SOLAR CELL FABRICATION WITH FACETING AND ION IMPLANTATION

Related Applications

This application claims priority under 35 U.S.C. § 119(e) of the co-pending U.S. provisional patent applications, Serial No. 61/131,687, filed June 11, 2008, and titled "Solar Cell Fabrication Using Implantation"; Serial No. 61/131,688, filed June 11, 2008, and titled "Application Specific Implant System for Use in Solar Cell Fabrications"; Serial No. 61/131,698, filed June 11, 2008, and titled "Formation of Solar Cell Selective Emitter Using Implant and Anneal Method"; Serial No. 61/133,028, filed June 24, 2008, and titled, "Solar Cell Fabrication with Faceting and Implantation"; and Serial No. 61/210,545, filed March 20, 2009, and titled "Advanced High Efficiency Crystalline Solar Cell Fabrications Method," all of which are incorporated by reference in their entireties.

Field of the Invention

This invention relates to semiconductor devices and methods of fabricating them. More specifically, this invention relates to methods of fabricating solar cells with reduced ohmic losses.

Background of the Invention

Semiconductor solar cells are well known for transforming light into electric current. The efficiency of solar cells is limited in part by ohmic losses, which are affected by the dopant diffusion and contact screen printing used to fabricate the solar cells.

Figure 1 shows a prior art solar cell 100. The solar cell 100 converts light striking photo-receptive regions 135 on its top surface into electric current, which can be transmitted to a load 150. The solar cell 100 includes an n-type emitter layer 115 overlying a p-type substrate 110, thereby defining a p-n junction 111. The emitter layer 115 contains highly doped n-wells 117 that form gridlines and can be covered with an anti-reflective coating (ARC) 120. Metallic fingers 125 are formed on top of the n-wells 117 to couple the n-wells to a busbar 130. The busbar 130 is coupled to the load 150, which in turn is coupled to a metallic contact 140 on a backside of the substrate 110.

The emitter layer 115 is formed by exposing the substrate 110 to a source of n-type ions, which then diffuse into a top surface of the base 100. The doping profile of the solar cell 100 has several drawbacks.

First, producing this profile results in excess un-activated dopants near the top surface, as the dopants are driven into the bulk of the substrate 100. This effect leads to varying levels of light absorption, the creation of electron-hole pairs, and unwanted recombination of electron-hole pairs. This is known as "dead layer," in which blue light is not absorbed close to the top surface of the photo-receptive regions 135. Because of the high doping level near the surface, electron-hole pairs created in the dead layer quickly recombine before they can generate any current flow. Facetting, used to reduce the amount of light reflected from the solar cell before it can generate current.

Second, diffusion techniques used to form a conventional profile are not optimal for the formation of selective doping regions with a homogenous high resistivity photo-receptive region and low-resistance regions for gridlines, contact fingers, busbars, metal-silicon interfaces, and backside metallization.

Third, direct overlay of metal on the semiconductor can result in different work functions at the interface between the conductive fingers 125 and the emitter layer 115. To better match the work functions between a metal contact and the doped silicon, some prior art techniques melt the contacts 125 to form a silicide at the interface. While forming a silicide may help tailor the work functions, there are still undesirable ohmic losses and the potential of metal shunting.

Finally, lateral positioning of dopants across a substrate is becoming difficult as the line widths and wafer thicknesses are decreasing. Geometries in solar cell gridlines are expected to drop from about 200 microns to 50 microns, and later to drop even smaller. Present screen-printing techniques are ill equipped to fabricate devices with such small displacements. Moreover, as wafers are getting ever thinner, vertical and batch diffusion and screen printing become extremely difficult.

Summary of the Invention

In accordance with embodiments, solar cells are fabricated by precisely placing dopants both laterally, across layers of the underlying substrate, as well as into the bulk of the substrate. Ion beams are directed to create heavily doped areas that form gridlines, as well as lightly doped areas between the gridlines. By tailoring parameters, an atomic dopant profile is simultaneously matched to provide electrical junctions at appropriate depths using predetermined substrate doping levels and to provide the resistivity required for the formation of contacts at the substrate surface. Such independent control is unique to implantation methods.

