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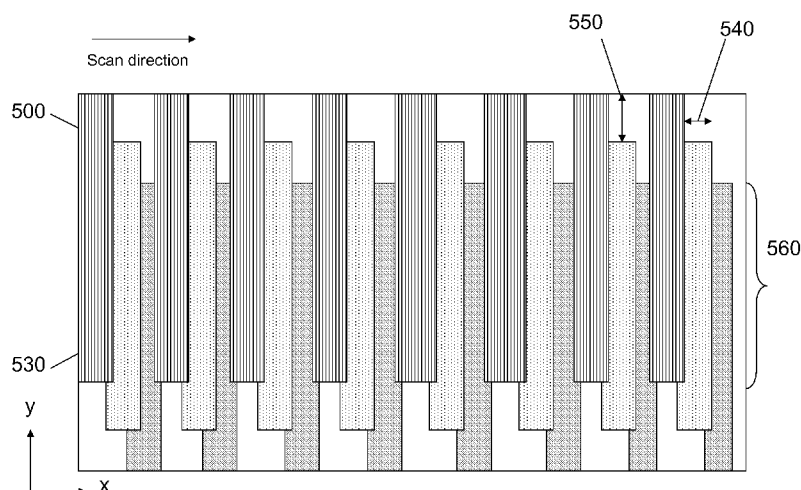
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(54) Title: SYSTEMS AND METHODS FOR THE CRYSTALLIZATION OF THIN FILMS

Figure 6



(57) Abstract: Crystallization of thin films using pulsed irradiation The method includes continuously irradiating a film having an x-axis and a y-axis, in a first scan in the x-direction of the film with a plurality of line beam laser pulses to form a first set of irradiated regions, translating the film a distance in the y-direction of the film, wherein the distance is less than the length of the line beam, and continuously irradiating the film in a second scan in the negative x-direction of the film with a sequence of line beam laser pulses to form a second set of irradiated regions, wherein each of the second set of irradiated regions overlaps with a portion of the first set of irradiated regions, and wherein each of the first and the second set of irradiated regions upon cooling forms one or more crystallized regions.

SYSTEMS AND METHODS FOR THE CRYSTALLIZATION OF THIN FILMS**Related Applications**

[0001] This application claims priority under 35 U.S.C. § 119(e) to U.S. application serial no. 61/111,518, entitled “Systems and Methods for the Crystallization of Thin Films,” filed on November 14, 2008, which is incorporated by reference herein in its entirety.

[0002] This application is related to co-pending, commonly owned U.S. application Serial No. 11/293655, filed December 2, 2005, U.S. Application Serial No. 12/063810, filed February 14, 2008, and PCT Application Serial No. PCT/US08/77704, filed September 25, 2008, all of which are incorporated by reference herein in their entireties.

Field

[0003] The disclosed subject matter generally relates to crystallization of thin films and particularly relates to crystallization of thin films using line beam pulsed laser irradiation.

Background

[0004] In recent years, various techniques for crystallizing or improving the crystallinity of an amorphous or polycrystalline semiconductor film have been investigated. Such crystallized thin films may be used in the manufacture of a variety of devices, such as image sensors and active-matrix liquid-crystal display (“AMLCD”) devices. In the latter, a regular array of thin-film transistors (“TFTs”) is fabricated on an appropriate transparent substrate, and each transistor serves as a pixel controller.

[0005] Prior art methods for improving the crystallinity of the semiconductor film typically involve irradiating the thin film with a shaped laser beam. The shaped laser beam optimally should be a long line beam with a uniform width, a top-hat short axis profile, and uniform energy along its length. However, producing such a beam is challenging and most line-beams will have non-uniformities along the length of the beam, while the cross-section of the beam is more rounded or, in some instances, Gaussian. The non-uniformities can have random and periodic components (hereinafter referred to as “random non-uniformities” and “periodic non-uniformities”, respectively). These non-uniformities in the laser beam can translate to non-uniformities in the film, which results in non-uniformities in the devices

implementing the films, for example, non-uniformities in the brightness of a display in a AMLCD application.

Summary

[0006] The application describes systems and methods for the crystallization of thin films using pulsed irradiation of a long, narrow beam shape that is continuously advanced over the film surface. The methods provide crystallized films in which variations in the quality and performance of the crystallized regions is reduced.

[0007] In one aspect, the application describes a method of processing a film. The method includes continuously irradiating a film having an x-axis and a y-axis, in a first scan in the x-direction of the film with a plurality of line beam laser pulses to form a first set of irradiated regions; translating the film a distance in the y-direction of the film, wherein the distance is less than the length of the line beam; and continuously irradiating the film in a second scan in the negative x-direction of the film with a sequence of line beam laser pulses to form a second set of irradiated regions, wherein each of the second set of irradiated regions overlaps with a portion of the first set of irradiated regions, and wherein each of the first and the second set of irradiated regions upon cooling forms one or more crystallized regions.

[0008] In any of the foregoing embodiments, each line beam laser pulse has a fluence that is sufficient to melt the film throughout its thickness in the first and second set irradiated regions, and wherein each of the first set of irradiated regions are spaced-apart from each other.

[0009] In any of the foregoing embodiments, each of the first set of irradiated regions upon cooling forms one or more laterally grown crystals and wherein each of the second set of irradiated regions upon cooling forms one or more laterally grown crystals that are extended relative to the one or more laterally grown crystals of the first set of irradiated regions

[0010] In any of the foregoing embodiments, the laser crystallization method employed is sequential lateral solidification.

[0011] In any of the foregoing embodiments, each of the first set of irradiated regions overlap each other.

