storage bin to a pressure below 0.1 mbar, and filling it with argon in a



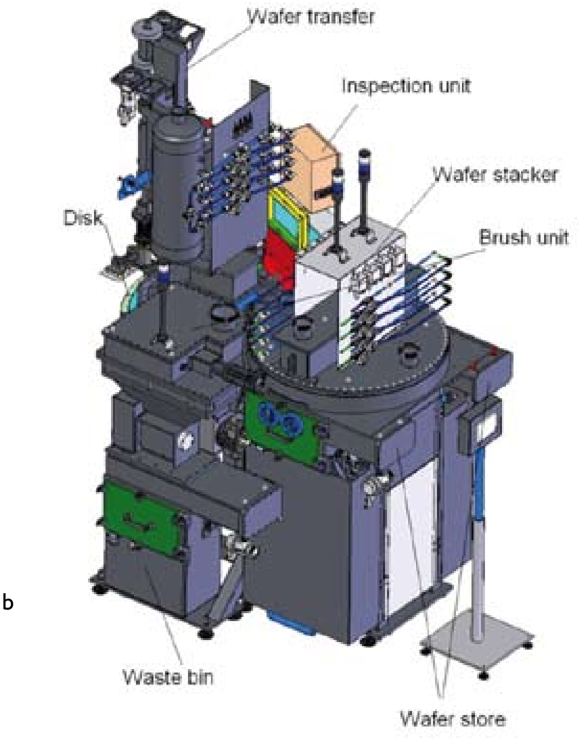


Figure 4. Wafer Outfeed (WO).
(a) Schematic of the process.
(b) Design.

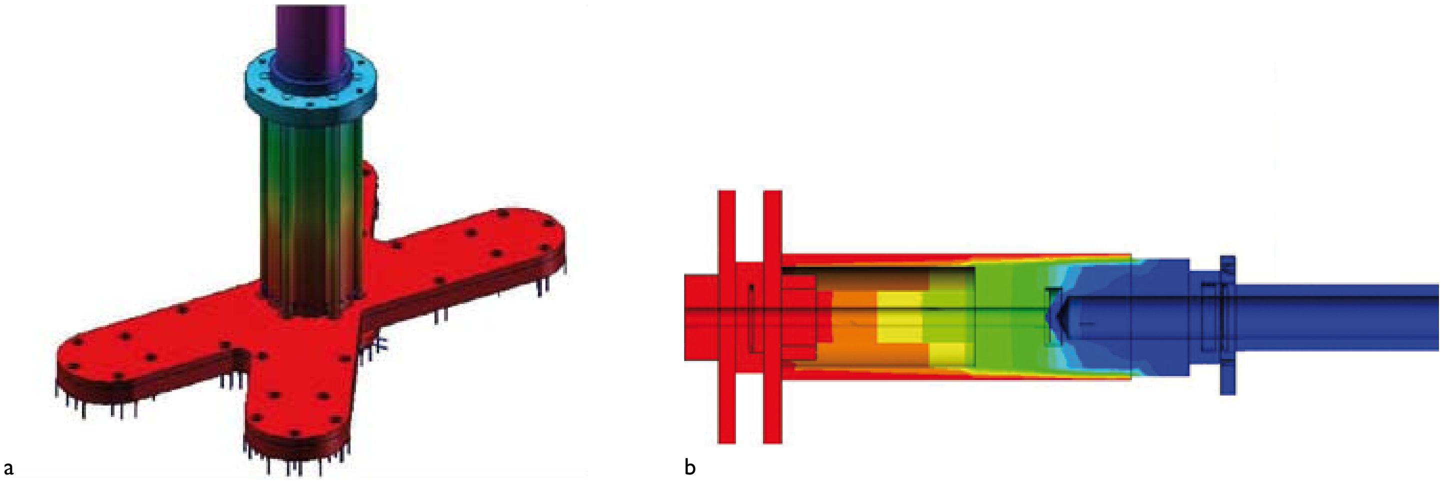


Figure 5. Examples of finite-element design calculations to examine the temperature of the materials in the wafer pick-up; the range is from room temperature (blue/purple) to 1,000 °C (red). The components studied are introduced below.
(a) Carrier of vacuum chucks with central rotation axis.
(b) The pusher unit.

well-controlled way to ensure a low oxygen level in the process environment.

Harsh environments and WO

One of the critical functions of the Wafer Outfeed is the pick-up of wafers from the transport at high temperatures with high yield. High wafer breakages would be critical for machine uptime and must be avoided. The main challenges were:

1. Wafers that are picked up can have a temperature of more than 1,000 °C, the pick-up construction has to be able to withstand this.
2. Wafers can only be accessed from the top for a pick-up.
3. As a result of casting process disturbances, wafers are not always completely flat when they are picked up.
4. The pick-up forces may not break the wafer.
5. The materials used for the pick-up must not contaminate the wafer.