In a first aspect, a semiconductor device includes a substrate having a surface that contains textured regions doped with a dopant to a first doping level and non-textured regions forming gridlines and doped with the dopant to a second doping level larger than the first doping level. The substrate is p-type or n-type; the dopant is of the opposite type. The semiconductor device includes conductive fingers coupled to the gridlines and a bottom portion that is coupled to a metallic contact containing impurities. The textured-regions are photo-receptive regions.

Preferably, each of the textured regions includes multiple textured elements, such as pyramidal elements having <111> planes, dome-shaped elements, or any other undulating (rising and falling) structures that reduce the amount of light reflected from the photo-receptive regions.

The dopant in each of the multiple textured elements has either a uniform thickness or a thickness that varies along the faces of the elements.

In one embodiment, each of the textured regions is covered with an anti-reflective coating. The dopants in the non-textured regions are interspersed with a metallic species.

In a second aspect, a method of fabricating a solar cell includes directing a uniform ion beam onto a surface of a substrate having non-textured and textured regions. Dopants are implanted into the textured regions at a first density and into the non-textured regions at a second density larger than the first density to form gridlines. The gridlines are coupled to contact fingers.

In one embodiment, the textured regions include multiple individual textured elements, such as pyramidal elements. Alternatively, the multiple textured elements are semi-spherical. The beam can be shaped to implant dopants into each of the textured elements individually or into a group of textured elements simultaneously.

Either the beam, the substrate, or both is rotated so that the beam is substantially perpendicular to faces of each of the multiple textured elements. The beam can also be scanned across the surface to thereby implant the dopants into the textured and non-textured regions.

In one embodiment, a cloud of ion plasma is used to conformally dope the whole of the substrate and any textured features on the surface.

In one embodiment, a resistance of the dopant in the non-textured regions is about 20 ohms per square, and a resistance of the dopant in the textured regions is less than about 100 ohms per square. A junction between the dopant in the textured region and the textured region is graded, a junction between the dopant in the non-textured region and the non-textured region is graded, or both.

The method also includes forming a silicide between the gridlines and the contact fingers and coupling the contact fingers to a busbar.

In a third aspect, a method of fabricating a solar cell includes etching a top surface of a substrate to form textured photo-receptive regions among planar regions. The textured regions include pyramidal shaped elements. The method also includes directing an ion beam onto the top surface, thereby implanting dopants into the textured regions at a first density and into the planar regions at a second density larger than the first density to form gridlines. A resistance of the dopant in the textured regions is less than 100 ohms per square, and a resistance of the dopant in the planar regions is about 20 ohms per square. The method also includes coupling contact fingers to the gridlines.

In a fourth aspect, a solar cell includes a substrate having a top layer and a bottom layer. The top layer has a surface containing pyramidal regions doped with a dopant to a first doping level and substantially planar regions forming gridlines and doped with the dopant to a second doping level larger than the first doping level. Adjacent ones of the planar regions are less than 50 microns apart. The gridlines are coupled to metallic fingers by silicide elements, and a metal contact is coupled to the bottom layer.

In a fifth aspect, a system for fabricating solar cells includes a source for producing ions, a beam shaper, and a controller. The beam shaper directs a beam containing the ions onto a substrate. The controller directs the beam shaper so that a textured photo-receptive region of the substrate is implanted with the ions to a first density and a planar region of the substrate defining a gridline is implanted with the ions to a second density larger than the first density.

The controller directs the beam shaper to step the beam to individually implant textured elements in the photo-receptive region. The controller also rotates, tilts, or translates the substrate, or any combination of these motions, when the beam is directed onto the substrate.

The controller directs the beam shaper and a duration of the implants so that a resistance of the photo-receptive region is less than 100 ohms per square and a resistance of the planar region is less than 20 ohms per square.

Brief Description of the Drawings

Figure 1 shows a prior art solar cell coupled to a load.

Figure 2 is a side cross-sectional view of a portion of a solar cell in accordance with one embodiment.

Figure 3 is a top view of a pyramidal facet of the solar cell of Figure 2.

Figure 4 is a graph of doping concentration versus depth for the planar region of the solar cell of Figure 2.

Figure 5 is a graph of doping concentration versus depth for the non-planar (textured) region of the solar cell of Figure 2.