[0012] In any of the foregoing embodiments, the number of laser beam pulses in the first scan is less than the amount needed to complete crystallization of the film.

[0013] In any of the foregoing embodiments, the number of laser beam pulses in the second scan is an amount needed to complete crystallization of the film.

[0014] In any of the foregoing embodiments, the laser crystallization method employed is excimer laser annealing.

[0015] In any of the foregoing embodiments, the crystallization method uses from about 10 to about 100 pulses or about 10 to about 40 pulses per unit area.

[0016] In any of the foregoing embodiments, the overlap between irradiation regions within each scan is less than 80% or less than 90%.

[0017] In any of the foregoing embodiments, the method includes at least 2 continuous scans or includes 2-8 continuous scans.

[0018] In any of the foregoing embodiments, the y-direction translation distance is about 10 μm to about 10 mm or about 100 μm to about 2 mm..

[0019] In any of the foregoing embodiments, the method includes rotating the film about 180 degrees between scans.

[0020] In another aspect, the application relates to a system for processing a film, the system including at least one laser for generating a plurality of laser beam pulses for pulsed laser crystallization of the film, wherein each laser pulse forms a line beam having a length and a width; a film support for positioning a film disposed thereon that is capable of movement in at least two directions; and a controller for providing instructions on controlling the movement of the film support in conjunction with the frequency the laser beam pulses. In any of the foregoing embodiments, controlling the movement of the film support includes continuously irradiating a film, having an x-axis and a y-axis, in a first scan in the x-direction of the film with a plurality of line beam laser pulses to form a first set of irradiated regions; translating the film a distance in the y-direction of the film, wherein the distance is less than

the length of the line beam; and continuously irradiating the film in a second scan in the negative x-direction of the film with a sequence of line beam laser pulses to form a second set of irradiated regions, wherein each of the second set of irradiated regions overlaps with a portion of the first set of irradiated regions, and wherein each of the first set and second set of irradiated regions upon cooling forms one or more crystallized regions.

[0021] In any of the foregoing embodiments, each line beam laser pulse has a fluence that is sufficient to melt the film throughout its thickness in the first and second set irradiated regions, and wherein each of the first set of irradiated regions are spaced-apart from a each other.

[0022] In any of the foregoing embodiments, each of the first set of irradiated regions upon cooling forms one or more laterally grown crystals and wherein each of the second set of irradiated regions upon cooling forms one or more laterally grown crystals that are extended relative to the one or more laterally grown crystals of the first set of irradiated regions

[0023] In any of the foregoing embodiments, the laser crystallization method employed is sequential lateral solidification.

[0024] In any of the foregoing embodiments, each of the first set of irradiated regions overlap each other.

[0025] In any of the foregoing embodiments, the number of laser beam pulses in the first scan is less than the amount needed to complete crystallization of the film.

[0026] In any of the foregoing embodiments, the number of laser beam pulses in the second scan is an amount needed to complete crystallization of the film.

[0027] In any of the foregoing embodiments, the laser crystallization method employed is excimer laser annealing.

[0028] In any of the foregoing embodiments, the crystallization method uses from about 10 to about 100 pulses per unit area.

[0029] In any of the foregoing embodiments, the crystallization method uses from about 10 to about 40 pulses per unit area.

[0030] In any of the foregoing embodiments, the overlap between irradiation regions within each scan is less than 80%.

[0031] In any of the foregoing embodiments, the overlap between irradiation regions within each scan is less than 90%.

[0032] In any of the foregoing embodiments, the method includes at least 2 continuous scans.

[0033] In any of the foregoing embodiments, the method includes 2-8 continuous scans.

[0034] In any of the foregoing embodiments, the y-translation distance is about 100 μm to about 10 mm.

[0035] In any of the foregoing embodiments, the y-translation distance is about 100 μm to about 2 mm.

[0036] In any of the foregoing embodiments, the film is rotated about 180 degrees between scans.

[0037] In another aspect, the disclosure relates to a product containing a film processed by the method of the disclosure. In any of the foregoing embodiments, the product is an liquid crystal display screen.

Drawings

[0038] The disclosed subject matter is described with reference to the following drawings, which are presented for the purpose of illustration only and which are not intended to be limiting of the invention.

[0039] Fig. 1A illustrates a TFT formed within films having crystalline microstructures formed by excimer laser annealing.

[0040] Figs. 1B-1D illustrate TFTs formed within films having crystalline microstructures formed by sequential lateral crystallization.

[0041] Figs. 2A-2D illustrate a line beam sequential lateral solidification process to produce uniform crystals according to certain embodiments.

[0042] Fig. 3 is a schematic illustration of a line beam pulse varying in width along its length.

[0043] Figs. 4-6 are schematic illustrations of a process according to one or more embodiments of a line scan SLS process in which periodic variations in crystallization quality are addressed, according to one or more embodiments of the present disclosure.

[0044] Figs. 7A-7B are schematic illustrations of a process according to one or more embodiments of an ELA process in which periodic variations in crystallization quality are addressed, according to one or more embodiments of the present disclosure.

[0045] Fig. 8 is a schematic illustration of a system for performing the method of crystallization of a thin film, according to one or more embodiments of the present disclosure

Detailed Description

[0046] In one aspect a thin film having more uniform properties is obtained by line beam irradiation using multiple scans of the laser beam across substantially the same region of the film. Line beam irradiation refers to irradiating a surface of a film using a line beam to induce crystallization in the film. The method may be practiced using any pulsed laser line beam crystallization method. For example, the method may use excimer laser annealing (“ELA”) or sequential lateral solidification (“SLS”) crystallization methods. Furthermore, it will be apparent from the description that follows that the method is not limited to silicon thin film crystallization and may be practiced for any thin film that re-crystallizes upon melting. For the purposes of discussion that follows, unless specifically noted, the methods may be used for any such material.

