

Solar Cell Cutting Method

Field of the Invention

The present invention relates to a method for cutting of solar cells and particularly, although not
5 exclusively, to a method of cutting solar cells by thermal laser separation.

Background

Traditional solar cell panels are made from a number of solar cells. There is an increasing trend
towards the use of half-cut cell modules due to the advantages provided by such modules: for
10 example half cut cell based modules may display lower resistive losses, and/or offer improved
performance under part-module shading. Indeed, as the size of cells increases, there is a trend
towards providing cells cut into greater number of pieces – for example, third- or quarter- cut
cells are also known.

However, to produce half-cut cells, it is necessary to perform a cutting process on the solar
15 cells. One known process for cutting a solar cell includes the use of high-power lasers to form a
scribe line on the surface of the solar cells, followed by application of mechanical force to cut or
separate the solar cell along the scribe line. Methods such as this are commonplace due to
their ease of application and low cost. However, the use of an applied mechanical force to cut
or separate the solar cell can result in poor quality of cutting, and risk of damage to the rest of
20 the solar cell.

Thermal laser separation (TLS) of solar cells is also known as a solar cell cutting method. In a
thermal laser separation method, the solar cell to be cut is locally heated, and immediately
cooled by applying a cooling medium to the locally heated region. The thermally induced
mechanical stresses result in thermal cracking of the solar cell.

25 Whilst TLS methods for cutting of solar cells can result in improved cell cutting in comparison to
traditional methods involving application of mechanical force, there is an ongoing need to
improve methods for cutting of solar cells, to minimise damage to the cells as a result of the
cutting method, and thereby improve the performance of the solar module.

The present invention has been devised in light of the above considerations.
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Summary of the Invention

The present inventors have realised that when cutting a solar cell into several parts via a TLS
method, the thickness of the solar cell to be cut may impact the quality of the cut that is
achievable based on a predetermined set operating parameters used in the TLS method.

Whilst it is not possible to easily change the thickness of the solar cell to be cut, it is however possible to change, or appropriately select, one or more operating parameters of the TLS method based on a measured thickness of the solar cell, to thereby improve the quality of the cut that is performed.

- 5 Accordingly, the present invention provides a method for thermal separation of a solar cell into several parts, the method including steps of:

operating a first laser according to a first set of predetermined operating parameters to form one or more crack initiation grooves on the solar cell;

- 10 operating a second laser according to a second set of predetermined operating parameters to heat at least a part of the solar cell to form a locally heated region; and

applying a cooling medium to the locally heated region of the solar cell to cool the locally heated region, thereby inducing thermal cracking of the solar cell in the locally heated region;

wherein at least one parameter of the second set of predetermined operating parameters is selected based on the thickness of the solar cell to be thermally separated.

- 15 The term “thermally separated” as used herein is generally interchangeable with the term “cut”. Accordingly, the phrases “solar cell to be thermally separated” and “solar cell to be cut” are generally interchangeable.

- The present inventors have found that by selecting at least one parameter of a set of operating parameters of a laser which operates to heat at least a part of the solar cell to form a locally
20 heated region in a TLS process based on the thickness of the solar cell, an improved quality of cutting may be achieved.

- In some embodiments, the thickness of the solar cell to be thermally separated may be an actual measured thickness. For example, the thickness of the solar cell may be obtained by direct measurement of the solar cell in question according to standard techniques known in the
25 art.

In other embodiments, the thickness of the solar cell to be separated may be an estimated thickness. For example, the thickness of the solar cell may be obtained by determining an average thickness for a batch of solar cells from which the solar cell originates.

- The method may be generally applicable to all types of solar cells. The method may be
30 particularly beneficial for solar cells comprising a Transparent Conductive Oxide film (TCO) film because it has been found that degradation of this film as a result of performing a TLS process can cause a particularly detrimental effect on solar cell performance, if appropriate operating parameters for the second laser are not selected.

- The method may also be particularly beneficial for heterojunction solar cells (HJT solar cells),
35 which are known to be relatively heat sensitive, and accordingly may be more sensitive to appropriate selection of operating parameters for the second laser which performs local heating of the solar cell than other kinds of solar cells.

The first laser may alternatively be referred to herein as the 'scribe laser'. The second laser may alternatively be referred to herein as the 'cleave laser'. The first and second laser may be provided as part of a thermal laser separation (TLS) processing unit, as discussed in further detail below.

- 5 The set of operating parameters of each laser may depend on the specific implementation of the TLS cutting process. However, in some methods, the first and/or second set of predetermined operating parameters each include one or more of the following parameters: laser power, laser wavelength, laser beam footprint size and/or shape, laser beam incidence angle, and/or laser dwell time.
- 10 Preferably, the power of the second laser is selected based on the thickness of the solar cell to be thermally separated. It has been found that there may be particular advantage to selecting the power of the second laser (the 'cleave laser') based on the thickness of the solar cell to be cut. This is because when the power of the cleave laser is too high for a given solar cell thickness, the heat generated by this laser may not be sufficiently dissipated through the
- 15 thickness of the cell and may therefore cause heat damage or degradation of the solar cell.

Furthermore, when the power of the cleave laser is too low for a given solar cell thickness, the cell may not be cut satisfactorily, because the locally heated region heated by the cleave laser may not reach a temperature high enough to induce thermal cracking when a cooling medium is applied to the locally heated region. Accordingly, the power of the second laser is preferably

- 20 selected to balance these factors: i.e. provide satisfactory cutting of the solar cell, whilst reducing or mitigating heat damage or cell degradation, which may lead to power loss of a module incorporating said solar cell.

