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(54) **Wire saw control system and wire saw**

(57) A wire saw control system (1) for operating a wire saw (100) is provided. The wire saw is adapted for cutting a wafer (304, 304, 306, 308) by moving the wire (230) relatively to the wafer with a selectable wire speed. The wire saw control system includes a camera (20) for inspecting the wire, and a camera control unit (25) for operating the camera in dependence of the wire speed. Furthermore, a wire saw including the wire saw control system is provided, and a method for inspecting a wire of a wire saw. The method includes moving the wire with a variable wire speed; and inspecting the wire in dependence of the wire speed, thereby obtaining an inspection result.

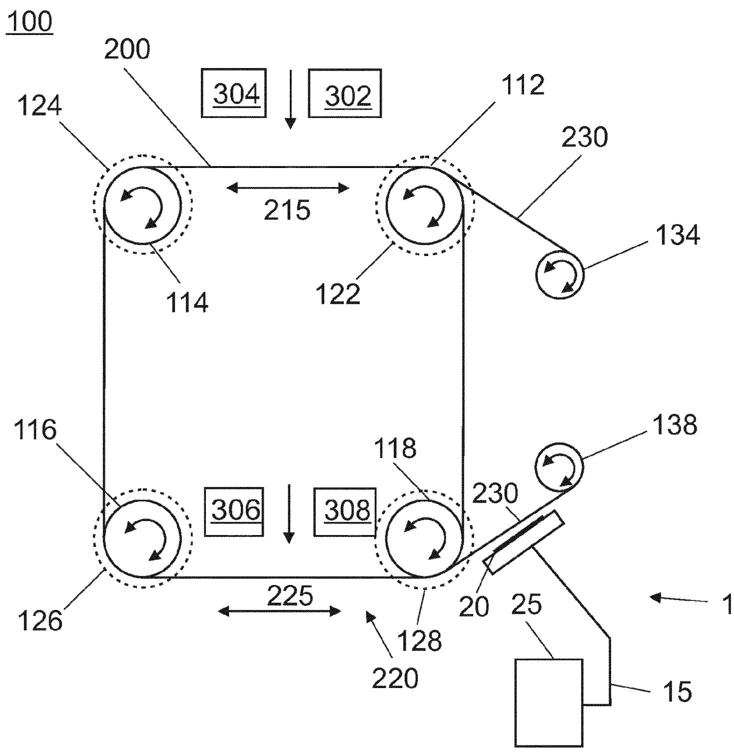


Fig. 5

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## Description

### FIELD OF THE INVENTION

**[0001]** Embodiments of the present invention relate to a wire saw control system, in particular for the inspection of a wire of a wire saw, a wire saw, a method for inspecting a wire of a wire saw, and a method for operating a wire saw. Existing wire saws may be retrofitted with the wire saw control system according to the present invention. More particularly, the invention relates to a wire saw control system for detecting defects, wear or breakage of a wire of a wire saw. The present invention particularly relates to multi-wire saws. Wire saws of the present invention are particularly adapted for cutting or sawing hard materials such as blocks of silicon or quartz, e.g., for cutting silicon wafers, for a squarer, for a cropper or the like.

### BACKGROUND OF THE INVENTION

**[0002]** Wire saws are used for cutting blocks or bricks, thin slices, e.g., semiconductor wafers, from a piece of hard material such as silicon. In such devices, a wire is fed from a spool and is both guided and tensioned by wire guide cylinders. The wire that is used for sawing is generally provided with an abrasive material. As one option, the abrasive material can be provided as slurry. This may be done shortly before the wire touches the material to be cut. Thereby, the abrasive is carried to the cutting position by the wire used for cutting the material. As another option, the abrasive can be provided on the wire with a coating, e.g. as a diamond wire. For example, diamond particles can be provided on a metal wire with a coating, wherein the diamond particles are imbedded in the coating of the wire. Thereby, the abrasive is firmly connected with the wire.

**[0003]** The wire is guided and/or maintained tensioned by wire guides. These wire guides are generally covered with a layer of synthetic resin and are scored with grooves having very precise geometry and size. The wire is wound around the wire guides and forms a web or wire web. During the sawing process, the wire is moved with considerable speed. The web generates a force opposite to the advance of a support beam or a support holding the piece to be sawed. During sawing, the piece to be sawed is moved through the wire web wherein the speed of this movement determines the cutting speed and/or the effective cutting area that can be sawed within a given amount of time.

**[0004]** Generally, there is a tendency to use thinner wires in order to reduce the thickness of the cut and, thereby, to decrease the material wasted. There is also a desire to use diamond wires. These thinner wires and diamond wires are generally more susceptible to damage and under high strain the wires may break more easily. Further, there is a desire to increase the cutting speed for improving the throughput of wire saws. The maximum speed for moving the piece through the web, and also the maximum effective cutting area within a given amount of time is limited by several factors including wire speed, hardness of the material to be sawed, disturbing influences, desired precision, and the like. When the speed is increased, the strain on the wire is generally increased as well. Hence, the above-mentioned issues of avoiding damage, undue wear or breakage of the wire are even more critical at higher sawing speeds.

**[0005]** The advantages of diamond wire, such as a higher achievable sawing speed, can be accompanied by aspects such as a lower resistance to breaking and a higher price per length. When employing diamond wire, measures can be taken to assure that the higher tendency to breaking does not lead to loss in production due to downtimes.

**[0006]** If the wire breaks during the sawing process, it is of utter importance to detect the breaking as soon as possible after it has occurred and to stop the wire movement immediately. At the same time, it is desirable to detect if the wire develops an undue wear or a tendency to break at one or more positions along its length during the sawing process. In the worst case, if a break occurs, unwanted consequences may arise. The loose ends of the wire may move around in the machine in an uncontrollable manner, which might harm the wire guide system or other parts of the machine. Further, if the wire breaks and moves on, it will be torn out of the object to be sawed.

**[0007]** Furthermore, it is desired to optimize the usage of the wire by considering the following trade-off. If the wire is spooled up at the spool for used wire when the wire would still be good enough to efficiently and safely saw further objects, such as a wafer, the wire is non-optimally used resulting in financial damage. If, on the other hand, the wire is continued to be used although it is not fit to further sawing processes any more, it may break or cause unsatisfactory sawing results. Hence, also this option is economically not acceptable.

### SUMMARY

**[0008]** In view of the above, a wire saw control system for operating a wire saw is provided. The wire saw is adapted for cutting a wafer by moving the wire relatively to the wafer with a selectable wire speed. The wire saw control system includes a camera for inspecting the wire, and a camera control unit for operating the camera in dependence of the wire speed.

**[0009]** According to one aspect, a wire saw including the wire saw control system as described herein is provided. In particular, the wire saw may be a multi-wire saw.

**[0010]** According to a yet further aspect, an existing wire saw may be retrofitted with the wire saw control system as described herein. A method for retrofitting a wire saw is disclosed including providing a wire saw with the wire saw control system as described herein.

**[0011]** According to a yet further aspect, a method for inspecting a wire of a wire saw is provided. The wire saw is adapted for cutting a wafer by a relative movement of the wire and the wafer. The method includes moving the wire with a variable wire speed; and inspecting the wire in dependence of the wire speed, thereby obtaining an inspection result.

**[0012]** According to a yet further aspect, a method for operating a wire saw is provided. The method for operating a wire saw includes the method for inspecting a wire as described herein.

**[0013]** Further advantages, features, aspects and details are apparent from the dependent claims, the description and the drawings.

**[0014]** Embodiments are also directed at apparatuses for carrying out the disclosed methods and include apparatus parts for performing each described method step. These method steps may be performed by way of hardware components, a computer programmed by appropriate software, by any combination of the two or in any other manner. Furthermore, embodiments according to the invention are also directed at methods by which the described apparatus operates. It includes method steps for carrying out every function of the apparatus.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0015]** So that the manner in which the above recited features of the present invention can be understood in detail, a more particular description of the invention, briefly summarized above, may be had by reference to embodiments. The accompanying drawings relate to embodiments of the invention and are described in the following:

**[0016]** Fig. 1 shows a schematic perspective side view of a wire saw control system and a wire saw according to embodiments described herein.

**[0017]** Fig. 2 shows a schematic perspective top view of a wire saw control system and a wire saw according to embodiment described herein.