[0047] The method may also be used on discontinuous films, for example films patterned by lithographic techniques or films deposited only in select regions, e.g., via ink-jet printing techniques or shadow-mask printing.

[0048] According to one aspect of the disclosure, in each pass of the multi-scan crystallization process, only a portion of the film is irradiated or the number of irradiation pulses per unit area is only a fraction or percentage of the number of irradiations needed to

complete the crystallization process. In between each scan, the film is displaced a short distance in the direction perpendicular to the scan direction, e.g., a “transverse shift.” A transverse shift can mean a ‘sideways’ translation, i.e., a translation of the panel in a direction perpendicular to the scan direction. Thus, if the scan direction is arbitrarily designated as a scan in the x-direction, then the film (or the laser beam) is displaced a short distance in the y-direction between scans. The translation distance can be small and is typically on the order of any periodic non-uniformity that arises along the length of the line beam. The translation distance may be as small as 100 microns or even 10 microns but could be as large as several millimeters or more.

[0049] When the beam is translated sideways with respect to the sample in between each of the scans, this will result in the (periodic) non-uniformities in the crystallized material arising from variations in laser line beam qualities being shifted with respect to those in the previous scan. As a result, there will not be one “stripe” or crystallized region in which all material was crystallized with the same peak intensity, but rather, there will be a number of stripes in which only a fraction of the material will have experienced such a peak. Devices that are placed within those regions will be less affected by the differences in the stripe properties, provided the dimensions of the devices span at least more than one crystallized region.

[0050] Crystalline semiconductor films, such as silicon films, have been processed to provide pixels for liquid crystal displays using various laser processes including ELA and SLS processes. SLS is well suited to process thin films for use in AMLCD devices, as well as active-matrix organic light emitting diode (“AMOLED”) devices.

[0051] In ELA, a region of the film is irradiated by an excimer laser to partially melt the film, which subsequently crystallizes. The process typically uses a long, relatively narrow beam shape that is continuously advanced over the substrate surface, so that the beam can potentially irradiate the entire semiconductor thin film in a single scan across the surface. ELA produces small-grained polycrystalline films; however, the method often suffers from microstructural non-uniformities, which can be caused by pulse to pulse energy fluctuations and/or non-uniform beam intensity profiles. Fig. 1A illustrates a random microstructure that may be obtained with ELA. The Si film is irradiated multiple times to create the random

polycrystalline film with a uniform grain size. This figure, and all subsequent figures, are not drawn to scale, and are intended to be illustrative in nature.

[0052] SLS is a pulsed-laser crystallization process that can produce high quality polycrystalline films having large and uniform grains on substrates, including substrates that are intolerant to heat such as glass and plastics. Exemplary SLS processes and systems are described in commonly-owned U.S. Patent Nos. 6,322,625, 6,368,945, 6,555,449, and 6,573,531, the entire contents of which are incorporated herein by reference. Figs. 1B-1D illustrate TFTs formed within films having crystalline microstructures formed by SLS.

[0053] SLS uses controlled laser pulses to melt a region of an amorphous or polycrystalline thin film on a substrate. The melted regions of film then laterally crystallize into a directionally solidified lateral columnar microstructure or a plurality of location-controlled large single crystal regions. Generally, the melt/crystallization process is sequentially repeated over the surface of a large thin film, with a large number of laser pulses. The processed film on substrate is then used to produce one large display, or even divided to produce multiple displays. Figs. 1B-1D show schematic drawings of TFTs fabricated within films having different microstructures that can be obtained with SLS. The SLS process can use a long, narrow beam that is continually advanced over the substrate surface, in which case the process is known as line scan SLS ("LS-SLS").

[0054] However, conventional ELA and SLS techniques can be limited by variation in the laser pulses from one shot to the next. Each laser pulse used to melt a region of film typically has different energy fluence than other laser pulses used to melt other regions of film. In turn, this can cause slightly different performance in the regions of re-crystallized film across the area of the display. For example, during the sequential irradiation of neighboring regions of the thin film, a first region is irradiated by a first laser pulse having a first energy fluence; a second region is irradiated by a second laser pulse having a second fluence which is at least slightly different from that of the first laser pulse; and a third region is irradiated by a third laser pulse having a third fluence that is at least slightly different from that of the first and second laser pulses, etc. The resulting energy densities experienced by the irradiated and crystallized first, second and third regions of the semiconductor film are all, at least to some extent, different from one another due to the varying fluences of the sequential beam pulses irradiating neighboring regions.

[0055] Shaping a laser beam into a very long line-beam that further has uniform width, preferably a top-hat short-axis cross sectional profile, and uniform energy along its length, is challenging. Non-uniformities in the long axis can be more pronounced, and therefore more detrimental. Furthermore, non-uniformities along the long axis may be on a scale that is very clearly visible to the human eye (e.g., a 10% brightness shift over one cm or a few mm). While the eye is reasonably tolerant to random pixel-to-pixel variations and also to very large-scale (10s of cm) and gradual pixel-to-pixel variations, it is not very tolerant to abrupt changes between regions of a display or to small-scale (millimeters to centimeters) gradual fluctuations.

[0056] Line-beams often will have non-uniformities in width and energy along the length of the beam, while the cross section often is more rounded or even Gaussian. Non-uniformities along the length of the beam may have a random component, and likely also will have periodic components. These are the result of coherence of the laser light in combination with details of the optical elements (e.g., lens arrays for homogenization). Such non-uniformities will likely translate into unacceptable levels of device uniformities that, in turn, result in non-uniformities of the brightness of the display. This is true for all pixel-based displays, but is especially true for AMOLED devices. For example, an intensity peak in the beam may result in a long stripe of material crystallized at higher energy along the direction of the scan and devices made within that stripe may have different properties from those outside of it.