- The power of the second laser may selected to satisfy the equation $P \leq 0.5x + 75$, or $P < 0.5x + 75$, where x is the cell thickness in μm , and P is a value in W. x may be in a range of from 50
- 25 to 300, for example in a range of from 100 to 200, in a range of from 130 to 180, or in a range of from 140 to 160. For example, x may be about 140, about 150 or about 160.

It has been found that by selecting the power of the laser such that it satisfies this equation, significant heat damage or cell degradation can be reduced or mitigated. More preferably, the power of the second laser may be selected to satisfy the equation $P \leq (x - 25)$, or $P < (x - 25)$.

- 30 It has been found that by selecting the power of the laser such that it satisfies this equation, significant heat damage or cell degradation can be further reduced or mitigated.

- The power of the second laser may be selected to satisfy the equation $(x - 45) \leq P$, or $(x - 45) < P$ where x is the cell thickness in μm , and P is a value in W. As above, x may be in a range of from 50 to 300, for example in a range of from 100 to 200, in a range of from 130 to 180, or in a
- 35 range of from 140 to 160. For example, x may be about 140, about 150 or about 160. It has been found that by selecting the power of the laser such that it satisfies this equation, satisfactory cutting of the solar cell may be achieved.

Preferably, the power of the second laser may be selected to satisfy the equation $(x - 45) \leq P \leq (x - 25)$, or $(x - 45) < P < (x - 25)$ where x is the cell thickness in μm , and P is a value in W . As above, x may be in a range of from 50 to 300, for example in a range of from 100 to 200, in a range of from 130 to 180, or in a range of from 140 to 160. For example, x may be about 140,
 5 about 150 or about 160. By selecting the power of the laser to be in this range, the method can provide both satisfactory cutting of the solar cell, whilst reducing or mitigating heat damage or cell degradation.

The size and shape of the locally heated region may depend on the footprint of this second laser. The footprint of the second laser may be the area of intersection of the second laser with
 10 a surface of the solar cell to be cut. In some embodiments, the locally heated region may have a width that is equal to or greater than the width of the cleave laser footprint.

In some arrangements, the laser footprint of the second (cleave) laser may be substantially circular in shape. In other arrangements, the laser footprint may be square, rectangular, or any other suitable shape.

15 The second laser footprint may have an area in a range of from 10 mm^2 to 100 mm^2 , e.g. in a range of from 19.6 mm^2 to 78.6 mm^2 . For example, the laser footprint may have an area of 15 mm^2 or more, 20 mm^2 or more, 30 mm^2 or more, 40 mm^2 or more, 50 mm^2 or more, 60 mm^2 or more, or 70 mm^2 or more. Where the laser footprint is circular, the diameter of the laser may be in a range of from 5 mm to 10 mm, e.g. about 5 mm, about 6 mm, about 7 mm, about 8mm,
 20 about 9 mm or about 10 mm. In one preferred arrangement, the laser footprint may be a circle having a diameter of 5 mm. In this case, the laser footprint may have an area of about 19.6 mm^2 .

It will be appreciated that by appropriately selecting both the power and the size or shape of the laser footprint, the laser power density may be set. Selecting the power density of the laser to
 25 lie within certain predetermined ranges may offer advantages as noted above in relation to selection of the absolute power of the laser.

The power density of the second laser may selected to satisfy the equation $P_d \leq 2.551x + 382.65$, or $P_d < 2.551x + 382.65$, where x is the cell thickness in μm , and P_d is a value in W/cm^2 . x may be in a range of from 50 to 300, for example in a range of from 100 to 200, in a
 30 range of from 130 to 180, or in a range of from 140 to 160. For example, x may be about 140, about 150 or about 160.

It has been found that by selecting the power density of the laser such that it satisfies this equation, significant heat damage or cell degradation can be reduced or mitigated. More preferably, the power density of the second laser may be selected to satisfy the equation $P_d \leq$
 35 $(5.102x - 127.55)$, or $P_d < (5.102x - 127.55)$ where x is the cell thickness in μm , and P_d is a value in W/cm^2 . It has been found that by selecting the power density of the laser such that it

satisfies this equation, significant heat damage or cell degradation can be further reduced or mitigated.

The power density of the second laser may be selected to satisfy the equation $(5.102x - 229.59) \leq P_d$, or $(5.102x - 229.59) < P_d$ where x is the cell thickness in μm , and P_d is a value in W/cm^2 . As above, x may be in a range of from 50 to 300, for example in a range of from 100 to 200, in a range of from 130 to 180, or in a range of from 140 to 160. For example, x may be about 140, about 150 or about 160. It has been found that by selecting the power of the laser such that it satisfies this equation, satisfactory cutting of the solar cell may be achieved.

Preferably, the power density of the second laser may be selected to satisfy the equation $(5.102x - 229.59) \leq P_d \leq (5.102x - 127.55)$, or $(5.102x - 229.59) < P_d < (5.102x - 127.55)$ where x is the cell thickness in μm , and P_d is a value in W/cm^2 . As above, x may be in a range of from 50 to 300, for example in a range of from 100 to 200, in a range of from 130 to 180, or in a range of from 140 to 160. For example, x may be about 140, about 150 or about 160. By selecting the power density of the laser to be in this range, the method can provide both satisfactory cutting of the solar cell, whilst reducing or mitigating heat damage or cell degradation. As mentioned above, the second laser is sometimes referred to as a 'cleave' laser. This laser performs a function of heating at least a part of the solar cell to form a locally heated region. The method may include a step of aligning the cell relative to the cleave laser, prior to operation of the cleave laser. This can help ensure that the locally heated region is formed in the intended location on the solar cell. The locally heated region may be formed at an approximately central region of the solar cell. For example, it may be formed at a midline of the solar cell.