Figures 6A and B show sequentially implanting ions in an emitter region and facet regions of a solar cell in accordance with one embodiment.

Figure 7 shows a pyramidal facet of a solar cell, having a uniform doping concentration in accordance with one embodiment.

Figures 8A-C show implanting ions into faceted regions of a solar cell in accordance with different embodiments.

Figures 9A-F show a solar cell during sequential fabrication steps for forming pyramidal facets in accordance with one embodiment.

Figure 10 is a flow chart of steps for fabricating a solar cell in accordance with one embodiment.

Figure 11 is a block diagram of a system for fabricating a solar cell in accordance with one embodiment.

Detailed Description of the Invention

Embodiments of the present invention are directed to methods of fabricating a solar cell by heavily doping its selective emitter region and more lightly doping its photo-receptive regions. In some embodiments, the selective emitter region and the photo-receptive regions are formed in the same processing step.

For the best performance of a solar cell, the photo-receptive regions are lightly doped to provide a homogeneous high sheet resistance. A more heavily doped region increases the chance of electron-hole recombination and thus decreases the efficiency of converting photons into electrical power. In accordance with embodiments, the n-doped layer of the photo-receptive regions of the solar cell is lightly doped to provide a sheet resistance of between 80 and 160 ohms per square, preferably 100 ohms per square, or an ion doping of around 1E+19 cm^{-3}. Preferably, the gridlines, over which the conductive finger contacts are formed, are more heavily doped to couple the generated charge to the finger contacts. To provide the desired resistance, the selective emitter regions are doped to a sheet resistance of 10-40 ohms per square, preferably 25 ohms per square, or an ion doping of around 1E+20 cm^{-3}. Preferably, the back surface of the solar cell is doped with a p-type layer to have a resistance between 30 and 70 ohms per square.

e embodiments use shaped and parallel beams to implg the implantation process to be completed more quickly and with a higher productivity. These beams help reduce the amount of unwanted dopants in the fabricated device.

Figure 2 shows a portion of a solar cell 200 in accordance with one embodiment, with a light beam 250 impinging on a photo-receptive region 225. As with all the figures, the same label refers to the same element throughout. The solar cell 200 contains a p-type substrate 210 sandwiched between a bottom metal contact 205 and an n-type emitter layer 215. The substrate 210 can be mono-crystalline or multi-crystalline silicon, thin-film deposited silicon, or any other materials used to fabricate solar cells and other semiconductor devices.

The interface between the p-type substrate 210 and the n-type emitter layer 215 forms a p-n junction 213. The photo-receptive region 225 contains one or more faceted regions. By directing light that would normally be reflected away from the solar cell 200 back onto the solar cell 200, the faceted region 225 decreases the amount of light lost by reflection, thereby increasing the efficiency of the solar cell 200. In one embodiment, the faceted region 225 is also covered by an anti-reflective coating.

The solar cell 200 also contains n-doped regions 220 (gridlines) having a substantially planar top surface coupled to metallic contact fingers 240.

Generally, solar cells contain more faceted regions and selective emitters than that shown in Figure 2. Figure 2 shows only one faceted region (containing facets 230A and 230B) and only one emitter region merely to simplify the drawing.

In the embodiment of Figure 2, the facets 230A and 230B are individual four-sided pyramidal elements, having exposed <111> planes.

Figure 3 is a top level view of the pyramidal facet 230A. Preferably, the height of the facet 230A is less that 10 microns, with a base having a comparable width. Those skilled in the art will recognize that the exemplary facet 230A can have other dimensions, as well as other shapes that reflect light back onto the surface of the solar cell 200. As one other example, the facet 230A is dome shaped.

Figure 4 shows a graph 300 that plots atomic concentration versus depth from a top surface (in angstroms) of the cell 200 for the planar regions 220. The graph 300 shows concentrations for a first implant stage 301 closest to the top surface, a second (main) implant stage 302, a third implant stage 303 closest to the PN junction 213, and the total concentration 310.

Figure 5 shows a graph 400 that plots atomic concentration versus depth from a top surface of the cell 200 (in angstroms) along the non-planar, textured (e.g., having an exposed <111> surface) regions 225. The graph 400 shows concentrations for a first implant stage

401 closest to the top surface, a second (main) implant stage 403, a third implant stage 405 closest to the p-n junction 213, and total concentration 410. This doping profile reduces the "dead layer" effect.