**[0018]** Fig. 3 shows a schematic perspective front side view of an excerpt of a wire saw control system and a wire saw according to embodiments described herein.

**[0019]** Fig. 4 shows a schematic perspective front side view of a wire saw control system and a wire saw according to embodiments described herein.

**[0020]** Fig. 5 shows a schematic perspective view of a wire saw control system and a wire saw according to embodiments described herein.

**[0021]** Fig. 6 shows a schematic perspective view of an embodiment for the inspection of a wire of a wire saw.

## DETAILED DESCRIPTION OF THE INVENTION

**[0022]** Reference will now be made in detail to the various embodiments of the invention, one or more examples of which are illustrated in the figures. Within the following description of the drawings, the same reference numbers refer to same components. Generally, only the differences with respect to individual embodiments are described. Each example is provided by way of explanation of the invention and is not meant as a limitation of the invention. Further, features illustrated or described as part of one embodiment can be used on or in conjunction with other embodiments to yield yet a further embodiment. It is intended that the description includes such modifications and variations.

**[0023]** Furthermore, in the following description, a "wire saw control system", or simply "control system", may be understood as a system controlling some or all functions of a wire saw. Generally, a wire saw as understood herein may be a cropper, a squarer, or a wafer cutting wire saw. Typically, the control system is connected to sensors in order to monitor parameters of the machine operation and the sawing process. The wire saw control system includes a camera and a camera control unit. The camera control unit is adapted for controlling the camera, for instance, by triggering when one or more pictures are taken by the camera. The camera or the camera control unit is typically adapted for performing an image recognition algorithm for evaluating the imaged pictures. The wire saw control system may also be connected to actuators and devices to steer the electric motors which move the wire. Generally, the wire saw control system may include devices for interaction with an individual in order to receive commands and to report the status of the sawing process. The control unit as described herein may also be connected to a computer network to be controlled directly or remotely by an individual or an automated system such as a computer.

**[0024]** According to embodiments described herein, the methods of operating a wire saw can be conducted by means of computer programs, software, computer software products and the interrelated controllers, which can typically have a CPU, a memory, a user interface, and input and output means being in communication with the corresponding components of the wire saw. These components can be one or more of the components: motors, wire break detection units, wire tracking devices, and the like, which will be described in more detail below.

**[0025]** Typically, the wire saw includes a wire guide for transporting and guiding the wire in a wire moving direction. The wire saw control system may provide control of the wire tension. The wire provided forms a wire web in the cutting area of the wire saw. Thereby, the term "wire web" normally relates to the web formed by the wire encircling repeatedly the wire guiding cylinders. It should be understood that a wire web may contain more than one working area which is defined as an area in which a sawing process is performed. Thus, according to some embodiments described herein, a wire web can have multiple working areas that are formed by a wire.

**[0026]** For modern wire saws like croppers, squarers, or wire saws, there is the desire to cut the hard material such as semiconductor material, for example, silicon, quartz, or the like at high speed. The maximum wire speed, that is the maximum speed of the wire moving through the wire saw can be, for example, 10 m/s or even higher. Typically, the maximum wire speed can be in a range of 10 to 15 m/s. However, higher wire speeds, such as of 20 m/s, 25 m/s or 30 m/s can also be desirable. In embodiments, the movement of the wire of the wire saw includes a back-and-forth movement of the wire. The term "back-and-forth" movement as understood herein shall include at least one change in the movement direction of the wire. Typically, the movement direction of the wire is changed repeatedly in selectable time intervals.

**[0027]** For unwinding the wire at the desired wire speed, the feed spool of unused wire rotates with a rotation speed of up to several thousands rotations per minute. For example, 1000 to 2000 rpm can be provided for unwinding the wire.

**[0028]** In embodiments, which can be combined with other embodiments described herein, the wires may have different diameters depending on the type of device. In an embodiment pertaining to a squarer, the wire diameter may be from about 250 μm to about 450 μm, e.g., 300 μm to 350 μm. In an embodiment pertaining to a wafer cutting wire saw, the wire diameter may be from 80 μm to 180 μm, more typically from 120 μm to 140 μm. For all of the former, a twisting of the wire might increase the risk of breaking of the wire or of damaging the coating, so that a twist-free operation is advantageous.

**[0029]** By using diamond wire, the throughput may be increased by a factor of 2 or even more in comparison to conventional steel wire. The speed with which the material to be sawed is moved relatively to the moving wire may be referred to as the material feed rate. The material feed rate in the embodiments described herein may be in the range of 2 μm/s to 15 μm/s, typically about 6 μm/s to 10 μm/s for a wafer cutting wire saw, respectively from 20 μm/s to 40 μm/s, typically from 28 μm/s to 36 μm/s for embodiments pertaining to a squarer.

**[0030]** According to typical embodiments, a multi-wire saw is used. Multi-wire saw allows high productivity and high quality slicing of silicon wafers for the semiconductor and photovoltaic industries. A multi-wire saw includes typically a high-strength steel wire that may be moved uni-directionally (i.e., only in the forward direction) or bi-directionally (i.e., backwards and forwards) to perform the cutting action. The wire may be provided with diamonds on its surface.

**[0031]** The wire may be wound on wire guides, herein referred to also as guiding cylinders, which are normally grooved with constant pitch, forming a horizontal net of parallel wires or wire web. The wire guides are rotated by drives that cause the entire wire-web to move at a relatively high speed of, for instance, 5 to 20 m/s. If desired, several high flow-rate nozzles may feed the moving wires with slurry. A slurry as understood herein refers to a liquid carrier with suspended abrasion particles (e.g., particles of silicon carbide). During the cutting action, the ingot may be pushed through the wire web. Alternatively, the ingot may be stationary while the wire web is pushed through it. Generally, and not limited to any specific embodiment described herein, the phrase "cutting a wafer" particularly includes "cutting an ingot into wafers". A wire feed spool provides the required new wire and a wire take-up spool stores the used wire.

**[0032]** Normally, after traveling through the entire wire saw, the wire exits the operation area of the wire saw at a diameter reduced in comparison to its initial diameter before the sawing process. The wear in wire is process dependant. In particular, the higher the cut rate, the higher the wire wear. Also, the higher the wire usage (length of wire used for a given application), the lower the wear is. Since on the one hand the wire wear increases the wire breakage probability and, on the other hand, the wire usage increases the costs of manufacturing a wafer, the present disclosure desires to control the usage of the wire for an optimized process at minimum overall costs.

**[0033]** Hence, the underlying concept of the present disclosure is an optimization of the wire usage. The present disclosure particularly relates to a multi-wire saw, that is, a process where several sawing processes take place at one point in time. Still, as will become more apparent from a discussion of the figures below, it is typically only one wire that is used for several sawing processes in one point in time.

**[0034]** It is desired to optimize the productivity of the wire saw, such as the overall throughput or the feed rate, by reducing the number of changes of the spools, in particular of the wire feed spool providing unused wire, and by avoiding down times due to wire failure. At the same time, it is desired to avoid unsatisfactory sawing results due to undue worn wires and to maintain a safety margin with respect to wire breakage.

**[0035]** Since slicing faster generates more wear of the wire which in turns increases the probability of wire breakage, it is desired to find one or more optimum operation parameters. According to the present disclosure, one or more optimum operation parameters are found in-situ during the sawing process. Typically, the one or more optimum operation parameter is constantly, such as in predetermined time intervals, updated in dependence of the actually measured wire condition.

**[0036]** According to embodiments, the wire is inspected during the sawing operation. For instance, the actual wire wear may be measured. The measurement, and possibly a subsequent analysis, allows immediate reacting, such as amending one or more of the operation parameters, in order to optimize the process. For instance, it is possible to increase the wire speed and/or reduce the table speed. Thus, the wear is reduced, which in turn also reduces the wire breakage probability. It is also possible that the outcome of the wire measurement and/or analysis is such that the wire's condition is considered suitable for longer use and/or sawing at a feed rate.