[0057] A line beam SLS process could, for example, use a one dimensional (1D) projection system to generate a long, highly aspected laser beam, typically on the order of 1-100 cm in length, e.g., a "line beam." The length to width aspect ratio may be in the range of about 50 or more, for example up to 100, or 500, or 1000, or 2000, or 10000, or up to about 2×10^5 , or more for example. A thin film that is irradiated by a highly aspected (long) irradiation pattern can be fabricated into TFTs that provide enhanced pixel-to-pixel brightness uniformity because a single scan will crystallize an area large enough for the entire display. The beam length is preferably at least about the size of a single display, e.g., a liquid crystal or OLED display, or a multitude thereof or is preferably about the size of a substrate from which multiple displays can be produced. This is useful because it reduces or eliminates the appearance of any boundaries between irradiated regions of film. Any stitching artifacts that may arise when multiple scans across the film are needed, will

generally not be visible within a given liquid crystal or OLED display. The beam length can be suitable for preparing substrates for cell phone displays, e.g., approximately a two inch diagonal for cell phones and ranging up to about a 10-16 inch diagonal for laptop displays (with aspect ratios of 2:3, 3:4 or other common ratios).

[0058] One conventional LS-SLS irradiation protocol, referred to herein as “uniform SLS” or “2-shot SLS,” may be used to prepare a uniform crystalline film characterized by repeating columns of laterally elongated crystals. The crystallization protocol involves advancing the film by an amount greater than the actual lateral growth length (“LGL”), e.g., $\delta > \text{LGL}$, where δ is the translation distance between pulses, and less than two times the lateral growth length, e.g., $\delta < 2 \text{ LGL}$. The characteristic lateral growth length refers to the distance of unimpeded lateral growth of a crystalline grain in a single irradiation step under set irradiation conditions and sample configuration. Ultimately, lateral growth is limited by the onset of nucleation in the supercooled liquid Si film. The characteristic lateral growth length therefore is a function of factors such as pulse duration, the amorphous silicon film thickness, and the substrate temperature. The actual lateral growth length may be shorter than the characteristic length if, for example, the growing crystals encounter a solid front originating from other Si portions that were not completely melted throughout their thickness. A typical lateral growth length for 50 nm thick films is approximately up to 2.0 to 3.0 microns, depending on the pulse duration. In the case for 2-shot SLS, the translation distance is more than once, but less than twice the length of the grains which, in the absence of nucleation, corresponds to half the beam width. Uniform crystal growth is described with reference to Figs. 2A-2D.

[0059] Referring to Fig. 2A, a first irradiation or scan is carried out on a film with a narrow, e.g., less than two times the characteristic LGL, and elongated, e.g., greater than 10 mm and up to or greater than 1000 mm, laser beam pulse having an energy density sufficient to completely melt the film. As a result, the film exposed to the laser beam (shown as region **400** in Fig. 2A), is melted completely and then crystallized. In this case, grains grow laterally from an interface **420** between the un-irradiated region and the melted region. By selecting the laser pulse width so that the molten zone width is less than about two times the characteristic LGL, the grains growing from both solid/melt interfaces collide with one another approximately at the center of the melted region, e.g., at centerline **405**, and the

lateral growth stops. The two melt fronts collide approximately at the centerline **405** before the temperature of the melt becomes sufficiently low to trigger nucleation.

[0060] Referring to Fig. 2B, after being displaced by a predetermined distance δ that is at least greater than about one LGL and less than at most two LGL, a second region of the substrate **400'** is irradiated with a second laser beam pulse. The displacement of the substrate, δ , is related to the desired degree of overlap of the laser beam pulse. As the displacement of the substrate becomes longer, the degree of overlap becomes less. It is advantageous and preferable to have the overlap degree of the laser beam to be less than about 90% and more than about 10% of the LGL. The overlap region is illustrated by brackets **430** and dashed line **435**. The film region **400'** exposed to the second laser beam irradiation melts completely and crystallizes. In this case, the grains grown by the first irradiation pulse serve as crystallizing seeds for the lateral growth of the grains grown from the second irradiation pulse. Fig. 2C illustrates a region **440** having crystals that are laterally extended beyond a lateral growth length. Thus, a column of elongated crystals are formed by two laser beam irradiations on average. Because two irradiation pulses are all that is required to form the column of laterally extended crystals, the process is also referred to as a “two shot” process. Irradiation continues across the substrate to create multiple columns of laterally extended crystals. Fig. 2D illustrates the microstructure of the substrate after multiple irradiations and depicts several columns **440** of laterally extended crystals.

[0061] It has been observed that there are variations in the width, the shape, and/or the energy density of the line beam along the length of the beam. In some instances the variations are periodic in nature. In some instances, the periodicity of the non-uniformity is greater at one end of the line beam than the other. An exemplary line beam **300** demonstrating periodic variation of the width of the beam in the irradiation pattern is shown in Fig. 3. A similar example could be given for the energy density. The line beam is not drawn to scale and in typical use is much narrower relative to the beam length than shown. The beam length shows regular periodic variation **310, 320** along the length of the beam. In some instances the periodicity can be broad, such as is shown in **310**. The periodicity is large enough that it spans several devices on the surface and so the variation is not as noticeable. In contrast, the periodicity in **320** can be much smaller. The periodicity can vary from distances ranging from microns to millimeters, e.g., 100 μm to 5 mm. This periodicity is small enough that it will introduce differences in crystalline quality from device to device.