Such simultaneous implantation of <111> and <100> crystalline-plane silicon leads to a unique atomic profile. The surface area is presented to the implant beam, that is, directed to the <100> plane. Due to the geometry changes, the dosage implanted into the <111> plane is 0.578 of the dosage simultaneously implanted into the <100> plane. Additionally, the angle of incidence changes for differently oriented planes, and thus the penetration of ions will vary as a cosine function. For example, for a 120 keV beam, the projected range can vary from 1610 angstroms from the surface of the <100> plane to 998 angstroms from the surface of the <111> plane.

Figures 6A and B show doping the regions 220 and 230A of Figure 2 using an ion beam source 500, during sequential steps. Figure 6A shows the ion beam source 500 first positioned above a surface of the substrate 200, implanting n-type dopants in the substantially planar region 220. Next, as shown in Figure 6B, the source 500 is positioned so as to implant n-type dopants into right-hand and left-hand portions of the facet 230A. Both the left- and right-hand portions of the facet 230A are doped to a predetermined density and profile. Advantageously, processing these left- and right-hand portions does not require precise alignment of the source 500 with a wafer geometry or the use of a narrowly focused ion beam.

Such a change in the angle of implant and thus the implanted area can be used to advantage. As the implant angle deviates from the normal incidence, the lateral depth of the dopant is reduced. Similarly, the beam is spread over a larger area, as a cosine of the angle. Thus, the dopant dose is reduced. Such variation can be used to produce regions of high doping concentrations and deeper junctions versus regions of lower doping concentrations and shallower junctions.

The added surface area provided by the facet 230A has other advantages. As one example, during ion implantation the added surface area spreads the heat generated by the source 500, allowing for the use of higher density beams that increase productivity.

As shown in Figure 6A, the left portion has a base labeled 240. In one embodiment, a diameter of the beam is much larger than the base 240, allowing a single beam to dope both the left and right portions simultaneously. In other embodiments, the diameter of the beam is large enough to implant multiple facets simultaneously. Those skilled in the art will recognize that other beam diameters can be used. Furthermore, a whole encompassing plasma beam can be used, such as to conformally dope the textured features on the surface.

odiment, the source 500 emits a beam with the same d er second) when the source 500 is positioned over the regions 220 and 230A. Because the region 230A is angled to the source, it provides a larger surface area for the beam, resulting in the same charge being deposited over a larger area in the region 230A than in the region 220. Accordingly, the region 220 is more highly doped than the region 230A.

In one embodiment, the exemplary facet 230A is formed of a silicon substrate etched along the <111> plane, resulting in facet faces that have an angle of 54.7° to the substrate surface.

Figures 6A-C show the beam source 500 non-perpendicular to the sloping (angled) face of the facet 230A. In this arrangement, the doping thickness along the facet 230A increases from the base of the facet 230A to its apex.

Figure 7 shows an arrangement in which a beam source 550 is positioned perpendicular to the sloping faces of the facet 230A. In the first position (labeled 550A), the source 550 is perpendicular to the left face of the facet 230A. In the second position (labeled 550B), the beam source is perpendicular to the right face of the facet 230A.

In one embodiment, a single beam source is sequentially positioned in the first and second positions (550A and 550B); in another embodiment, separate beam sources are simultaneously positioned in the first and second positions so that the left- and right-portions are doped concurrently.

In accordance with embodiments, the substrate 200 and one or more ion beam sources are moved relative to each other in different ways to dope the substantially planar region 220 and the faceted region 230, which includes the individual facets 230A and 230B. To simplify the drawings, Figures 8A-C show only a single faceted region 230. As one example, Figure 8A shows ions from the one or more ion beam sources aimed perpendicular to the top surface of the substrate 200.

In one embodiment, the facets 230A and 230B are individually doped by scanning an ion beam separately across each of them. Alternatively, separate parallel ion beams concurrently dope the individual facets 230A and 230B. In this way, the doping level of each facet or group of facets can be individually controlled, allowing a more precise and tailored doping profile of the solar cell 200.