**[0037]** Fig. 1 shows a schematic side view of a wire saw 100 including the wire saw control system 1, and Fig. 2 shows a schematic top view of the wire saw 100 including the wire saw control system 1. The wire saw control system 1 may include at least one camera 20 for picking up at least one picture of the wire. Thereby it is possible that the camera takes a picture of several adjacent wires at the same time. The camera 20 is typically connected to a camera control unit 25 via a cable or wireless connection 15. The control unit 25 may be part of or act as the wire saw control for controlling the sawing process.

**[0038]** The wire saw 100 has a wire guide device including four wire guide cylinders 112, 114, 116, 118. Typically, wire guide cylinders 112, 114, 116, 118 are covered with a layer of synthetic resin and are scored with grooves having very precise geometry and size. The distance between the grooves, or the pitch of the grooves, determines the distance D1 between two adjacent strings or lines of wire 230. The distance D1 minus the wire's diameter sets an upper limit for the thickness of the slices cut by the wire saw.

**[0039]** For example in the event a third media such as slurry is used, the slices may be about 10 $\mu$m to 40 $\mu$m thinner than the difference of the distance D1 and the wire's diameter. Typically, the wire thickness is between 120 $\mu$m and 140 $\mu$m while distance D1 is from 230 $\mu$m to 450 $\mu$m, typically in the range of 330 $\mu$m to 370 $\mu$m. As an example, the grooves may have a pitch or distance of below 300 $\mu$m. According to some embodiments, which can be combined with the other embodiments described herein, the pitch or distance of the groove results in spacing between adjacent wires of about from 110 $\mu$m to 350 $\mu$m, typically 190 $\mu$m to 250 $\mu$m. In light of the above, embodiments described herein may provide a large cutting area and a high cutting rate

**[0040]** According to different embodiments, which can be combined with other embodiments described herein, the pitch, i.e. the distance between grooves, can be in a range of 330 $\mu$m to 370 $\mu$m, for example 350 $\mu$m or below; the distance between adjacent wires can be in a range of 110 $\mu$m to 350 $\mu$m, for example, 190 $\mu$m to 250 $\mu$m or even 220 $\mu$m or less; and/or the resulting wafer thickness can be in a range of 120 $\mu$m to 250 $\mu$m, for example, 180 $\mu$m to 220$\mu$m or even 200 $\mu$m or below. Thereby, it should be noted that the groove pitch, and the groove geometry, is typically adapted to a wire thickness and wire type and is adapted to the wafer thickness.

**[0041]** Furthermore, each wire guide cylinder 112, 114, 116, 118 may be connected to a motor or drive 122, 124, 126, 128 (shown in dashed lines in Fig. 1). Each motor may be adapted for performing a back-and-forth movement of the wire. The back-and-forth movement of the wire is denoted with reference numbers 215, 225 in the Figures. In embodiments, as those shown in Figs. 1 and 2, wire guide cylinders 112, 114, 116, 118 are directly driven by motors 122, 124, 126, 128. As shown in Fig. 2, each wire guide cylinder 112, 114 may be directly mounted to the motor shaft 123, 125 of the corresponding motor 122, 124. In some embodiments one or more of the motors are water-cooled. The one or more motors are typically controlled by the wire saw control. Information about the motor speed is used by the camera control unit for operating the camera.

**[0042]** During the cutting action, one or more ingots 302, 304, 306, 308 may be pushed through the wire web in order to slice it. This is indicted by the arrows sandwiched between ingots 302, 304, and 306, 308, respectively. Typically, the one or more ingots are supported by a table (not shown) which can be moved with a speed which is called "table speed" herein. The table speed may also be referred to as feed rate. Generally, and not limited to any specific embodiment described herein, the table speed may be synchronized with the wire speed. In particular, once the wire is stopped for changing its movement direction, it is possible that also the table speed is reduced to zero or close to zero for this moment.

**[0043]** Alternatively, the ingots 302, 304, 306, 308 may be stationary while the wire web is pushed through it. According to embodiments, the one or more ingots are sliced into a multitude of wafers, such as at least 500 or even more. Typical lengths of the ingots are in the range of up to 250 mm, in particular in the case of multi-crystalline Silicon, and up to 500 mm, in particular in case of mono-crystalline Silicon.

**[0044]** According to typical embodiments, a wire feed spool 134 is provided with a wire 230 reservoir. The wire feed spool 134, if still complete, typically holds several hundred kilometers of wire. The wire 230 is fed to the guide cylinders 112, 114, 116, 118 from the wire feed spool 134. A wire take-up spool 138 may be provided on which the used wire 230 is recoiled. In the embodiment shown in Fig. 1, the rotational axis of wire feed spool 134 and take-up spool 138 are parallel to the rotational axes of the wire guide cylinders 112, 114, 116, 118. Accordingly, typically no deflection pulley or similar device is required for feeding the wire to the wire guide 110. Due to the zero degree angle on the wire, the risk of wire breakage can be reduced. Typically, further devices such as low inertia pulleys (not shown) and tension arms (not shown) for wire tension regulation with optional digital coders on the tension arms may be provided.

**[0045]** During operation, e.g. during the sawing process, the motors 122, 124, 126, 128 may drive the wire guide cylinders 112, 114, 116, 118 so that the wire guide cylinders rotate about their longitudinal axis. According to typical embodiments, the wire is moved back and forth in order to perform the sawing. Thereby it is typical that the forth movement takes place for a first time interval or a first distance that is larger than the second time interval or second distance for which the back movement of the wire takes place. Thereby, despite an alternating back-and-forth movement of the wire, the wire is slowly transported from the wire feed spool 134 to the wire take-up spool 138.

**[0046]** The wire 230 is spirally wound about the wire guide cylinders 112, 114 and forms a layer of parallel wires between the two wire guide cylinders. This layer is typically referred to as a wire web 200. According to the embodiments illustrated, four wire webs are provided. Sawing takes place using at least one wire web, typically two wire webs at the same time (as illustrated in Fig. 1).

The number of parallel wire portions typically corresponds to the number of slicing processes. For instance, the wire may be wound up in such a way that the resulting wire web includes 100 wire portions arranged in parallel. A wafer pushed through this web of 100 wires is sliced into 101 pieces.

**[0047]** The transport speed of the wire is, for example, in the range of up to 20 m/s or even 25 m/s. The motors driving the wire are typically motors having a small momentum in order to stop and accelerate within a short time period. This is particularly useful in the embodiments of the present disclosure providing a back-and-forth movement. For instance, the direction of wire movement may change at least every 10 sec, at least every 30 sec, or at least every 1 min.

**[0048]** According to embodiments, the wire movement direction is amended at least 10 times, typically at least 100 times or at least 500 times during sawing one ingot (or several ingots in parallel). Amending the wire movement direction during the sawing of ingots reduces an overall tapering of the resulting wafers. If the wire moves through the ingot in the same direction for the complete ingot, it may happen that the resulting wafers have a trapezoidal shape since the wire at the side of entrance into the ingot carries more slurry than the wire at the exit side of the ingot. However, if, the movement direction through the ingot is amended from time to time, this effect can be compensated.

**[0049]** In one embodiment, one of the motors, e.g. motor 122, serves as a master motor whereas the remaining motors 124, 126, 128 serve as slave motors. In other words, master motor 122 may control the operation of slave motors 124, 126, 128 so that slave motors 124, 126, 128 follow master motor 122. Thus, synchronicity of operation of motors 122, 124, 126, 128 is improved and can be maintained during the sawing process. Furthermore, the information about the operational status of the several motors or the master motor, i.e., its actual speed of the several motors or the master motor, may be transmitted to the camera control unit 25 in order to synchronize the motor speed with the operation of the camera.

**[0050]** According to some embodiments, which can be combined with other embodiments described herein, two or more spools are provided for forming at least one wire web. For example, two, three or even four spools can be used to provide the wire. Thereby, according to different embodiments a method of sawing thinner wafers, e.g., in a range of 100 $\mu$m to 170 $\mu$m can be provided. Typically, the thinner wafers can also be sawed at higher speed, such as having a material feed rate is in the range of 2 $\mu$m/s to 12 $\mu$m/s, typically about 5 $\mu$m/s to 7 $\mu$m/s.

**[0051]** Compared to a single wire system, the load on each wire can be reduced by having two or more spools and, thus, two or more wires. Generally, for a single wire web the load is increased as compared to a dual wire web, due to the increase of the wafer surface to wire surface area. The increased load can result in lower cutting speeds. Accordingly, using two or more wires can increase the cutting speed, e.g., such that an effective cutting area or a cutting area rate of 12 $m^2$/h or more can be provided.