The second (cleave) laser may have a wavelength of 1500 nm or less, e.g. 1400 nm or less, 1300 nm or less, 1200 nm or less, or 1100 nm or less. In one suitable arrangement, the cleave laser may have a wavelength of 1064 nm. The cleave laser may be a fibre laser, a solid state laser or a diode laser. One example of a commercially available laser suitable for use as a cleave laser is a Nd:YAG laser configured for emission of light at 1064 nm.

The second (cleave) laser may be arranged such that a central axis of the laser beam forms an incidence angle in a range of from 75° to 105° with the surface of the solar cell, e.g. an angle of about 90° with the surface of the solar cell. In other words, the laser may be arranged such that the laser beam is substantially perpendicular to the solar cell.

In some methods, the solar cell may be moved relative to the second laser (or vice versa) during the method. The solar cell may be moved linearly relative to the second laser during the method. In such arrangements, the locally heated region heated by the second laser may be a linear region. The linear region may extend in the direction of movement of the solar cell relative to the second laser. The relative movement speed of the solar cell and the second laser may be in a range of from 300 to 400 mm/s, e.g. about 340 mm/s or about 350 mm/s. The

second laser may be operated continuously or substantially continuously as the solar cell is moved relative to the second laser.

The second laser dwell time may be determined by dividing the laser footprint size (maximum dimension of the footprint in the relative movement direction) by the speed of relative movement of the solar cell and the second laser. The second laser dwell time may be in a range of from 0.405 s to 0.540 s, e.g. about 0.5s. The temperature to which the locally heated region is heated may be a predetermined temperature. The locally heated region may be heated to a temperature in a range of from 250 °C to 350 °C. In some embodiments, the locally heated region may be heated to a temperature of 260 °C or more, 270 °C or more, 280 °C or more, or 290 °C or more. In some embodiments, the locally heated region may be heated to a temperature of 350 °C or less, 340 °C or less, 330 °C or less, 320 °C or less, 310 °C or less, or 300 °C or less. In preferred arrangements, the locally heated region may be heated to a temperature of about 290 °C.

As discussed above, prior to operating the cleave laser, a scribe laser is first operated according to a first set of predetermined operating parameters to form one or more crack initiation grooves on the solar cell. Providing one or more such crack initiation grooves can assist in ensuring that thermal cracking of the solar cells occurs in a defined manner, for example along a predetermined dividing line.

The method may include a step of aligning the cell relative to the scribe laser, prior to operation of the scribe laser. This can help ensure that the one or more crack initiation grooves are formed in the intended location on the solar cell. The one or more crack initiation grooves may be formed at an approximately central region of the solar cell. For example, they may be formed at a midline of the solar cell. The crack initiation groove may be formed on only a single side of the solar cell. In some methods, the solar cell may be moved relative to the first laser (or vice versa) during the method. The solar cell may be moved linearly relative to the first laser during the method. In such arrangements, the crack initiation grooves formed by the first laser may be linear grooves. The linear grooves may extend in the direction of movement of the solar cell relative to the first laser. The relative movement speed of the solar cell and the first laser may be in a range of from 300 to 400 mm/s. The length of the crack initiation groove may be determined by the operation time of the scribe laser in combination with the relative movement speed of the laser and the solar cell. The scribe laser may be pulsed (i.e. not operated continuously). The length of a pulse (or of each pulse) may be 200 ns or less, e.g. in a range of from 50 to 150 ns, e.g. about 100 ns. In some methods, the crack initiation groove may be formed by a single pulse. In other methods, the crack initiation groove may be formed by a plurality of pulses of the first laser.

The first laser dwell time may be determined by dividing the laser footprint size (maximum dimension of the footprint in the relative movement direction) by the speed of relative movement of the solar cell and the second laser. The first laser dwell time may be in a range of from

0.00125 s to 0.00333 s. The power of the first laser may be selected to be in a range of from 10 W to 20 W. For example, it may be 10 W or more, 11 W or more, 12 W or more, 13 W or more, 14 W or more or 15 W or more. It may be 20 W or less, 19 W or less, 18 W or less, 17 W or less, 16 W or less or 15 W or less.

- 5 A laser having a power in the ranges described above may allow for the crack initial groove(s) to be formed, without causing substantial heating of the solar cell which could lead to heat damage.

It will be appreciated that by appropriately selecting both the power and the size or shape of the laser footprint, the laser power density may be set. The power density of the scribe laser may
10 be selected to be in a range of from 0.010 to 0.114 W/ μ^2 . In some arrangements, the laser footprint of the scribe laser may be substantially circular in shape. In other arrangements, the laser footprint may be square, rectangular, or any other suitable shape.

The scribe laser footprint may have an area in a range of from 176 μm^2 to 963 μm^2 . For example, the scribe laser footprint may have an area of 200 μm^2 or more, 300 μm^2 or more,
15 400 μm^2 or more, 500 μm^2 or more, 600 μm^2 or more, 700 μm^2 or more or 800 μm^2 or more. In one suitable arrangement, the scribe laser footprint may be a circle having a diameter of about 20-30 μm . In this case, the laser footprint may have an area of about 314 μm^2 to 707 μm^2 .