As shown by the vertical and circular lines under Figure 8B, the substrate 200 can be translated vertically (along the x-axis), rotated (along the y-axis), tilted, or any combination of these motions, relative to the one or more ion beam sources, so that the entire surface of the substrate 200 is implanted with dopants. In the example shown in Figure 8C, the one or more ion beam sources are directed so that the ions are directed substantially perpendicular to the faces of the pyramidal facets. Again, the substrate 200 can be translated vertically,

rotated, tilted, or any combination of these motions, relative to the one or more ion beam sources to implant the entire surface of the substrate 200 with dopants. Indeed, the ion beam can be an engulfing plasma of ions that conformally dope these textured features. This is particularly advantageous for multigrade silicon, where the faceting on the surface has no unique geometry and furthermore can have pin holes and re-entrant hillock features that may be observed by a line-of-sight dopant system. Such conformal doping will provide consistent doping independent of any surface features.

In still other embodiments, the ion beam is directed onto the substrate 200 so that it impinges at angles other than perpendicular to the planar region or perpendicular to the faces of the facets 230A and 230B. These other angles can be determined based on the desired doping profile to fit the particular application at hand. In one embodiment, the angle is no more than 20 degrees off perpendicular to a top of the substrate surface.

Figures 9A-F are side cross-sectional views of a portion of a semiconductor device 600, during the steps for fabricating a solar cell in accordance with one embodiment. Generally, a solar cell contains many portions similar to that shown in Figures 9A-F. The portion of Figures 9A-F and no others is shown merely to simplify the drawings.

As shown in Figure 9A, a p-type substrate 601 is masked with a photoresist material 650, leaving the regions 655A and 655B exposed. The photoresist material 650 is patterned using photolithographic or standard contact printing or inkjet printing techniques known to those skilled in the art. The region below the material 650, where the gridlines are to be formed, is about 50 to 100 microns wide. Accordingly, the large geometries provide for the use of photolithography techniques of lower precision relative to techniques required for semiconductors with sub-micron geometries.

Next, as shown in Figure 9B, the top layer of the device 600 is etched to form the faceted region, and the sacrificial material 650 is removed to expose the substantially planar surface 603. Preferably, the etching uses an acidic or alkaline etch, such as potassium hydroxide (KOH), to expose the <111> planes (textured regions) of the substrate 601, which contains the pyramidal facet regions 605A and 605B. Those skilled in the art will recognize that the regions 605A and 605B can be formed using other techniques, including optical, mechanical, and chemical techniques. Those skilled in the art will also recognize that the regions 605A and 605B can be formed into shapes other than pyramids, such as half domes, undulating waves, and other textured shapes.

Next, as shown in Figures 9C-E, the regions 605A, 603, and 605B are all implanted, respectively, using a uniform beam of n-type dopants, directed substantially perpendicular to the surface 603, thereby forming the regions 615A, 613, and 615B, respectively. As explained above with respect to Figures 6A-C, because the regions 615A and 615B have

centimeter is larger in the region 613 than in the regions 615A and 615B. Accordingly, the sheet resistance of the regions 615A and 615B is larger than that of the region 613. The region 613 is also referred to as the selective emitter region.

Figure 9F shows the device 600 after later processing steps. During these steps (not shown), a thin layer of metal ions 620 is implanted into the top surface of the region 613, which is then topped with a metallic conductive finger 660. The metal ions 610 help to better match the work function between the finger 660 and the selective emitter 613. Examples of metal ions 610 include, but are not limited to, tantalum, aluminum, copper, or any combination of these. Preferably, the device 600 contains multiple fingers 660, all coupled by a busbar (not shown). In one embodiment, the fingers 660 are 50-100 microns wide and spaced apart by about 2-3 millimeters. Those skilled in the art will recognize that other widths and spacings are also possible.

Next, also as one of these later processing steps, p-type ions are implanted into the bottom of the substrate 601, forming the P+ region 630, thereby improving the conductivity of subsequently formed layers. Additional metal ions are then implanted into the P+ region 630 forming a metal silicon region 640, attached to a metal back side contact 645. The region 640 reduces the work function between the P+ silicon 630 and the contact 645.