**[0052]** Fig. 3 shows a front view of an embodiment of a saw control system 1 for a wire saw. In Fig. 3, for illustration purposes, wire portions in front of the device are shown (as dotted lines). The camera control unit 25 is typically adapted to detect a change in at least one physical condition of the wire 230 by analyzing the pictures taken by the camera. If a break of a wire 230 occurs, or in case the wire exhibits a non-acceptable thinning, the control unit detects the change and typically initiates a reaction. Such a reaction can generally, and not limited to the present embodiment, be an increase of the wire speed, a reduction of the table speed, and/or the control of the wire movement in such a way that compared to the operation prior to the detection, the portion of forward movement is increased in comparison to the portion of backward movement.

**[0053]** For instance, the wire might exhibit a physical condition such as a wearing, , wire diameter, wire homogeneity, diamond concentration and/or diamond repartition which is, according to the picture taken by the camera, exceeding a first threshold value. Hence, in such a case, the wire saw control system might be programmed to increase the wire speed by a selectable value, such as by at least 10%, the tension of the wire by a selectable value (for reducing the breaking probability), such as by at least 10%, the back-movements of the wire by a selectable value, such as at least 20%. In addition or alternatively, the wire saw control system might be programmed to reduce the table speed by a selectable value, such as by at least 10%. Thereby, the wire is used for fewer sawing processes.

**[0054]** According to some embodiments, the wire is continuously checked for at least one physical condition. "Physical condition" in this respect pertains primarily to the question whether the wire shows large wear or in homogeneities, or whether the wire has any type of defects, small cracks, ruptures, changes in its metallographic structure (such as grain size etc.), a high level of usage (e.g., a large thinning) or the like. Continuously as understood in this context is understood as repeatedly in selectable time intervals. The time intervals are typically identical to the duration of the wire movement in one direction. Once the wire is stopped in order to move it in the opposite direction, according to embodiments, the wire is inspected. In the case that the wire's physical condition exceeds the threshold value, the mode of operation is amended as a reaction thereof. It is possible that the mode of operation is reset to normal operation once the respective parameter or all parameters inspected are back within the allowable range again.

**[0055]** A camera as understood herein typically includes the capability to process visible radiation. According to further embodiments, it is possible that the camera is adapted for processing radiation in the extra-optical range, such as infrared, ultraviolet radiation, X-rays, alpha particle radiation, electron particle radiation, and/or gamma rays. According to typical embodiments, a source for one or more of the listed radiation types is part of the set-up. For instance, in the case of a camera that is adapted to process radiation in the optical range (400-800 nm), environmental light or the use of a LED might act as the respective light source. The camera may be applied in the form of a photo sensor or a CCD-sensor (charged coupled devices).

**[0056]** The camera is typically provided adjacent to a portion of the wire which shall be monitored or supervised. In a wire saw employing a wire web as described above, the camera may be provided adjacent to portions of the wire which protrude parallel to each other as is depicted in Fig. 2. In an embodiment, the camera 20 is mounted to a support, typically the surface of a board, solid body or housing, which may be of plastic, metal or any other suitable material.

**[0057]** According to some embodiments, a multitude of cameras is provided. This particularly applies to wire saws that include two or more wires. In such a case, typically, at least one camera per wire is provided. In operation, each wire is inspected by at least one camera. The two or more cameras may be operated by the same camera control unit in dependence of the respective wire speed, or each camera may have a camera control unit for operating the camera. Either way, each of the multitudes of cameras is operated in dependence of the speed of the wire the respective camera is directed to.

**[0058]** Further, according to yet further embodiments, which can be combined with other embodiments, thinner wires can be used, for example wires having a thickness of maximally 120 $\mu$m or maximally 80 $\mu$m. Thereby, the cutting area is increased. Typically, in the case of sawing supported by a slurry, the wire thickness reduces during usage of the wire. Thus, if a single wire is used for a larger cutting area, there is a risk that the wire thins very quickly until breakage of the wire results. Accordingly, the use of two wires to build a wire web, for example, a continuous wire web, on the one hand reduced the load on the wire and thereby allows for higher cutting speeds and, on the other hand, allows for thinner wires, which allows for smaller wire distance and thereby increased cutting area.

**[0059]** Generally, and not limited to any embodiment, each camera is adapted to inspect at least one wire portion. Typically, the multitudes of cameras, such as two, three, or more, are substantially arranged in a row. If the distance between the parallel wire portions is small, as is typical for some wire saws for semiconductor processing, each camera may cover a multitude of wire portions, typically from 4 to 100 parallel wire portions, more typically from 20 to 50 wire portions. Fig. 4 shows schematically an embodiment wherein a multitude of four cameras is provided. Although the embodiment shows the use of one wire only, as discussed, it would also be possible that two or four wires are used and inspected in the illustrated embodiment.

**[0060]** In embodiments described herein the distance between the wires is from 110 $\mu$m to 310 $\mu$m. The distance between the camera 20 and the wire 230 portions is dependent on a plurality of factors, e.g. of the employed type of camera, their technical specifications, the type and thickness of wire etc. Typically, the distance is typically from 1 cm to 20 cm, more typically between 5 cm and 15 cm such as 10 cm +/- 2.5 cm. According to embodiments, up to 10 mm, in particular between 1 mm and 5 mm, of the web is within the field of view of the camera. Typically, this corresponds to an imaging of up to 30 wires, more typically of between 5 and 20 wires at one time.

**[0061]** The signals of the one or more cameras 20 are communicated to the control unit 25 via the connecting wires 15. As discussed, the camera control unit is typically the controller of the wire saw, but it is also possible that it is a separate device. The controller is adapted to inspect and analyze the signals of the one or more cameras during operation of the wire saw. As discussed, if the wire exhibits any physical condition that is defined as non-normal, the control unit detects the change and triggers a reaction.

**[0062]** In an embodiment, the camera control unit immediately causes the operation of the wire saw to stop in case of a detected wire defect, in order to prevent undesirable consequences which may result from a further operation with a wire defect described above. It is furthermore possible that the camera control unit additionally signals an alarm. The alarm signal is typically signaled acoustically, e.g. by means of a beeper, a horn, or a loudspeaker and may also be signaled optically by means of a light emitting device. The unit may also send a signal to an operator screen or an external device via a computer network or the like. The location of the non-normal wire portion may be displayed graphically via a graphical representation of the wire web including the plurality of wire portions.

**[0063]** In an embodiment, the camera control unit is able to distinguish between different grades of degradation of the wire, such as defects, wear, abrasion, inhomogeneities, or the like. This means, a slight change of the camera signal caused by a minor change of the wire's s at least one property, e.g. a decrement of the wire's diameter exceeding a limit value, may be identified. It may then be flagged as an anomaly. The control unit of the device is, in embodiments, adapted to decide if the change of the wire's properties should result in a change of one or more operation parameters of the wire saw, or not. A change of one or more operation parameters may include one or more of the following actions:

**[0064]** According to embodiments, the wire speed may be increased as a reaction. According to typical embodiments, increasing the wire speed is accompanied by reducing the table speed. Alternatively, only the table speed is reduced without amending the wire speed at the same time.

**[0065]** There are several options to increase the wire speed according to the understanding of the present disclosure. One option is to increase the minimum speed of the wire, for instance, by at least 10% or at least 20%. It is possible to reduce the table speed at the same percentage which represents the increase of the wire speed. For instance, if the wire is moved with, for example, a speed of at least 15 m/s, the wire's speed may be increased to at least 18 m/s (which corresponds to an increase of the wire speed by 20%).

**[0066]** Another option, which may be combined with the aforementioned option, is to reduce the wire acceleration after a change of direction. Slow down of the acceleration is particularly useful in case a crack or the like is sensed.

**[0067]** According to embodiments, another reaction may be to increase the length of the wire which is moved forward and/or to decrease the length of the wire which is moved backwards.