The scribe laser may have a wavelength of 1500 nm or less, e.g. 1400 nm or less, 1300 nm or less, 1200 nm or less, or 1100 nm or less. In one suitable arrangement, the scribe laser may
20 have a wavelength of about 1064 nm. The cleave laser may be a fibre laser, a solid state laser or a diode laser. One example of a commercially available laser suitable for use as a cleave laser is a Nd:YAG laser configured for emission of light at 1064 nm.

The first (scribe) laser may be arranged such that a central axis of the laser beam forms an incidence angle in a range of from 75° to 105° with the surface of the solar cell, e.g. an angle of
25 about 90° with the surface of the solar cell. In other words, the laser may be arranged such that the laser beam is substantially perpendicular to the solar cell. The size and shape of the crack initiation groove(s) is not particularly limited. The crack initiation grooves may be formed to extend across only part of the cell, by suitable operation of the scribe laser. The scribe laser may be operated to form a crack initiation groove having a length in a range of from 0.1 to 10
30 mm. For example, the crack initiation grooves may be formed to extend for a distance of 5 mm or less, 4 mm or less, 3 mm or less, 2 mm or less, 1 mm or less, or 0.5 mm or less. More preferably, the crack initial groove may have a length in a range of from 0.5 to 1 mm.

The crack initiation grooves may be formed to extend from an edge of the solar cell. In preferred arrangements, the scribe laser is operated to form the crack initiation groove such that
35 it extends for a distance of about 0.5 mm from an edge of the solar cell.

The crack initiation grooves may have a depth in a range of from 20%-50% of the thickness of the solar cell to be thermally separated. In some embodiments, the grooves may have a depth

of 25% or more, 30% or more, 35% or more, 40% or more or 45% or more of the thickness of the solar cell to be thermally separated. For a solar cell having a thickness of about 150 μm , the crack initiation groove may have a depth of from 30 μm to 75 μm .

5 The cooling medium which is applied to the locally heated region of the solar cell to cool the locally heated region may be any suitable cooling medium. In some arrangements, the cooling medium may be a liquid cooling medium. In other arrangements, the cooling medium may be a gaseous cooling medium. In one preferred arrangement, the cooling medium may comprise water. Water is cheap, readily available, and offers suitable cooling properties for cooling the locally heated region.

10 The cooling medium may be applied to the locally heated region by a cooling medium application module. The cooling medium may be applied in any suitable manner. For example, it may be poured, sprayed, or misted onto the locally heated region. In one suitable arrangement, the cooling medium is applied via a spray nozzle at a rate of 2.5 to 4.5 ml/s, e.g. at about 3 ml/s, or at about 4 ml/s.

15 The cooling medium may have a temperature in a range of from 20 to 30 °C. The cooling medium may have a temperature which is at least 200 °C cooler than the temperature to which the locally heated region is heated. In some embodiments, the cooling medium may have a temperature which is 210 °C or more cooler, 220 °C or more cooler, 230 °C or more cooler, 240 °C or more cooler, 250 °C or more cooler, 260 °C or more cooler, 270 °C or more cooler, 280 °C
20 or more cooler, 290 °C or more cooler, up to 300 °C cooler than the temperature to which the locally heated region is heated. Providing such a temperature difference between the cooling medium and the temperature to which the locally heated region is heated can help to ensure suitable thermal cracking of the solar cell on application of the cooling medium to the locally heated region. In one example, the locally heated region may be heated to about 290 °C, and
25 the cooling medium may have a temperature in a range of from 20 °C to 30 °C, such that the temperature difference between the cooling medium and the locally heated region is 260 °C – 270 °C.

Preferably, the crack produced as a result of thermal cracking in the locally heated region is a through-thickness crack, extending through the entire thickness of the solar cell to thereby
30 separate the solar cell into separate pieces.

As discussed above, the first and second lasers may be provided as part of a TLS processing unit. The TLS processing unit may further comprise a cooling medium application module.

As mentioned above, the method may include steps of moving the solar cell to be cut and components of the TLS processing unit relative to one another. This may be achieved by
35 arranging the solar cell to be stationary within the TLS processing unit, and for all relative movements between the solar cell and the components of the TLS processing unit to be realized by movement of the components of the TLS processing unit relative to the solar cell.

However, in a preferred arrangement, the solar cell may be moved relative to the TLS processing unit. In such an arrangement, the components of the TLS processing unit may therefore remain in a substantially fixed position.

One convenient way of allowing for such relative movement of the solar cell with respect to the TLS unit is to provide a conveyor having a defined transport path, said transport path passing through or beneath the TLS processing unit. The transport path may extend, for example, from a loading area, to the TLS process unit, to an unloading area.

The method may accordingly include a step of arranging a solar cell to be cut on a conveyor having a defined transport path and conveying the solar cell to the laser processing unit via the conveyor. The movement speed of the solar cell along the linear transport path may be in a range of from 300 mm/s - 400 mm/s e.g. about 340 mm/s or about 350 mm/s.

The step of arranging the solar cell to be cut on the conveyor may be performed in a loading area. For example, a cell may be unloaded from a cell box located in the loading area and placed on the conveyor. This cell unloading and placement may be performed manually, for example by a human operator. Preferably, this cell unloading and placement step is performed by a robotic handling system that is configured for handling of solar cells (this may be referred to as a solar cell loading module). Such systems are well known in the art and therefore will not be described in further detail here.