Those skilled in the art will recognize that the process steps described in Figures 9A-F, as with all the process steps described in this Specification, are merely illustrative. Some of the steps can be deleted, other steps can be substituted, and the steps can be performed in different orders. As one example, the entire surface of the device 600 is faceted. A laser beam is then used to form the substantially planar region in which the selective emitter (603) is to be formed. The laser beam melts the facets in the selective emitter region, thereby melting the peaks of the facets and filling in the valleys between the peaks. The doping and other steps discussed with respect to Figures 9C-E are then performed.

Those skilled in the art will recognize many other ways to fabricate solar cells and other semiconductor devices in accordance with the embodiments. As one example, dopants are placed by implanting or depositing doped paste and then rapidly annealing the substrate, such as using a flash lamp or laser annealing to provide gridline doped layers.

Figure 10 shows the steps of a process 700 for fabricating a solar cell in accordance with one embodiment. The process 700 starts in the step 701. In the step 703, the planar region (*e.g.*, element 613 in Figure 9C) and the non-planar regions (e.g., elements 615A and 615B in Figure 9C) are formed on a semiconductor substrate. Next, in the step 705, the doping profiles (*e.g.*, doping levels based on depth, such as shown in Figure 5) are determined, based on the desired solar cell characteristics. Next, in the step 707, a next

element (e.g., an emitter region, faceted region, or individual facet) is doped using an ion beam. In the step 709, the process determines whether there is another element (*e.g.*, a next facet) to be doped. If there is another element, the ion beam is moved in step 711, and the process loops back to the step 707. In an alternative embodiment, in which a plasma is used, rather than stepping an ion beam in the step 711, a plasma engulfing beam is used to engulf the entire surface of the substrate. Otherwise, the process continues to the step 713.

A substrate can be implanted in any number of stages to fit the desired doping profile. As one example, implanting is performed in three stages, such as illustrated by the multiple doping profiles in Figure 5.

In the step 713, contacts (e.g., fingers, busbars, and any backside contacts) are formed, followed by the step 715, in which the substrate is annealed. Annealing the substrate–heating it to a temperature below melting–restores the crystal structure damaged by ion implantation. Next, in the step 717, any post-processing steps are performed. These post-processing steps include cleaning, removing any contaminants from, and adding any protective coatings to the finished substrate. Finally, in the step 719, the process ends.

In one embodiment, the substrate has alignment markers on its surface, used to orient and step the beam during the step 711.

While the step 711 describes an ion beam being moved, it will be appreciated that the substrate, rather than the beam, can be moved, such as illustrated in Figures 8B and 8C.

Figure 11 shows a system 800 for fabricating solar cells in accordance with one embodiment. The system 800 includes a single-gas delivery module 805, an ion source 810, an accelerator 815, a skewed Beam Scanning, Mass Analysis, and Beam Shaping module 820, a Measurement and Control module 825, and a single load lock 830 to handle the substrate 600. In another embodiment (not shown), the single-gas delivery module 805 and ion source 810 are replaced with a plasma source module, and the Beam Shaping module 820 is replaced with a spreader for engulfing the substrate 600 with a plasma beam.

In one embodiment, the ion source 810 has a long slot. In alternative embodiments, the ion source 810 includes multiple ion sources for the formation of broad and narrow, or plasma beams. The ion source 810 produces beam currents up to 100 mA of all species but can be dedicated to a single species at one time. The ion source 810 is also plug-compatible for each specific application: when a new application with a different ion beam source is required, the ion source 810 can be pulled out and replaced with a different one that meets requirements (e.g., different dopant) of the next application. The ion source 810 has a beam slot of less than 5 to 10 cm and a width of 1 to 2 mm. Alternatively, the ion source 810 is a plasma source and can be configured to produce a broad beam. The length can be stretched to cover one dimension of a 156 mm x 156 mm substrate or both dimensions of the substrate.

In operation, the single-gas delivery module 805 and ion source 810 together generate an ion beam, which is accelerated by the accelerator 815, either in DC fashion or pulsed. In one embodiment, the accelerator has extraction and focusing elements with a limited energy range, such as between 15 and 150 keV. In other embodiments, other limited energy ranges are used. In one embodiment, to limit the energy requirements of the system 800, the accelerator 815 does not operate above 100 keV. In one embodiment, the substrate 600 is inserted into the system 800 after it has been etched, as shown in Figure 9B.