In order to meet the requirements, a pick-up unit was designed using high-temperature ceramics such as graphite and reinforced carbon. Several thermal analyses have been carried out to ensure that all materials used remain below a process design temperature in order to avoid the contamination of the product; see Figure 5.

Vacuum chuck

To be able to pick up the wafers at the top surface, a special vacuum chuck was designed; see Figure 6. In a test set-up the different chuck designs were built and tested to optimise the design regarding sufficient force for reliable picking without wafer breakage. During these tests, the challenge was to find high-temperature ceramics with sufficient lifetime to allow long-time operation of the chuck under hot conditions and to find a shape-adapting high-temperature material to compensate for the non-flatness of the produced wafer.

The pick-up unit has two pairs of vacuum chucks. While one pair picks up the wafers from the transport line, the other pair lays down the wafers on the cooling disk. After that, the unit lifts up, rotates 180° and moves down, and the cycle repeats itself. The movements of the unit are powered by two servo actuators connected to a special spindle unit that can move in a linear, rotational and spiral-shaped way.

Each vacuum chuck can be individually pressurised and depressurised. The central axle was designed to allow the individual pressure and vacuum supply to be combined

Figure 6. One of the metal prototypes of the vacuum chucks used in the test system.

with the water cooling that is needed for temperature control. To allow a rotational movement, the axle is sealed with a ferrofluidic rotational seal.

When the wafers are lowered on the cooling disk, they enter a unit that allows rapid wafer cooling down by a combination of gas treatment, vacuum sucking and individual water cooling. Due to these measures the wafer can undergo a large temperature drop in a short period of time. After that treatment, the wafer is “cold” enough for further handling.

Cassette Infeed & Cassette Outfeed

The Cassette Infeed (CI) and Cassette Outfeed (CO) are two almost identical units, both responsible for the exchange of worn or damaged cassettes with clean new ones; see Figure 7. The wafers are cast on graphite-based cassettes. Continuous casting on these cassettes results in wear, pollution and sometimes damaging of the cassettes. For this purpose, units had to be designed that can replace cassettes under hot operational conditions in the machine. When the CO takes a cassette out of the process line, the CI fills the gap with a new cassette at process temperature. Due to the continuous casting principle, no gaps are allowed between cassettes at the casting process. The bottom part of the units consists of a cassette storage unit, which in the CI case is supplied with an additional heating unit. The upper part is a loadlock compartment divided by a large gate valve that allows the exchange of cassettes via a loadlock procedure. A pusher or puller unit and a Cassette Transfer Module (CTM) were built to transport the cassette from the storage to the track and vice versa. The loadlocking procedure and all materials in the units were designed in a way that the casting process will not be contaminated by material evaporation or leakage to the oxygen-containing atmosphere.

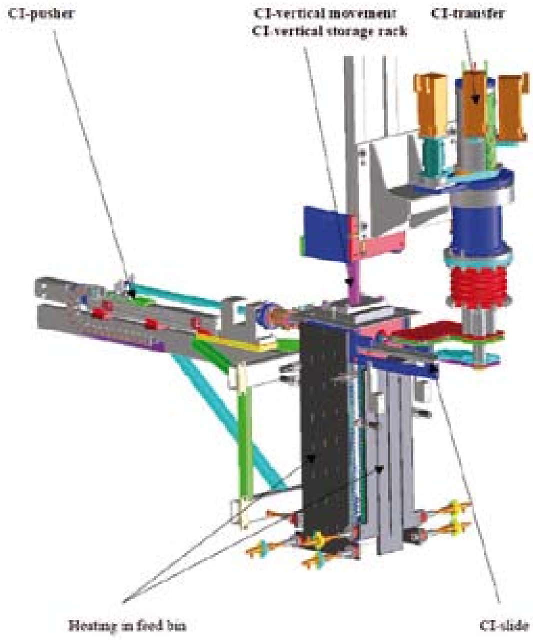


Figure 7. Model of the cassette handling system of the Cassette Infeed (CI) unit.

Cassette Transfer Module

The CI is equipped with a pusher unit that pushes new cassettes from the cassette rack to the CTM pick-up position. A reversed action is required for the CO; hence it is equipped with a puller unit. The CTM does the actual exchange of cassettes. The CTM of the CO takes the cassettes out of the process line, and the CTM of the CI places new cassettes in the process line. Since both units need to be perfectly synchronised, the unit movements are driven by servo motors, which results in a ten-axle motion control system.