Prior to entering the TLS processing unit, a step of aligning the solar cell to be cut may be performed. The cell may be aligned relative to the conveyor on which the solar cell is disposed, or may alternatively or additionally be aligned with respect to components of the TLS processing unit. For example, a midline of the cell may be aligned with a midline of the conveyor, or be aligned with one or more components of the TLS processing unit. This alignment step may be performed manually, for example by a human operator. However preferably, this alignment step is performed by a mechanical system – for example, by a robotic handling system (this may be referred to as a solar cell alignment module).

Steps performed in the TLS processing unit (i.e. scribing of the solar cell with the first laser, heating of the solar cell with the second laser, and application of a cooling medium to the solar cell) are discussed in detail above, and accordingly will not be repeated here.

After passing through the TLS processing unit, the solar cell having been cut (i.e. the thermally separated pieces of the solar cell), may be conveyed away from the TLS processing unit. The thermally separated pieces may then be removed from the conveyor. The step of removing the cell from the conveyor may be performed in an unloading area. This unloading step may be performed manually, for example by a human operator. However preferably, this unloading is performed by a mechanical system – for example, by a robotic handling system (this may be referred to as a solar cell unloading module).

After unloading, the thermally separated pieces of the solar cell may be placed into a cell box, e.g. for shipment of the solar cell pieces.

The method may be a continuous process for the thermal separation of a plurality of solar cells.

The invention includes the combination of the aspects and preferred features described except
5 where such a combination is clearly impermissible or expressly avoided.

Summary of the Figures

Embodiments and experiments illustrating the principles of the invention will now be discussed with reference to the accompanying figures in which:

10 Figure 1 is a schematic figure illustrating a thermal laser processing unit performing a method according to the present invention.

Figure 2 is a schematic figure illustrating a plan view of a solar cell during and after performing a thermal laser separation method according to the present invention.

Figure 3 is a graph showing optimum and maximum cleave laser power (P) as a function of
15 solar cell thickness.

Figure 4 is a graph showing optimum and maximum cleave laser power density (Pd) as a function of solar cell thickness.

Detailed Description of the Invention

20 Aspects and embodiments of the present invention will now be discussed with reference to the accompanying figures. Further aspects and embodiments will be apparent to those skilled in the art. All documents mentioned in this text are incorporated herein by reference.

Fig. 1 is a schematic figure illustrating a thermal laser processing unit 100 performing a method according to the present invention and Fig. 2 is a schematic figure illustrating a plan view of a
25 solar cell 1 (a) near the start of the thermal laser separation method; (b) during the thermal laser separation method and (c) after performing a thermal laser separation method using the thermal laser processing unit shown in Fig. 1. These figures will be discussed together.

The thermal laser separation (TLS) processing unit 100 shown in Fig. 1 includes a first laser module 3, which will herein be referred to as a 'scribe laser' module, a second laser module 5
30 which will herein be referred to as a 'cleave laser' module, and a cooling medium application module 7. Each of these modules is statically fixed within the laser processing unit. The modules are arranged sequentially within the TLS processing unit, in the order: (1) first laser module 3; (2) second laser module 5; (3) cooling medium application module 7. The modules are arranged to be linearly adjacent to one another.

A conveyor 9 is also provided, to allow for relative movement of a solar cell 1 disposed on the conveyor with respect to the TLS processing unit. The conveyor has a defined transport path from a loading area (not shown) to an unloading area (also not shown). The direction of movement of the conveyor is indicated with an arrow.

- 5 The scribe laser module 3 is configured to operate according to the following parameters to produce a laser beam 4: scribe laser footprint diameter = 20-30 μm ; scribe laser wavelength = 1064 nm; scribe laser power = 10-20 W. The scribe laser is operable to form a scribe length of 0.5 – 1 mm on a solar cell to be cut, by pulsed operation of the scribe laser – Fig. 2(a) illustrates the thermal laser separation method near the start of the method during a time in which the
- 10 scribe laser module 3 is in operation (scribe laser beam 4 is shown). Fig. 2(b) illustrates the thermal laser separation method during a subsequent time in the thermal laser separation method, wherein the scribe laser module 3 is not in operation. It can be seen from Fig. 2(a) that the scribe laser has a substantially circular laser footprint.

- The cleave laser module 5 is configured to operate according to the following parameters to
- 15 produce a laser beam 6: cleave laser diameter = about 5 mm; cleave laser wavelength = 1064 nm; cleave laser power = variable, based on a measured or otherwise predetermined thickness of the solar cell to be cut. It can be seen from Fig. 2(a) that the cleave laser has a substantially circular laser footprint.

- The thickness of the solar cell to be cut is indicated in Fig. 1 by the 'X'. The thickness of the
- 20 solar cell to be cut may in some cases be directly measured, prior to performing the TLS method. In other cases, the thickness of the solar cell to be cut may be estimated based on e.g. a known range of thicknesses of a batch of solar cells from which the solar cell is obtained. As one example, where the solar cell to be cut originates from a batch of solar cells having thicknesses which are known to be in a range of from 100 μm to 200 μm , the thickness of the
- 25 solar cell may be estimated as 150 μm (the average of the end points of the range of thicknesses in the batch of solar cells).