By translating each scan on the order of the periodicity of the variations, the variation in crystalline quality is averaged out so that a more uniform structure is obtained.

[0062] Turning now to Figs. 4-6, a method of crystallization using LS-SLS is described. For an LS-SLS process, in which complete crystallization of a selected region accomplished in “n” scans across the region, only a fraction of the material is fully processed (for example, approximately 1/nth thereof) or only 1/nth of the total irradiation pulses necessary for complete crystallization are used. For example, as shown in Figs. 4-6, if n=3, for a substrate **500** the in-between-pulse translation distance is three times that in a regular scan process. Each pulse will irradiate a region **510**. As a result of this long translation distance, amorphous material **515** will remain in between crystallized regions. The laser beam advances in the direction shown by the arrow indicating scan direction under a stationary laser line beam. In other embodiments, the substrate is stationary and the laser is scanned. Upon the second scan shown in Fig. 5, the in-between pulse translation distance is again three times the regular distance, but now the pulses are offset a length **525** in the x-direction with respect to the first scan so that the pulses overlap to a pre-selected extent with the regions irradiated in the first scan. In addition the substrate is translated a distance **535** in the y-direction. As noted above, the y-translation is selected based on the periodicity of the variation in the laser beam length. Finally turning to Fig. 6, a third scan is performed in which the substrate is scanned in the direction indicated by the arrow in Fig. 6. The substrate is again translated before the scanning begins, with a long translation distance **550** in the y-direction and again with an offset **540** in the x-direction. After three scans, accompanied by the appropriate offsets in the x directions and translations in the y-directions, the entire width of a preselected region **560** of the substrate is irradiated. Upper and lower portions of the substrate are not completely crystallized, leaving a region **560** that is fully crystallized and usable for the preparation of devices as well as more uniform than using conventional methods.

[0063] This method relates to crystallizing the entire panel or a portion of the substrate, depending on the length of the beam. If the panel is sufficiently large, multiple crystallized regions within one panel can be made by applying the described method to different areas of the panel.

[0064] In other embodiments, the devices are prepared at an angle with respect to the grain boundaries, so that each device intentionally spans several grain boundaries. This tilt angle can be obtained by preparing the devices at an angle with respect to the x-y axes of the substrate. In other embodiments, the tilt can be introduced into the film directly by scanning the substrate at a tilt angle, e.g., the x-y axes of the translation and offset during crystallization are not parallel to the square edges of the substrate. Using a tilted scan direction with respect to the TFT matrix may alleviate the issue somewhat in a sense that non-uniformities will be distributed. See, United States Application Serial Number 11/293,655, entitled "Line Scan Sequential Lateral Solidification of Thin Films" filed December 2, 2005, the entire contents of which are hereby incorporated by reference.

[0065] The current application also contemplates that a similar approach may be used for floor irradiation techniques using a line beam, for example in the partial melting or the near-complete melting regimes; referred to as line-beam ELA crystallization. Excimer laser annealing technology allows the rapid (on the order of less than a microsecond) melting and re-crystallization of thin film materials. In this technique, the thin film is exposed to many pulses of irradiation, as the narrow laser beam is moved across the surface. Each pulse melts a portion of the film, which re-solidifies and re-crystallizes. For a typical line-beam ELA process that is used in manufacturing of low-temperature polycrystalline silicon (LTPS) based displays, at least some of the pulses are at an energy density sufficient to induce near-complete melting of the film. With near-complete melting it is meant that the film may melt throughout its thickness in many parts of the film but that at least some solid portions remain distributed along the interface with the below layer. From this near-complete melt condition, lateral growth proceeds and crystals having a diameter exceeding the film thickness can be obtained. This near-complete melting regime and the subsequent super-lateral growth phenomenon was described in detail in for example James S. Im et al, Appl. Phys. Lett. 63 (1993) p 1969. The multiple cycles of melt and re-crystallization help to organize the material in the film to induce certain surface roughness and produce a small, but uniformly sized grain structure. The size of the crystals is typically found to be related to the wavelength of the laser light, for example approximately 300 nm grains in a XeCl-gas excimer laser process ($\lambda=308\text{nm}$). Typical ELA processes irradiate a given portion of the film with at least 10 or 20 laser pulses, and in many cases it can be even higher, e.g., from between at least 30 and at least 50 laser pulses.

[0066] Fig. 7A depicts a conventional ELA single-scan, showing the cross section of the line beam 700 on its short axis as the beam 700 scans a film 709. The beam 700 is advanced in the direction of the arrow 705 and a region 707 of the film 709 can be irradiated with multiple laser pulses as the beam 700 moves across the film 709. Fig. 7B depicts the ELA scheme of the present method. This method incorporated two beam scans, 710, 712 of the substrate: a first scan 710 in the direction of arrow 715, for example, the x-direction and a second scan 712 in the direction of arrow 720, for example, the negative x-direction. The second scan 712 in the direction of arrow 720 also can include a translation 715 of the beam 700 in the direction perpendicular to the direction of arrows, 715 and 720, for example, the y-direction. Notably, while the total number of laser pulses in each individual scan of the present method is less than the number of laser pulses in the conventional ELA methods, because of the reverse scan, region 717 can be irradiated by the same number of laser pulses as region 707 in the conventional ELA method. For example, if the total number of pulses per unit area for the ELA process should be 100, then, if using two ELA scans according to an embodiment of the present method, the first scan would result in 50 pulses per unit area and the second scan would result in 50 pulses per unit area.