Next, the resulting skewed beam is controlled using the Beam Scanning, Mass Analyzing, and Shaping module 820 to implant the substrate 600, such as shown in Figures 9C-D (for the substrate 600) or as shown in Figures 6A, 6B, and 7 (for the substrate 200 of Figure 2). In one embodiment, the Beam Scanning, Mass Analyzing, and Shaping module 820 includes electrostatic and electromagnetic optics used to focus or shape the beam onto the substrate 600. The beam is further measured and controlled using the Measurement and Control module 825 before or at the same time as the beam impinges on the substrate 600. The substrate 600 can be stepped in front of the beam to implant dopants according to a predetermined pattern, using a single beam to cover the entire surface of the substrate 600. The substrate 600 can also be rotated, translated, and tilted, such as shown in Figures 8A-C.

The ion beam can be a broad beam (e.g., 10s of centimeters in diameter) that provides a constant flux of ions across the plane of the substrate 600, that is, scanned across the plane of the substrate 600. The beam is preferably scanned at an even rate across the plane of the substrate 600, across the entire planar and faceted regions. The scanning rate can be altered to achieve varying regions of high doping and low doping by overlapping the Gaussian spread of the beam.

The ion beam causes localized heating. Thus, slow scanning can be used with a wider ion implantation beam and faster scanning can be used with a narrower beam. Multiple passes may be needed to reach the required doping density, such as shown by the three implant steps in Figure 5.

Preferably, the Beam Scanning, Mass Analyzing, and Shaping module 820 includes logic for doping substrates in accordance with the embodiments. Alternatively, the logic is contained in another element of the system 800. Preferably, the logic includes a memory containing machine-readable instructions for performing process steps (e.g., any one or more of the steps 703, 705, 707, 709, 711, 713, 715, and 717 in Figure 10) and a processor for executing those steps.

In one embodiment, the substrate 600 is 156 mm x 156 mm, but the system 800 is capable of processing wafers of other dimensions. In alternative embodiments, a wafer is deployed before the beam on a moving platen, or one or more wafers on a tray are exposed to the beam or plasma.

Finally, the processed single substrate 600 is removed from the system 800 through the single load lock 830.

It will appreciated that the embodiments described above are merely exemplary. For example, the embodiments show a p-type substrate with an n-type emitter layer. It will be appreciated that an n-type substrate with a p-type emitter layer can also be fabricated in accordance with the embodiments.

The following co-pending patent applications, each of which is incorporated by reference in its entirety, describe different ways of fabricating solar cells: Serial No. XX/XXX,XXX, filed June 11, 2009, titled "Solar Cell Fabrication Using Implantation," by Babak Adibi and Edward S. Murrer, and having Attorney Docket No. SITI-00100; Serial No. XX/XXX,XXX, filed June 11, 2009, titled "Application Specific Implant System and Method for Use in Solar Cell Fabrications," by Babak Adibi and Edward S. Murrer, and having Attorney Docket No. SITI-00200; and Serial No. XX/XXX,XXX, filed June 11, 2009, titled, "Formation of Solar Cell-Selective Emitter Using Implant and Anneal Method," by Babak Adibi and Edward S. Murrer, and having Attorney Docket No. SITI-00300.

Though the embodiments are directed to solar cells, other embodiments can be used for other types of semiconductor devices, with any number of doping profiles. These distributions include gradual and abrupt distributions, such as box junctions, as well as other distributions that prevent the formation of electrical barriers.

While limitations in the prior art have been discussed, it will be appreciated that each embodiment will not necessarily solve all the limitations. Some embodiments may solve some limitations and other embodiments may solve other ones.

It will be readily apparent to one skilled in the art that other modifications may be made to the embodiments without departing from the spirit and scope of the invention as defined by the appended claims.

Claims

What is claimed is:

1. A semiconductor device comprising:
a substrate having a surface that contains textured regions doped with a dopant to a first doping level and non-textured regions forming gridlines and doped with the dopant to a second doping level larger than the first doping level; and
conductive fingers coupled to the gridlines.