- The cooling medium application module 7 is configured to operate to produce a jet of water 8 via a spray nozzle at a rate of 2.5-4.5 ml/s, wherein the water is at a temperature of from 20 to 30 °C. It can be seen from Fig. 2(a) that the jet of water has a substantially circular footprint,
- 30 although we note that this shape is not so limited, and could be any suitable shape – For example, the footprint of the water could be selected to be rectangular to fit around the laser area.

- A thermal laser separation method using the thermal laser processing unit shown in Fig. 1 proceeds as follows. Firstly, a solar cell 1 is removed from a cell box and loaded onto conveyor
- 35 9 in a loading area by a robotic handling system, or solar cell loading module (not shown in this figure). After being loaded onto the conveyor, the cell may undergo an optional alignment step, whereby a robotic handling system or solar cell alignment module operates to align a midline of the cell with one or more components of the TLS processing unit (for example, with the scribe

laser module 3 and/or the cleave laser module 5). This alignment step is optional because in some methods, the cell may be loaded onto the conveyor in a suitably aligned manner.

Once the solar cell 1 has been loaded onto conveyor 9, it is conveyed beneath or through the TLS processing unit along the linear transport path defined by the conveyor. The movement
5 speed of the solar cell along the linear transport path is about 340 mm/s.

On this transport path, the solar cell first encounters the scribe laser beam 4, which forms a crack initiation groove 11 on the surface of the cell. The scribe laser is arranged such that a central axis of the scribe laser beam forms an angle of around 90° with the surface of the solar cell – i.e. is substantially perpendicular to the solar cell. The crack initiation groove is a linear
10 groove which extends in the direction of movement of the solar cell relative to the scribe laser. The crack initiation groove does not extend through the thickness of the solar cell, but instead extends for a depth in a range of from 20%-50% of the thickness of the solar cell to be thermally separated. The scribe laser beam 4 is operated in a pulsed manner, with the length of time of the pulse being selected to limit the length of the crack initial groove to a length of around 0.5
15 mm.

Next, the solar cell encounters the cleave laser beam 6. The cleave laser is arranged such that a central axis of the cleave laser beam forms an angle of around 90° with the surface of the solar cell – i.e. is substantially perpendicular to the solar cell. As discussed above, the power of the cleave laser is selected based on the thickness of the solar cell 1. In the present case, the
20 solar cell 1 is from a batch of solar cells having thicknesses which are known to be in a range of from $130\text{ }\mu\text{m}$ to $170\text{ }\mu\text{m}$, and so the thickness of the solar cell is estimated as $150\text{ }\mu\text{m}$. The power of the laser is selected to be within an optimal range of $(x - 45) \leq P \leq (x - 25)$, where x is the cell thickness in μm , and P is a value in W – in the present case, this is a range of from 105 W to 125W. Conveniently, a value at the mid-point of this range is selected, and accordingly
25 the cleave laser is operated at a power of 115 W. This power ensures that satisfactory cutting of the solar cell can be achieved, and that heat damage or cell degradation can be reduced or mitigated. As the diameter of the cleave laser footprint is about 5 mm, the area of the footprint is about 0.196 cm^2 , and the power density of the laser therefore also falls within an optimal range of $(5.102x - 229.59) \leq P_d \leq (5.102x - 127.55)$ where x is the cell thickness in μm , and P_d
30 is a value in W/cm^2 .

Where the cleave laser beam intersects the surface of the solar cell 1, a locally heated region 13 is formed. This is indicated in Fig. 2(a) and Fig. 2(b) by an area having a different shading to the remainder of the solar cell. It can be seen here that the locally heated region 13 is an approximately linear region formed at a midline of the solar cell and extending in the direction of
35 movement of the solar cell relative to the cleave laser.

The width of the locally heated region is shown in Fig. 2(a),(b) as being substantially equal to the width of the cleave laser beam. However, as the person skilled in the art will be well aware,

in practice, the width of the locally heated region may be slightly wider than the width of the cleave laser beam, due to heat transfer through the material of the solar cell.

The locally heated region is heated by the cleave laser beam 6 to a local temperature of about 290 °C.

- 5 Next, the solar cell encounters the water jet 8. As discussed above, the water jet is at a temperature of 20-30 °C. The large temperature differential between the temperature of the water jet and the temperature of the locally heated region causes rapid cooling of the locally heated region of the solar cell, which in turn induces thermal cracking of the solar cell in the locally heated region, along the crack initial groove previously formed. Accordingly, a crack 15
- 10 is formed, which follows the crack initial groove, and extends linearly in the direction of movement of the solar cell relative to components of the TLS processing unit. The crack is a through-thickness crack which extends through an entire thickness of the solar cell, such that once the crack 15 propagates along the entire length of the solar cell, the solar cell is divided into two separate pieces, 1a and 1b, as shown in Fig. 2(b).
- 15 After thermal separation of the solar cell 1 into pieces 1a 1b has been achieved, thermally separated pieces of the solar cell 1a and 1b, are conveyed away from the TLS processing unit to an unloading area (not shown). The thermally separated pieces of solar cell are then unloaded from the conveyor 9 by a robotic handling system, or solar cell unloading module, and placed into a cell box e.g. for shipment of the solar cell pieces.
- 20 The method shown in Fig. 1 and described here is a continuous process for the thermal separation of a plurality of solar cells. That is, at any one time, a plurality of solar cells may be arranged on conveyor 9 for consecutive and continuous processing of the plurality of cells by the TLS processing unit. In this way, a large number of solar cells may be cut in an efficient manner.