**[0068]** Generally, and not limited to the embodiment described, the wire may be moved forward a first wire length, and the wire may subsequently be moved backward a second wire length. According to some embodiments typically referring to a normal operation of the wire, the first wire length is slightly larger than the second wire length. "Slightly" as understood in this context particularly refers to a difference of up to 10%, more typically up to 5% or only 1%. According to other embodiments, the first wire length is larger than the second wire length, for instance, by between 5 m and 50 m, typically by between 5 m and 20 m, such as between 5 m and 10 m. Thereby, after one forward movement and backward movement, the wire has moved forward by a length defined as the difference between first length and second length. Typically, this difference length is spooled up on the take-up spool because it is normally considered not to be suitable for further use.

**[0069]** As an extraordinary reaction, the operation may be halted. That is, in this embodiment, the inspection result is such that the wire saw is stopped. An alarm signal may be triggered in order to inform an operator of the halt. A stop of the wire may be caused, for instance, if the wire's diameter goes below a halt threshold value. It is a general effect of the present invention that an operation stop is avoided.

**[0070]** According to some embodiments, the camera is positioned adjacent the take-up spool. The term "adjacent" as understood herein is to be understood in that the camera is positioned at a wire's location after the sawing. Hence, after passing the camera, the wire might run over one or more guiding rolls or the like, and after that the wire is spooled up at the take-up spool. Such an embodiment is exemplarily illustrated in Fig. 5.

**[0071]** In some embodiments of the present disclosure the wire saw is controlled such that the wire moves forwards and backwards in an alternating manner. As discussed, it is typical that the wire length moving forwards is larger than the wire length moving backwards, such as by between 0.5% and 5%, more typically by between 0.5% and 3%. Typically, each movement direction (i.e., forwards and backwards) is operated for a time interval of between 10 s and 5 min, more typically between 10 s and 1 min. As discussed, it is possible that the time interval for the forward movement is larger than the time interval for the backward movement, such as by at least 0.5% or 1%.

**[0072]** According to aspects of the present invention, the operation of the camera and the operation of the wire are synchronized. Thereby, it is possible to inspect the wire at those times when the obtained picture quality is maximized. For instance, according to some embodiments, the camera is triggered to always take a picture at those times when the wire's s speed is zero or substantially zero. The term "substantially zero" may include a speed of up to +/- 1 m/s. Typically, the operation of the camera is triggered when the moving direction of the wire is changed, for instance, from a forward movement to a backward movement, or from a backward movement to a forward movement.

**[0073]** According to some embodiments, the camera takes one picture when its operation is triggered, according to other embodiments, the camera takes at least two, three or even more pictures when its operation is triggered, and according to yet further embodiments, the camera may be adapted to take pictures constantly, such as at least 30 or 50 pictures per second (e.g., the camera may be a video camera). It is generally possible that all the pictures taken are analyzed in order to inspect the wire, or alternatively, that only one picture of the set of pictures is used for further analysis, specifically the one picture that outperforms the other pictures in terms of picture quality such as contrast. Alternatively or additionally, it is also possible that the wire saw control system as described herein includes at least a second camera that may be adapted to take pictures of the wire at the same time as the first camera. It is possible that the pictures taken by the first camera and the pictures taken by the second camera are used for the analysis of the inspection, or it is possible that only one picture is used, specifically the one picture that outperforms the at least one other picture in terms of picture quality, such as contrast.

**[0074]** The feature that the camera is operated in dependence of the wire speed does typically not exclude the possibility that the camera constantly takes pictures. For instance, the camera may be a video camera. In this case, however, it is typical that only those pictures that were taken at a wire speed allowing appropriate result quality are analyzed. In other words, according to embodiments, the pictures that were taken at high speed might be disregarded whereas the picture(s) taken at a reduced speed or even zero speed of the wire is/are analyzed.

**[0075]** The feature that the camera is operated in dependence of the wire speed does typically not exclude the possibility that the camera constantly takes pictures and that all of the pictures are analyzed. However, according to embodiments, only the analysis results of those pictures that were taken at a reduced wire speed or even zero speed of the wire can cause an amendment of at least one operation parameter of the wire saw.

**[0076]** Inspection of the wire as understood herein particularly includes an analysis of wire parameters such as the wire diameter and/or wire homogeneity, i.e., variation in the diameter. It is possible to define threshold values that might be stored in a data storage unit, which may be part of or associated with the wire saw control system. For instance, camera control unit 25 illustrated in the Figures may be provided with such a data storage (not shown). The wire saw control system may be adapted for comparing the measured values of the wire parameters with the stored threshold values. In dependence of the result, an action may be triggered.

**[0077]** For instance, a set of threshold values may be defined including, for example, a first threshold value, and a second threshold value. The threshold values may refer to the wire's diameter and thus indicate the wire's wear.

**[0078]** The second threshold value may define a diameter wherein underrunning this diameter causes the operation of the wire saw to switch to a second operation mode. The second operation mode typically includes a higher speed of the wire than under normal operation. The term "normal operation" thereby refers to an operation mode wherein the wire saw is operated at a speed as intended and not influenced by the underrun of any threshold value. For instance, the speed of the second operation mode may be increased by at least 5% or at least 10% as compared to normal operation.

**[0079]** The first threshold value may define a diameter wherein underrunning this diameter causes the operation of the wire saw to switch to a first operation mode. The first operation mode typically includes a higher speed of the wire than under normal operation. Furthermore, the first operation mode may include a speed of the wire that is still smaller than the speed as under the second operation mode. For instance, the speed of the first operation mode may be increased by at least 3% or by at least 6% as compared to normal operation. Alternatively or additionally, the first and second operation mode may include a larger ratio between the forth movement and the back movement of the wire as compared to normal operation.

**[0080]** Whereas this embodiment referred to discrete threshold values, it may generally also be possible to define a function relating an operation parameter of the wire saw, such as the wire speed, to one or more measured wire parameter(s), such as the wire diameter. For example, let d be the measured wire's diameter, and let v be the speed with which the wire saw is operated, then the wire saw is operated with a speed that is a function of the wire's diameter, that is, according to $v = f(d)$. It is typical that the function $f(d)$ is a steadily decreasing function, for instance, v may be inversely proportional to d. Obviously, these exemplary relations typically relate to situations above the minimum speed with which the wire saw can be normally operated.

**[0081]** The phrase "operating the camera in dependence of the wire speed" particularly includes the synchronization of the wire speed and the operation of the camera. Several embodiments described herein synchronize the operation of the camera with the back-and-forth movement of the wire. However, synchronizing as understood herein does not necessarily require a change of the movement direction of the wire. Instead, the wire may be moved only in one direction, such as the forward direction, for a specific time interval, wherein it may be nevertheless desired to inspect the wire during this movement. It is possible that the wire's speed is reduced in specific time intervals in order to trigger the operation of the camera, and thus allow an image result of high quality.

**[0082]** For instance, the wire may be moved with a first speed. The first speed may be the maximum speed of the wire saw. After a selectable time interval, the wire's speed is reduced to a lower speed value to take a picture of the wire. The lower speed may be between (including) zero and (excluding) the maximum speed. For instance, the maximum speed may be in the range of between 15 and 25 m/s, and the lower speed for taking a picture may be in the range of between 0 and 10 m/s, typically between 0 and 5 m/s. Immediately after taking the picture, the wire's speed is increased again, typically to the maximum speed. This way of operation may be repeated in selectable time intervals.

**[0083]** It is also possible that, maybe after a number of these selectable time intervals (e.g., after five or ten), the wire's movement direction is changed. Triggering the camera's operation is possible when the wire's movement direction is changed, and during the subsequent movement of the wire in further selectable time intervals, which are typically identical to the selectable time intervals previously described in this paragraph.

**[0084]** According to embodiments, the present disclosure is directed at a picture analysis system that takes pictures of a wire, typically a diamond wire or a steel wire, during the process of sawing. The scales of the pictures as directed at herein are microscopic. According to some illustrated embodiments, the wire is moved with a speed of up to 20 m/s in a back-and-forth movement, wherein typically each forward movement is followed by a backward movement (at least for as long as the wire is not used up or the process is altered for other reasons).

**[0085]** In embodiments, during the change of direction (i.e., from backward movement to forward movement or from forward movement to backward movement), the speed of the wire is equal to 0 m/s. The present disclosure proposes synchronizing the wire speed with the operation of the camera in order to take a picture of the wire and perform an analysis of the one or more pictures taken. From this analysis it is possible to gain information about the wire's properties at the measured location(s), for instance, of the wearing, the quality, the homogeneity, the diamond concentration and diamond repartition in the wire. In case of steel wires, the wearing is typically largely associated with the wire's resulting diameter.