2. The semiconductor device of claim 1, wherein the textured-regions are photo-receptive.

3. The semiconductor device of claim 1, wherein each of the textured regions comprises multiple textured elements.

4. The semiconductor device of claim 3, wherein each of the textured elements is pyramidal shaped.

5. The semiconductor device of claim 4, wherein each of the textured elements has a <111> plane.

6. The semiconductor device of claim 3, wherein each of the textured elements is dome shaped.

7. The semiconductor device of claim 3, wherein a thickness of the dopant on each of the multiple textured elements is uniform.

8. The semiconductor device of claim 1, wherein each of the textured regions is covered with an anti-reflective coating.

9. The semiconductor device of claim 1, wherein the dopants are n-type and the substrate is p-type.

10. The semiconductor substrate of claim 1, wherein the dopants are p-type and the substrate is n-type.

11. The semiconductor device of claim 1, wherein the dopants in the non-textured regions are interspersed with a metallic species.

12. The semiconductor device of claim 1, wherein the substrate has a bottom portion coupled to a metallic contact containing impurities.

13. A method of fabricating a solar cell comprising:
exposing a surface of a substrate having non-textured and textured regions to ions, thereby implanting dopants into the textured regions at a first density and into the non-textured regions at a second density larger than the first density to form gridlines; and
coupling contact fingers to the gridlines.

14. The method of claim 13, wherein the textured regions each comprise multiple textured elements.

15. The method of claim 14, wherein the multiple textured elements are pyramidal.

16. The method of claim 14, wherein the multiple textured elements are semi-spherical.

17. The method of claim 13, wherein exposing the surface comprises directing an ion beam containing the dopants onto the surface.

18. The method of claim 17, wherein the beam is shaped to implant dopants into each of the multiple textured elements individually.

19. The method of claim 17, further comprising linearly scanning the beam across the surface to thereby implant the dopants.

20. The method of claim 13, wherein exposing the surface comprises engulfing the surface with a plasma beam.

21. The method of claim 13, wherein the textured regions are photo-receptive.

22. The method of claim 13, further comprising rotating a source of the ions, the substrate, or both so that the ion source is substantially perpendicular to faces of each of the multiple textured elements.

23. The method of claim 13, wherein a resistance of the dopant in the non-textured regions is about 20 ohms/square.

24. The method of claim 13, wherein a resistance of the dopant in the textured regions is about 100 ohms/square.

25. The method of claim 13, further comprising coupling the gridlines to metallic contact fingers.

26. The method of claim 25, further comprising forming a silicide between the gridlines and the contact fingers.

27. A method of fabricating a solar cell comprising:
etching a top surface of a substrate to form textured photo-receptive regions among planar regions, wherein the textured regions comprise pyramidal shaped elements;
directing an ion beam onto the top surface, thereby implanting dopants into the textured regions at a first density and into the planar regions at a second density larger than the first density to form gridlines, wherein a resistance of the dopant in the textured regions is less than 100 ohms per square and a resistance of the dopant in the planar regions is about 20 ohms per square; and
coupling contact fingers to the gridlines.

28. A solar cell comprising:
a substrate having a top layer and a bottom layer, wherein the top layer has a surface containing pyramidal regions doped with a dopant to a first doping level and substantially planar regions forming gridlines and doped with the dopant to a second doping level larger than the first doping level, distances between adjacent substantially planar regions are less than 50 microns, and the substrate having a thickness of less than 50 microns;
silicide elements coupling the gridlines to metallic fingers; and
a contact coupled to the bottom layer.

29. A system for fabricating solar cells comprising:
a source for producing ions;
a beam shaper to direct a beam containing the ions onto a substrate; and
a controller programmed to direct the beam onto the substrate such that a textured photo-receptive region of the substrate is implanted with the ions to a first density and a planar region of the substrate defining a gridline is implanted with the ions to a second density larger than the first density.

30. The system of claim 29, wherein the controller is also programmed to step the beam to individually implant textured elements in the photo-receptive region.

31. The system of claim 30, wherein the controller is also programmed to perform any combination of rotating, tilting, or translating the substrate when the beam is directed onto the substrate.

32. The system of claim 30, wherein the controller is programmed to direct the beam so that a resistance of the photo-receptive region is about 100 ohms per square.

33. The system of claim 30, wherein the controller is programmed to direct the beam so that a resistance of the planar region is about 10 ohms per square.