[0067] In ELA, a line beam is used for the overlapped scanning. The line beam is generally wider than the line beam used for the SLS embodiment. For example, a line beam for the ELA process can have a width of about 300 microns to about 400 microns, while a line scan SLS beam is generally around about three to six microns wide and can be up to eight to ten microns wide. Some SLS line beams can be up to 50 microns in width. For 2-shot SLS, the SLS line beam is required to be narrow enough to avoid nucleation; however, this width can vary based on the pulse duration and the film thickness. While SLS is a controlled lateral growth technique, ELA is essentially a flood irradiation technique where no control of lateral dimensions of the melted regions is necessary and ELA processes, therefore, can use wider beams. Further, the fluences of the ELA beams are selected to not induce complete melting of the film. Therefore, the ELA beam should have a fluence lower by about 5% to 20% of the fluence value that induces complete melting in the given film. The fluence of the beam in the SLS embodiment should be about 10% or about 20% or about 50% or even 80% or 100% higher than the complete melt fluence, in order to guarantee complete melting of the film and induce sufficient lateral growth. The fluence value that induces complete melting is dependent upon the thickness of the film and the duration of the pulse.

Further, the ELA beams could have relatively low frequency (compared to the relatively high frequency, i.e., three, four, or six kHz that is desirable for SLS line beams) and have repetition rates of about 300 Hz to about 600 Hz. The lasers used for both ELA and SLS can be high frequency and high power pulsed lasers, with a power of about 300 W to about 600 W and even up to about 1 kW. The high power laser provides sufficient energy per pulse to provide adequate energy density across the length of an irradiated region so that the pulse may melt a film within that region. Other pulsed laser sources, such as solid state lasers, can be used as well and may have lower power, such as 100 W or 200 W and shorter line beams. Diode-pumped solid state lasers (DPSS) are commonly used after frequency doubling with a wavelength of about 532 nm. Their high frequencies (for example 10,000 Hz or 100,000 Hz, or more) can result in very rapid scanning and can be applied to small size devices, such as small displays, other electronics (such as chips for radio frequency identification (RFID)), or electronics integration regions at the perimeter of displays. However, the embodiments are not limited to lasers of any particular frequencies. For example, low frequency lasers, e.g., less than 1 kHz, are also compatible with the irradiation schemes described herein.

[0068] For example, the ELA line beam may be created from a relatively low frequency laser source resulting in a relatively wide beam (up to about 400 μ m), such as from a JSW crystallization system (The Japanese Steel Works, Ltd., located at Gate City Ohsaki-West Tower, 11-1, Osaki 1-chome, Shinagawa-ku, Tokyo, Japan), or it may be created from a relatively high frequency laser source resulting in a relatively narrow beam (from about 10 μ m or less to about 40 μ m or more), such as from a TCZ crystallization system (TCZ Pte. Ltd. located at No. 1 Yishun Avenue 7 Singapore 768923).

[0069] One of the major non-uniformities arising with ELA is the issue of mura, meaning the light/dark lines in the panel brightness. For example, shot to shot energy density variation can lead in mura perpendicular to the scan direction, while beam non-uniformity along the length of the beam (e.g., through interference) can lead to mura parallel to the scan direction. The latter form of mura may be addressed by subjecting the substrate to multiple ELA scans with in-between transverse translations in the y-direction of the sample with respect to the beam so that the interference features in the beam are shifted with respect of previous scans and the mura pattern is 'broken.' Unlike the SLS process described above, in which portions of the substrate remain un-irradiated between pulses, ELA irradiation uses significant overlap

between pulses. Typically for conventional ELA processes, there is at least 90% overlap from one pulse to the next, for example, there is between about 90-99% overlap between pulses. In applying the concept of multiple scan irradiation using x-direction offset and y-direction translation to ELA, the percent overlap is reduced in each scan and multiple scans are conducted over substantially the same area to arrive at the desired level of overlap for the region. For example, rather than doing one scan with 90% overlapping, one can do two scans each with 80% overlapping with a transverse shift in the y-direction in between. Although the overlapping need not be the same in each case, it does have a benefit, because the stage velocity will be the same and stages are manufactured to be especially stable for one particular stage velocity. Also, subsequent scans can be in opposite directions, but they can also be in the same direction wherein the stage needs to return to the start position before conducting the next scan. The laser may be blocked or shut off during reverse stage movement.

[0070] While the disclosed method is effective in virtually eliminating the parallel mura, it also can be beneficial for significantly reducing the perpendicular mura. Pulse to pulse variations are not always uncorrelated. One example is that the average pulse energy may slowly drift over a time scale of many pulses (for example 100s of thousands or millions or more). In some systems that are commercially available, this issue is addressed by constantly monitoring the energy density and using this as feedback to compensate for any drift in the pulse energy. If a drift is detected, the pulse energy can be adjusted by stepping the pumping power, (for example, the high voltage in an excimer laser); or by refreshing the lasing medium (for example, adding fresh gas to the gas mixture in an excimer laser); or by adjusting the transmission of an optical attenuator. Such feedback could for instance result in a more abrupt fluctuation of the pulse energy as opposed to a gradual drift. Feedback compensation also may not be effective in correcting for gradual changes that are on a shorter time scale (for example 10s or 100s or 1000s of pulses). Fluctuations thus described may be too large and may result in mura. The multiple scanning, as taught in this disclosure, has as an additional benefit that it also reduces the perpendicular mura by overlapping with a second scan of which the energy fluctuations are uncorrelated compared to previous scans.

[0071] In order to achieve the appropriate combination of pulse rate and scan rate, higher stage scan velocities, lower laser repetition rates (i.e., laser frequencies), or a combination thereof is required. However, lower repetition rates will significantly decrease throughput.