**[0086]** By inspecting the wire when the wire speed is reduced or even zero, the outcome of the taken pictures is massively improved as compared to techniques wherein the inspection takes place during normal (full speed) operation. Hence, high-precision analysis is possible allowing gaining accurate information about one or more of the wire properties, such as those discussed previously. This in turn allows using this information for controlling the further operation of the wire saw in an optimized manner.

**[0087]** Thereby it turned out that, according to some embodiments, it is particularly beneficial to locate the camera at a position of the wire where the wire has finished the sawing process. In other words, it is particularly beneficial to locate the camera close to the winding-up spool. This position allows full information about the wire's status after running through the wire saw completely, and the synchronization as described allows high-precision analysis. The gained and analyzed information can be used for further controlling the operation of the wire saw, such as controlling the wire speed.

**[0088]** Hence, the present disclosure provides a measurement of the actual wire wear produced by an on-going sawing process. It generally allows undertaking immediate actions to reduce wear. As described, the camera may be positioned after the wire exits the wire web. A fast picture acquisition system is typically used as the camera. It may monitor the actual wire diameter that exits the slicing room in real-time. This information may then be used to maintain the operating parameters, to slow down, or to accelerate the cut rate and/or the wire speed in order to maintain a constant wear, yielding thus optimized wire consumption along with low wire breakage occurrence rate. It is possible that dedicated software displays the diameter and provides means for automatic machine regulation.

**[0089]** In addition, it is generally also possible that the camera is positioned adjacent to the spool providing the unused wire. Hence, the present disclosure can also be used for new wire diameter measurements, in particular, checking the tolerance status and sorting out wire that is out of specification. It can furthermore be used for printing statistical reports for Process Control and Quality Certification. During operation of the wire saw, the wire tension may be maintained constant, for instance at 10-30 N. However, according to embodiments of the present disclosure, it is possible that the wire tension is temporarily changed in reaction to inspection results of the unused wire. For instance, if the unused wire exhibits a crack or the like, it may be possible to reduce the tension until the respective wire portion is spooled up on the wire spool again.

**[0090]** According to embodiments, the camera is additionally provided with one or more of the features discussed in the following with exemplary reference to Fig. 6. A laser shadowing device may be provided that is, according to specific embodiments, positioned at or inside a wire saw. It may include protections in order to avoid damages or malfunctions such as caused by, e.g., slurry splashing or the like.

**[0091]** Referring to the exemplary illustration of Fig. 6 in more detail, a laser shadowing device 680 may be provided. The laser shadowing device is generally arranged such that the wire 230 can be inspected. In the present case, the wire 230 is accommodated in the recess 690 of the device. The wire shadowing device includes a rotatable mirror 600. The rotatable mirror seems to have a circular cross-section although, on a small scale, the mirror consists of a plurality of planar plates arranged in a neighboring location to each other. Thereby, the reflection direction of the mirror is alternating constantly once the mirror pivots.

**[0092]** A light source such as a laser diode 640 is provided for generating a beam 650 of laser light. The beam of laser light is directed at the rotatable mirror 600. It reflects the beam 650 in an alternating manner to mirrors 610 and 611. In the shown illustration of Fig. 6, the beam 650 is reflected towards mirror 610. These mirrors reflect the beam through further optional optical devices such as the shown lenses 630 and 631, respectively, as well as through lenses 670 and 671, respectively. Thereby, the wire 230 is encircled by the measuring laser beam from both sides in an alternating manner. The laser beam is registered in the cameras 621 and 622. The cameras 621 and 622 can be cameras as described herein, in particular, they can be photodiodes. The cameras 621 and 622 are linked to a video signal processing unit 660 adapted for commonly evaluating the measurement results. The camera control unit as described herein can act as the video signal processing unit.

**[0093]** While the foregoing is directed to embodiments of the invention, other and further embodiments of the invention may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

## Claims

1. A wire saw control system (1) for operating a wire saw (100) adapted for cutting a wafer (304, 304, 306, 308) by moving the wire (230) relatively to the wafer with a selectable wire speed, the wire saw control system comprising:

   a) a camera (20) for inspecting the wire;
   b) a camera control unit (25) for operating the camera in dependence of the wire speed.

2. The wire saw control system according to claim 1 adapted for amending at least one operation parameter of the wire saw (100) in dependence of the outcome of the inspection, wherein the at least one operation parameter is optionally chosen as one or more of the following group: increasing the wire

speed, reducing the table speed, and increasing the ratio between forward movement and backward movement.

**3.** The wire saw control system according to any of the preceding claims, wherein inspecting the wire includes inspecting one or more of the following properties: wire wearing, wire diameter, wire homogeneity, diamond concentration of the wire and diamond repartition of the wire.

**4.** A wire saw (100) comprising the wire saw control system (1) according to any of the preceding claims.

**5.** The wire saw according to claim 4, further comprising a take-up spool (138), wherein the camera (20) is positioned adjacent to the take-up spool (138).

**6.** The wire saw according to any of claims 4 and 5, further comprising at least one drive (122, 124, 126, 128) for driving the wire, wherein the drive is adapted for performing a back-and-forth movement (215, 225).

**7.** The wire saw control system according to any of the claims 4 to 6, wherein the wire (230) is a diamond wire.

**8.** A method for inspecting a wire of a wire saw, the wire saw being adapted for cutting a wafer by a relative movement of the wire and the wafer, the method comprising:

a) moving the wire with a variable wire speed; and
b) inspecting the wire in dependence of the wire speed, thereby obtaining an inspection result.

**9.** The method according to 8, wherein inspecting the wire includes taking at least one picture of the wire with a camera.

**10.** The method according to any of claims 8 and 9, wherein inspecting the wire includes inspecting one or more of the following properties: wire wearing, wire quality, wire diameter, wire homogeneity, diamond concentration of the wire and diamond repartition of the wire.

**11.** A method for operating a wire saw comprising the method for inspecting the wire of a wire saw according to any of claims 8 to 10.

**12.** The method for operating a wire saw according to claim 11, wherein the wire is moved in a first direction for a first time interval, and in a second direction for a second time interval, wherein the first and the second directions are opposite to each other.

**13.** The method for operating a wire saw according to any of claims 11 to 12, wherein the second time interval is smaller than the first time interval.

**14.** The method for operating a wire saw according to any of claims 11 to 13, wherein the wire is inspected when the wire speed is substantially zero.

**15.** The method for operating a wire saw according to any of claims 11 to 14, further comprising changing at least one operating parameter of the wire saw in dependence of the inspection result, wherein the at least one operation parameter is optionally chosen as one or more of the following group: increasing the wire speed, reducing the table speed, and increasing the ratio between forward movement and backward movement.