25

Examples

- A study was done to investigate the effect of selecting at least one parameter of the set of operating parameters of the cleave laser based on the thickness of the solar cell to be thermally separated. Specifically, the effect of selecting the power of the cleave laser based on the
- 30 thickness of the solar cell to be thermally separated was investigated.

- A series of solar cell samples were obtained and subjected to a cutting process as discussed above. The cells were HJT cells obtained from commercial solar cell suppliers. Information about the cells is provided in the tables below. For each test, the cell was taken from a batch having cells of a range of thicknesses between 150-180 µm. The mean thickness of cells in the
- 35 batch was calculated to be 160 µm. This mean thickness was therefore taken to be an estimated thickness for any given cell in the batch. As can be seen from the table below, this estimated thickness was 160 µm for all samples tested.

The cells were then subjected to a cutting process according to a protocol as described above in relation to Fig. 1 and Fig. 2, and the power of the cleave laser was varied between 125 W and 160 W, to determine the effect of this power variation on the performance of a module incorporating the given cut solar cell samples. The module incorporating the given cut solar cell samples includes a white back sheet, and had a module area of 1.749 m², consisting of 120 pcs half cells with the full cell dimension of 161.7 mm x 161.7 mm pseudo square, cell area 0.025827 m², under standard test condition of irradiance 1000W/m², temperature 25 °C and air mass (AM) of 1.5.

The maximum power point (P_{mpp} /W) and Fill Factor (FF /%) was then determined for modules incorporating the cut samples. These values were determined in a conventional manner. The results are set out below.

Test	Cell thickness /μm		Cell Efficiency/%	Cleave Laser /W	P _{mpp} /W	FF /%
	Mean	Batch Range				
1	160	150-180	23.40	160	337.9	75.2
2	160	150-180	23.40	125	354.6	79.3
	Delta				16.7	4.1
3	160	150-180	24.20	160	341.4	76.8
4	160	150-180	24.20	125	361.8	80
	Delta				20.4	3.2

It can be seen from this data that significant power loss, and loss in FF% was observed when the cells were subjected to a TLS process in which the cleave laser operated at 160 W, as compared with cell subjected to a TLS process in which the cleave laser was operated at 125W, with the cells subjected to the higher-power laser demonstrating a fill factor loss of 4.1% and 3.2% respectively, and a maximum power loss of 16.7 W and 20.4 W respectively. Accordingly, it can be determined that for a solar cell having a thickness of 160, a cleave laser power of 125 W is superior to a cleave laser power of 160 W. It can be seen that the power of 125 W satisfies the equation $(x - 45) \leq P \leq (x - 25)$, as 125 is in the range of from 115 W to 135 W (and, conveniently, is the mid-point of this range).

A further investigation was also performed to assess how the power of the cleave laser might be optimised for cutting of solar cells have a cell thickness in the range of from 140 to 170 μm. As set out in the table below, various cell samples were subjected to a TLS cutting process, and the power of the cleave laser used in the TLS process was varied across the samples. As above, for each test, the cell was taken from a batch having cells of a range of thicknesses between 140-170 μm. The mean thickness of cells in the batch was calculated to be 150 μm. This mean thickness was therefore taken to be an estimated thickness for any given cell in the batch. As can be seen from the table below, this estimated thickness was 150 μm for all samples tested.

The maximum power point (Pmpp /W) and Fill Factor (FF /%) was then determined for modules incorporating the cut samples. These values were determined in a conventional manner. The results are set out below.

Test	Cell thickness / μm		Cell Efficiency/ %	Sample Size	Cleave Laser /W	Pmpp /W	FF /%
	Mean	Range					
5	150	140-170	24.00	7	125	369.1	79.4
6	150	140-170	24.00	6	115	372.6	80.2
7	150	140-170	24.00	6	105	372.5	80.1

5

It can be seen that for cells having an estimated thickness of 150 μm , the optimal power for the cleave laser was about 105W – 115W. When the power of the cleave laser was 125 W, a reduction in both Pmpp and FF% was seen.

- Further investigation was done to determine both (a) an optimum cleave laser power & power density range having a low end and a high end; and (b) a maximum cleave laser power & power density value, for solar cells having a range of thicknesses. The results are shown in Fig. 3 and Fig. 4. From these graphs, it can be seen that a low end bound of the optimum cleave laser power was determined to be a line defined by the equation $P = x - 45$, and a high end bound of the optimum cleave laser power was determined to be a line defined by the equation $P = x - 25$.
- A low end bound of the optimum cleave laser power density was determined to be a line defined by the equation $P_d = 5.102x - 229.59$, and a high end bound of the optimum cleave laser power density was determined to be a line defined by the equation $P_d = 5.102x - 127.55$. Within these ranges of power and power density range it was determined that satisfactory cutting of the solar cell, whilst reducing or mitigating heat damage or cell degradation can be achieved.
- A maximum cleave laser power was determined to be a line defined by the equation $P = 0.5x + 75$, and a maximum cleave laser power density was determined to be a line defined by the equation $P_d = 2.551x + 382.65$. It was determined that operating the cleave laser at powers / power densities greater than defined by this line led to heat damage or cell degradation of the solar cells during the thermal laser separation process, resulting in power loss of a module incorporating the cut solar cell pieces.

25

The features disclosed in the foregoing description, or in the following claims, or in the accompanying drawings, expressed in their specific forms or in terms of a means for performing the disclosed function, or a method or process for obtaining the disclosed results, as appropriate, may, separately, or in any combination of such features, be utilised for realising the invention in diverse forms thereof.