Fortunately, scan velocities are typically low for line-scan SLS. Therefore, increasing scan velocity may be the best way to achieve the appropriate combination of pulse rate and scan rate. Some reduction in throughput is still encountered as a result of the need to turn around (i.e., reverse the scan direction) for subsequent scans and the time associated with the corresponding deceleration and acceleration. Throughputs with current excimer laser based 2-shot line-scan SLS schemes are higher than those obtained with 2-D projection systems largely as a result of the higher power of the lasers used. Also, the number of turn arounds is smaller for the 2-shot line-scan SLS schemes.

[0072] Finally, for the multiple-scan LS-SLS process, what is needed is accurate placement of the pulses. For this, previously, “stage-synchronized” laser control has been implemented and has been found to be very accurate. The accuracy of such a system was demonstrated for stages moving at tens of cm/s, so for slower moving stages accuracy should not be a problem. For multiple-scan ELA, such stage-synchronized laser control may not be needed because the process is a flood irradiation process and lateral placement of the pulses with respect to previous pulses is less critical. On the other hand, stage-synchronized laser control may be beneficial to get more uniform material by controlled placement of the beam edges (in the short dimension) and better reproducibility from panel to panel. For both embodiments, it is even contemplated that rather than, or in addition to, sideways translations, the stage is rotated about 180 degrees in between scans.

[0073] Another aspect of the present disclosure relates to a system for crystallization of thin films. The system, as shown in Fig. 8, can include a film **800** to be crystallized, which can be disposed on a substrate **805**, at least one laser for generating one or more laser beam pulses **810** for pulsed laser crystallization of the film, a film support **815** for positioning the film that is capable of movement in at least two directions, and a controller for controlling the movement of the film support in conjunction with the frequency the laser beam pulses.

[0074] In the SLS embodiment, the laser beam source is configured such that each laser pulse forms a line beam having a length, a width, and a fluence that is sufficient to melt the film throughout its thickness of the film. In the SLS embodiment, the controller controls the movement of the film support and the frequency of the laser beams as described above with respect to the method.

[0075] In the ELA embodiment, the laser beam source is configured to form a line beam having a length and a width. In the ELA embodiment, the line beam is moved at a velocity selected such that each pulse irradiates and melts a portion of the film that overlaps a previously irradiated portion and the total pulses that irradiate a portion of the film is less than the amount needed to complete crystallization. In the ELA embodiment, the controller controls the movement of the film support and the frequency of the laser beams as described above with respect to the method.

[0076] While there have been shown and described examples of the present invention, it will be readily apparent to those skilled in the art that various changes and modifications may be made therein without departing from the scope of the invention as defined by the appended claims. Accordingly, the invention is limited only by the following claims and equivalents thereto.

[0077] What is claimed is:

Claims

1. A method of processing a film, the method comprising:

continuously irradiating a film having an x-axis and a y-axis, in a first scan in the x-direction of the film with a plurality of line beam laser pulses to form a first set of irradiated regions;

translating the film a distance in the y-direction of the film, wherein the distance is less than the length of the line beam; and

continuously irradiating the film in a second scan in the negative x-direction of the film with a sequence of line beam laser pulses to form a second set of irradiated regions,

wherein each of the second set of irradiated regions overlaps with a portion of the first set of irradiated regions, and wherein each of the first and the second set of irradiated regions upon cooling forms one or more crystallized regions.
2. The method of claim 1, wherein each line beam laser pulse has a fluence that is sufficient to melt the film throughout its thickness in the first and second set irradiated regions, and wherein each of the first set of irradiated regions are spaced-apart from each other.
3. The method of claim 2, wherein each of the first set of irradiated regions upon cooling forms one or more laterally grown crystals and wherein each of the second set of irradiated regions upon cooling forms one or more laterally grown crystals that are extended relative to the one or more laterally grown crystals of the first set of irradiated regions.
4. The method of claim 1, wherein the laser crystallization method employed is sequential lateral solidification.
5. The method of claim 1, wherein each of the first set of irradiated regions overlap each other.
6. The method of claim 1, wherein the number of laser beam pulses in the first scan is less than the amount needed to complete crystallization of the film.

7. The method of claim 1, wherein the number of laser beam pulses in the second scan is an amount needed to complete crystallization of the film.
8. The method of claim 1, wherein the laser crystallization method employed is excimer laser annealing.
9. The method of claim 8, wherein the crystallization method uses from about 10 to about 100 pulses per unit area.
10. The method of claim 8, wherein the crystallization method uses from about 10 to about 40 pulses per unit area.
11. The method of claim 8, wherein the overlap between irradiation regions within each scan is less than 80%.
12. The method of claim 8, wherein the overlap between irradiation regions within each scan is less than 90%.
13. The method of claim 1, wherein the method includes at least 2 continuous scans.
14. The method of claim 1, wherein the method includes 2-8 continuous scans.
15. The method of claim 1, wherein the y-direction translation distance is about 10 μm to about 10 mm.
16. The method of claim 1, wherein the y-direction translation distance is about 100 μm to about 2 mm.
17. The method of claim 1 comprising rotating the film about 180 degrees between scans.
18. A system for processing a film comprising:
 - at least one laser for generating a plurality of laser beam pulses for pulsed laser crystallization of the film, wherein each laser pulse forms a line beam having a length and a width;
 - a film support for positioning a film, having an x-axis and a y-axis, disposed thereon that is capable of movement in at least two directions; and

a controller for providing instructions on controlling the movement of the film support in conjunction with the frequency the laser beam pulses, wherein controlling the movement of the film support comprises:

continuously irradiating a film disposed in a first scan in the x-direction of the film with a plurality of line beam laser pulses to form a first set of irradiated regions;

translating the film a distance in the y-direction of the film, wherein the distance is less than the length of the line beam; and

continuously irradiating the film in a second scan in the negative x-direction of the film with a sequence of line beam laser pulses to form a second set of irradiated regions,

wherein each of the second set of irradiated regions overlaps with a portion of the first set of irradiated regions, and wherein each of the first set and second set of irradiated regions upon cooling forms one or more crystallized regions.