Due to the harsh environment with respect to temperature and material choices, as well as due to the rapid but well-controlled movement, the CTM design was very challenging; see Figure 8. The CTM consists of two “jaws” between which the handled cassettes are clamped. The jaws need to be able to individually make a vertical movement in order to clamp and release a cassette. Also the jaws need to be able to move simultaneously in a vertical direction, as well as a horizontal rotation. The vacuum/argon environment and the extreme temperatures demanded that all actuators for the various movements were placed outside the process chamber. A multi-core-axle solution was designed in which each jaw is vertically moved with two axles. The four axles are combined in a single rotating axle. Each axle is individually sealed to prevent contamination of the vacuum/argon environment. A combination of bellows and special elastomer seal is used. The combination of bellow and elastomer seal allows linear and rotational movement, while maintaining a perfect seal on the metal axles.

Figure 8. The Cassette Transfer Module (CTM).

The transition between the metal axles and the high-temperature graphite parts was designed by using a combination of radiation shields and water cooling, in order to meet the given maximum process design temperature for the metal parts. This statement has been confirmed by thorough finite-element method (FEM) analysis. For the hot section of the CTM that is inside the process chamber, graphite or carbon fiber reinforced carbon (CFC) components were used.
The CTM operates at a positional accuracy better than 0.1 mm at gripper point, taking all servo actuators, thermal expansion and deformation of the bins into account.

Cassette pick-up

Due to the process environment and the rapid movement, the cassettes can not be reliably held in place using friction between the parts only. Therefore, a high-accuracy positioning pin system between the cassette and the handler was designed; see Figure 9. In order to overcome an overdefined positional situation when the cassettes are taken over from the track by the CTM, flexible graphite components were constructed to allow a transition phase using a flexible spring element. This spring allows a gentle first contact of the gripper positioning pins with the cassette when lifting it from the carrier positioning pins. The chamfer on top of all the positioning pins allows this transition phase without overdefining the construction. A double-leafspring construction was designed, consisting entirely of CFC.

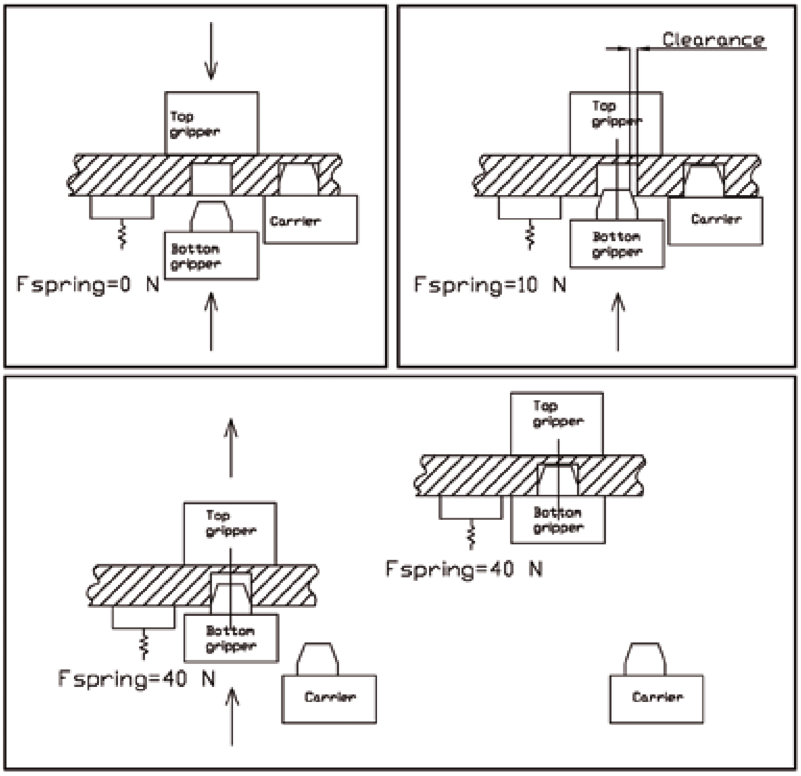


Figure 9. Flexible pick-up without overdefining the cassette position.

Conclusions

The design principles used in the handling units for the RGS silicon wafer casting machine can also be used in other technological fields where high-accuracy, high-speed mechatronics is required under vacuum conditions combined with extreme temperatures and strict requirements for materials to meet process contamination limits. Examples of these applications can be vacuum brazing ovens, nuclear fusion reactors, and space applications.

For the RGS machine, the design principles required the use of special high-temperature ceramic materials, such as graphite and CFC. Using these ceramics with their special characteristics in high-temperature, high-accuracy handling of fragile products at high speed was a challenging engineering task. By applying finite-element thermal modeling, water or fluid cooling solutions in combination with construction elements such as radiation shields and thermal isolation were found. These solutions guarantee that all materials used are operated below the maximum tolerable process temperatures.

Leakage rates, process environment, accuracy, materials and handling speed requirements formed the challenges to develop a unique mechatronic solution that is an important component in enabling the cost reduction in silicon wafer production for solar cells by the RGS process.