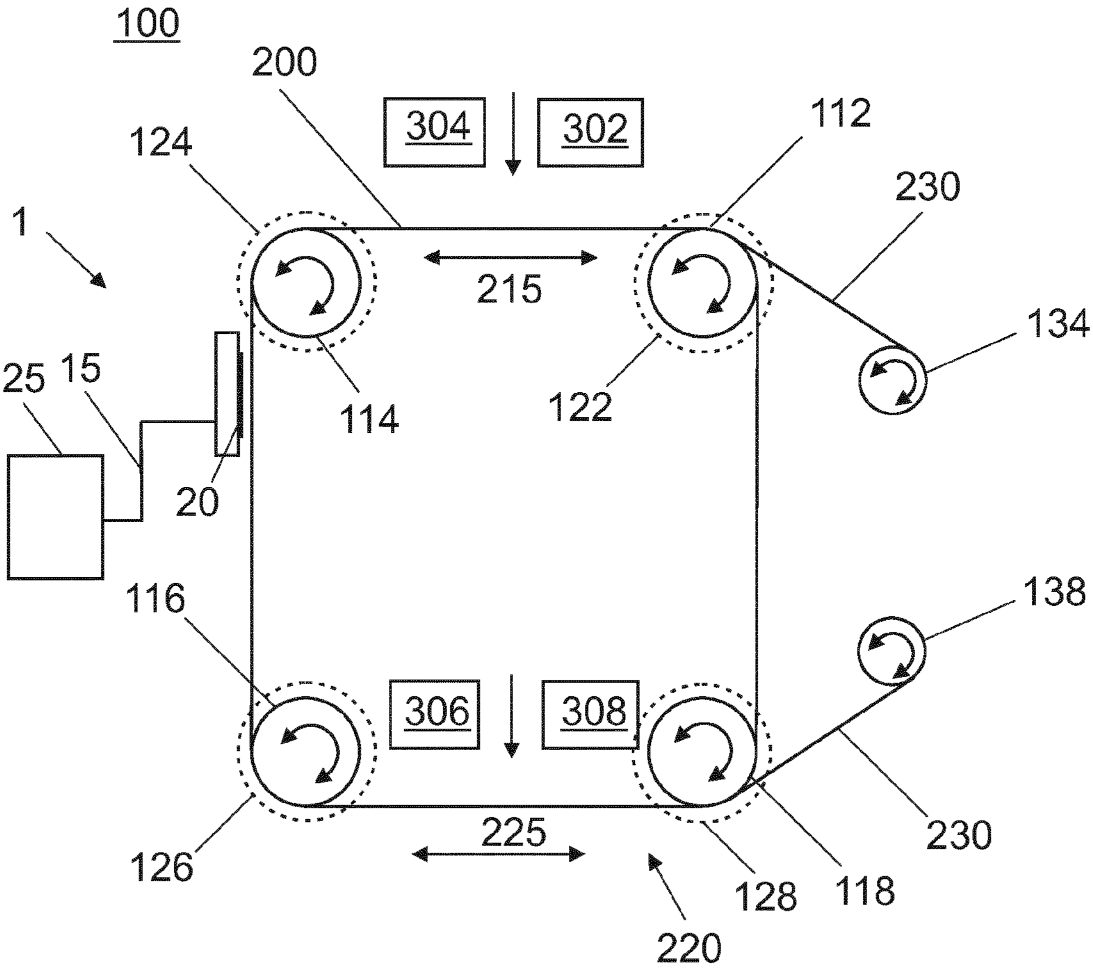
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Fig. 1