30

While the invention has been described in conjunction with the exemplary embodiments described above, many equivalent modifications and variations will be apparent to those skilled in the art when given this disclosure. Accordingly, the exemplary embodiments of the invention

set forth above are considered to be illustrative and not limiting. Various changes to the described embodiments may be made without departing from the spirit and scope of the invention.

5 For the avoidance of any doubt, any theoretical explanations provided herein are provided for the purposes of improving the understanding of a reader. The inventors do not wish to be bound by any of these theoretical explanations.

Any section headings used herein are for organizational purposes only and are not to be construed as limiting the subject matter described.

10 Throughout this specification, including the claims which follow, unless the context requires otherwise, the word “comprise” and “include”, and variations such as “comprises”, “comprising”, and “including” will be understood to imply the inclusion of a stated integer or step or group of integers or steps but not the exclusion of any other integer or step or group of integers or steps.

15 It must be noted that, as used in the specification and the appended claims, the singular forms “a,” “an,” and “the” include plural referents unless the context clearly dictates otherwise. Ranges may be expressed herein as from “about” one particular value, and/or to “about” another particular value. When such a range is expressed, another embodiment includes from the one particular value and/or to the other particular value. Similarly, when values are expressed as approximations, by the use of the antecedent “about,” it will be understood that the particular value forms another embodiment. The term “about” in relation to a numerical value is optional
20 and means for example +/- 10%.

Claims:

1. A method for thermal separation of a solar cell into several parts, the method including steps of:
operating a first laser according to a first set of predetermined operating
5 parameters to form one or more crack initiation grooves on the solar cell;
operating a second laser according to a second set of predetermined operating
parameters to heat at least a part of the solar cell to form a locally heated region; and
applying a cooling medium to the locally heated region of the solar cell to cool the locally
heated region, thereby inducing thermal cracking of the solar cell in the locally heated region;
10 wherein at least one parameter of the second set of predetermined operating
parameters is selected based on the thickness of the solar cell to be thermally separated.
2. The method according to claim 1 wherein the first and second set of predetermined
operating parameters each include one or more of the following parameters: laser power, laser
wavelength, laser beam footprint size and/or shape, laser beam incidence angle, and/or laser
15 dwell time.
3. The method according to claim 2 wherein the power and/or the laser beam footprint size
of the second laser is selected based on the thickness of the solar cell to be thermally
separated.
4. The method according to claim 3 wherein:
20 (i) the power of the second laser is selected to satisfy the equation $P \leq 0.5x + 75$, where
x is the cell thickness in μm , and P is a value in W; and/or
(ii) the power density of the second laser is selected to satisfy the equation $P_d \leq 2.551x$
+382.65 where x is the cell thickness in μm , and P_d is a value in W/cm^2 .
5. The method according to claim 3 or claim 4 wherein:
25 (i) the power of the second laser is selected to satisfy the equation $(x - 45) \leq P \leq (x -$
25), where x is the cell thickness in μm , and P is a value in W; and/or
(ii) the power density of the second laser is selected to satisfy the equation $(5.102x -$
229.59) $\leq P_d \leq (5.102x - 127.55)$, where x is the cell thickness in μm , and P_d is a value in
 W/cm^2 .
- 30 6. The method according to claim 4 or claim 5 wherein x is a value in the range of from 100
to 200 μm
7. The method according to any one of the preceding claims wherein the second laser has
a laser beam footprint area in a range of from 10 mm^2 to 100 mm^2 .
8. The method according to any one of the preceding claims wherein the locally heated
35 region is a substantially linear region.

9. The method according to any one of the preceding claims wherein the locally heated region is heated to a temperature in a range of from 250 °C to 350 °C.
10. The method according to any one of the preceding claims wherein the power of the first laser is selected to be in a range of from 10 W to 20 W.
- 5 11. The method according to any one of the preceding claims wherein the first laser has a laser footprint having a spot size of 20-30 micron.
12. The method according to any one of the preceding claims wherein the crack initiation groove has a length in a range of from 0.1 to 10 mm.
13. The method according to any one of the preceding claims wherein the crack initiation
10 grooves have a depth in a range of from 20%-50% of the thickness of the solar cell sheet to be thermally separated.
14. The method according to any one of the preceding claims wherein the first and/or second laser have a wavelength of 1064 nm.
15. The method according to any one of the preceding claims wherein the cooling medium is
15 water.
16. The method according to any one of the preceding claims wherein the cooling medium has a temperature in a range of from 20 to 30°C.
17. The method according to any one of the preceding claims wherein the cooling medium is applied via a spray nozzle at a rate of 2.5-4.5 ml/s.
- 20 18. The method according to any one of the preceding claims wherein the method includes a step of aligning the cell relative to the first and/or the second laser, prior to operating the first and/or second laser.
19. The method according to any one of the preceding claims wherein the first and second lasers are provided as part of a thermal laser separation, TLS, processing unit, and wherein:
25 prior to the step of operating the first laser, the method includes a step of conveying the solar cell to the TLS processing unit via a conveyor having a defined transport path; and
after the step of applying a cooling medium to the locally heated region of the solar cell to cool the locally heated region, thereby inducing thermal cracking of the solar cell in the locally heated region, the method includes a further step of conveying the thermally separated pieces
30 away from the TLS processing unit along the transport path of the conveyor.