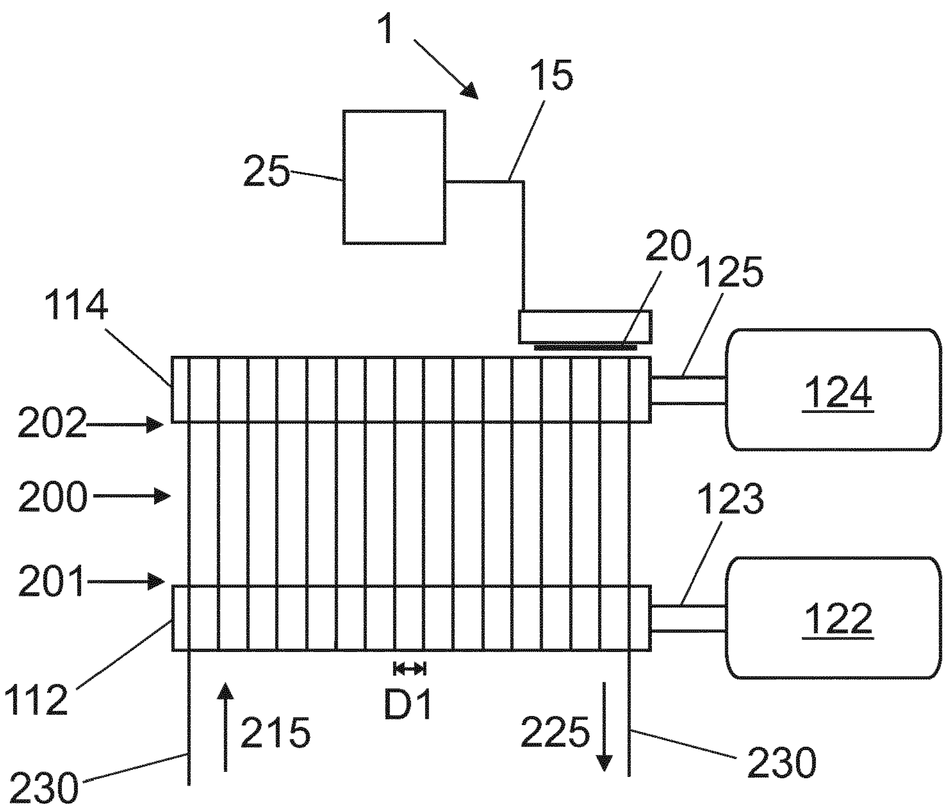


Fig. 2

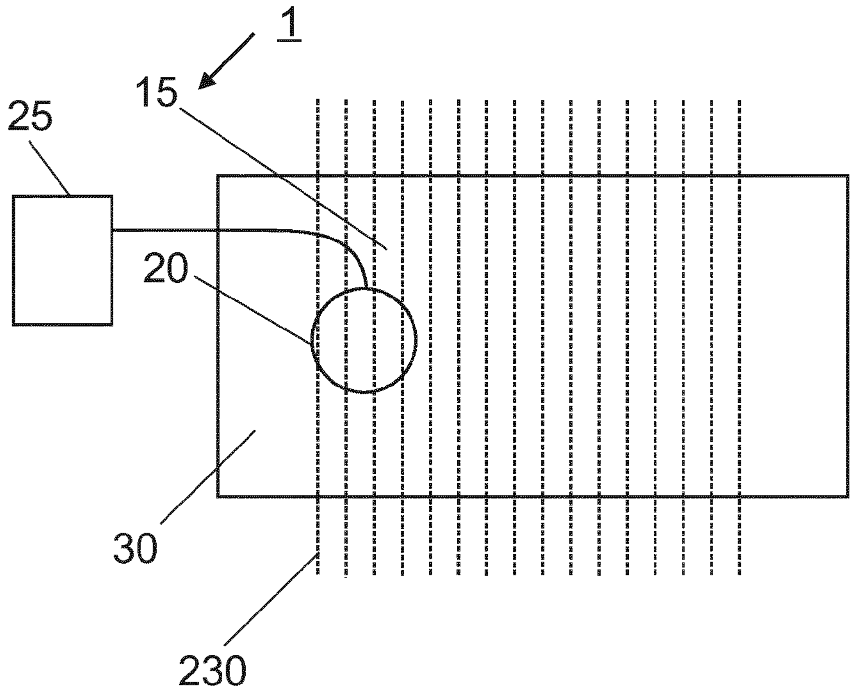


Fig. 3

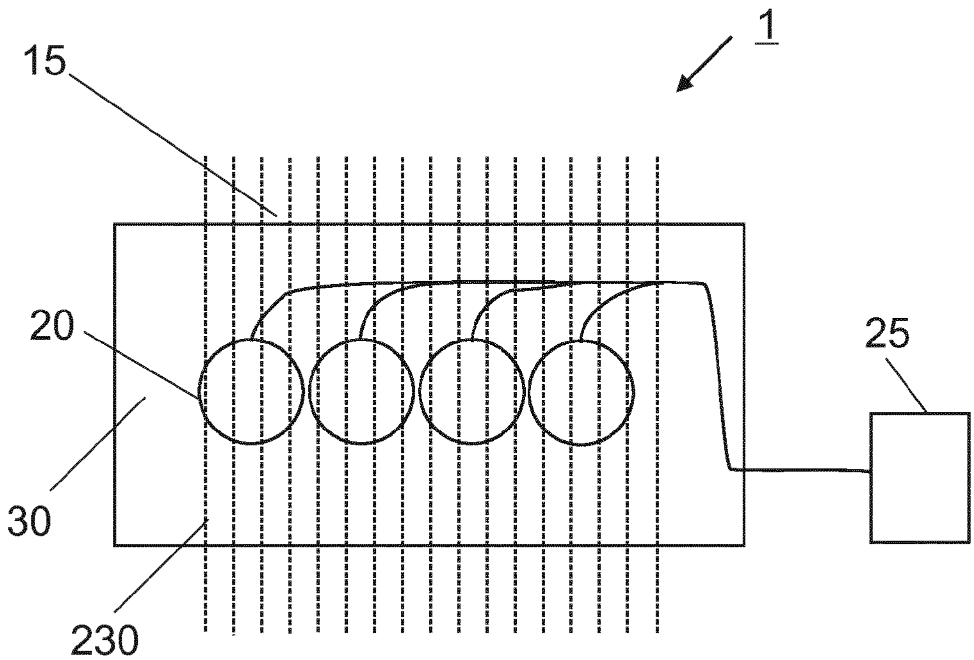


Fig. 4

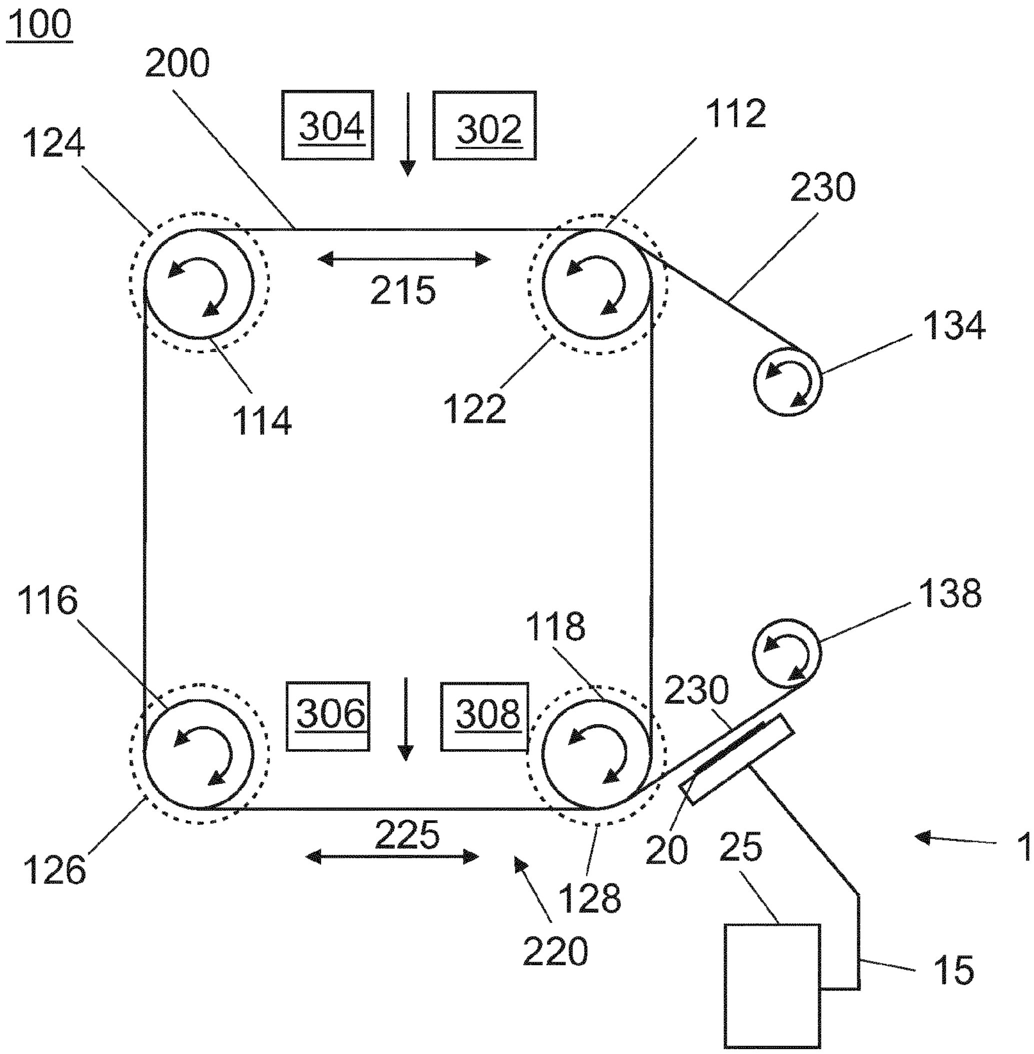
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Fig. 5

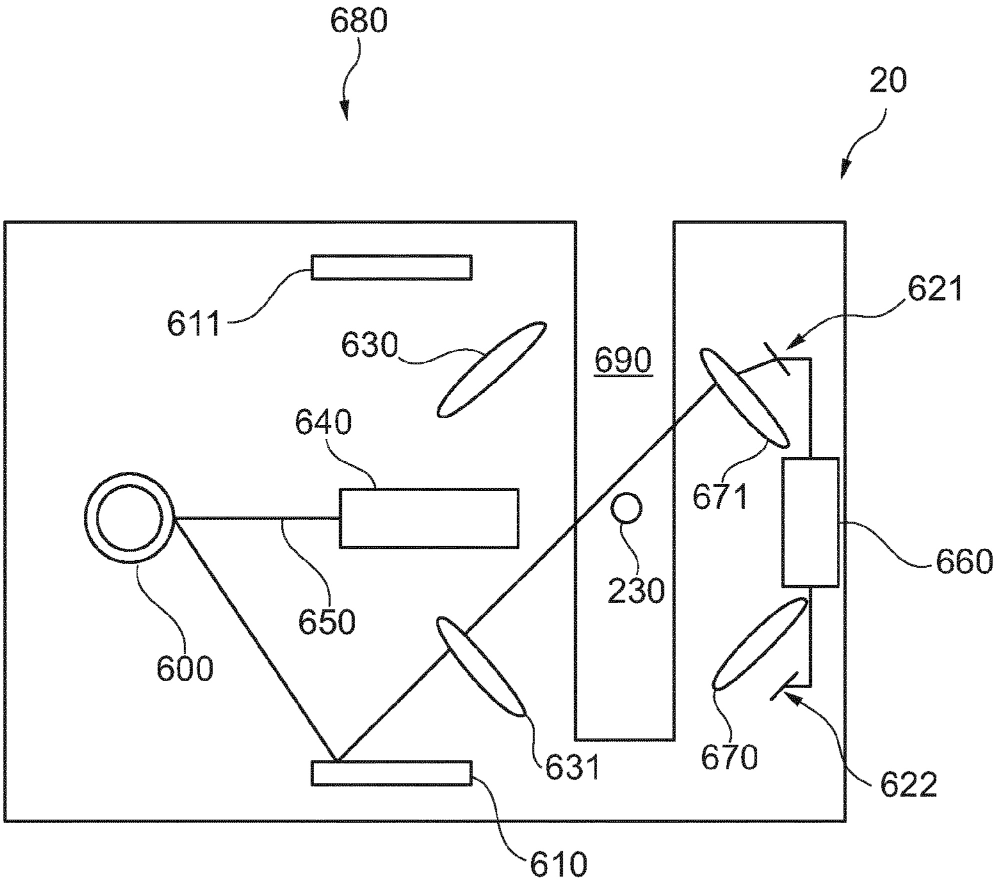


Fig. 6

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European Patent Office
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# EUROPEAN SEARCH REPORT

Application Number
EP 11 18 7049

## DOCUMENTS CONSIDERED TO BE RELEVANT

| Category | Citation of document with indication, where appropriate, of relevant passages | Relevant to claim | CLASSIFICATION OF THE APPLICATION (IPC) |
|---|---|---|---|
| A | WO 2011/070386 A1 (APPLIED MATERIALS INC [US]; ROSSET JEAN-MARC [CH]; SCHULER REMY [CH]) 16 June 2011 (2011-06-16)<br>* abstract *<br>* paragraph [0042]; figures *<br>----- | 1,8 | INV.<br>B28D5/00 |
| | | | TECHNICAL FIELDS SEARCHED (IPC) |
| | | | B28D |

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The present search report has been drawn up for all claims

| Place of search | Date of completion of the search | Examiner |
|---|---|---|
| The Hague | 3 May 2012 | Vaglienti, Giovanni |

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
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E : earlier patent document, but published on, or after the filing date
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## ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 11 18 7049

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report.
The members are as contained in the European Patent Office EDP file on
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03-05-2012

| Patent document cited in search report | Publication date | Patent family member(s) | Publication date |
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| WO 2011070386 A1 | 16-06-2011 | NONE | |

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For more details about this annex : see Official Journal of the European Patent Office, No. 12/82