19. The system of claim 18, wherein each line beam laser pulse has a fluence that is sufficient to melt the film throughout its thickness in the first and second set irradiated regions, and wherein each of the first set of irradiated regions are spaced-apart from a each other.

20. The system of claim 19, wherein each of the first set of irradiated regions upon cooling forms one or more laterally grown crystals and wherein each of the second set of irradiated regions upon cooling forms one or more laterally grown crystals that are extended relative to the one or more laterally grown crystals of the first set of irradiated regions.

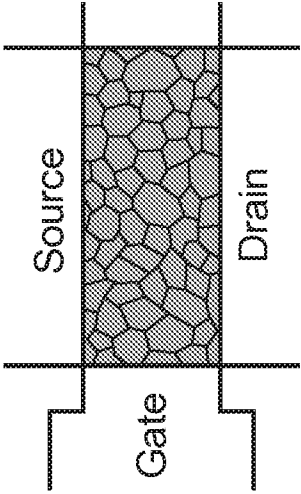
21. The system of claim 19, wherein the laser crystallization method employed is sequential lateral solidification.

22. The system of claim 18, wherein each of the first set of irradiated regions overlap each other.

23. The system of claim 18, wherein the number of laser beam pulses in the first scan is less than the amount needed to complete crystallization of the film.

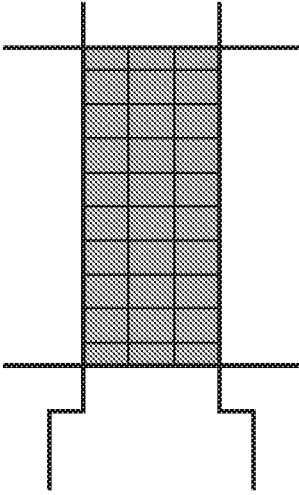
24. The system of claim 18, wherein the number of laser beam pulses in the second scan is an amount needed to complete crystallization of the film.
25. The system of claim 18, wherein the laser crystallization method employed is excimer laser annealing.
26. The system of claim 25, wherein the crystallization method uses from about 10 to about 100 pulses per unit area.
27. The system of claim 25, wherein the crystallization method uses from about 10 to about 40 pulses per unit area.
28. The system of claim 25, wherein the overlap between irradiation regions within each scan is less than 80%.
29. The system of claim 25, wherein the overlap between irradiation regions within each scan is less than 90%.
30. The system of claim 18, wherein the method includes at least 2 continuous scans.
31. The system of claim 18, wherein the method includes 2-8 continuous scans.
32. The system of claim 18, wherein the y-translation distance is about 100 μm to about 10 mm.
33. The system of claim 18, wherein the y-translation distance is about 100 μm to about 2 mm.
34. The system of claim 18, wherein the film is rotated about 180 degrees between scans.
35. A product containing a film processed by the method of claim 1.
36. The product of claim 35, wherein the product is an liquid crystal display screen.

Fig. 1A



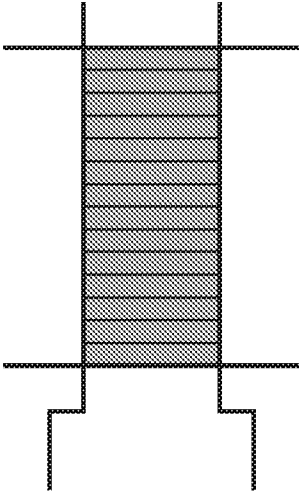
Random

Fig. 1B



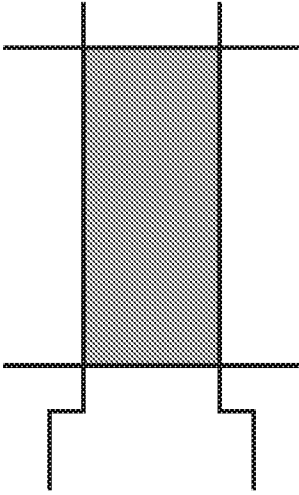
Uniform

Fig. 1C



Directional

Fig. 1D



Single-crystal islands

Fig. 2A

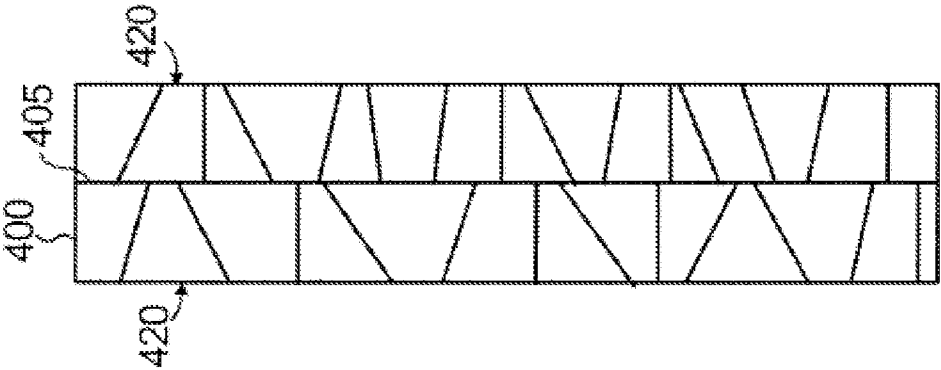


Fig. 2B

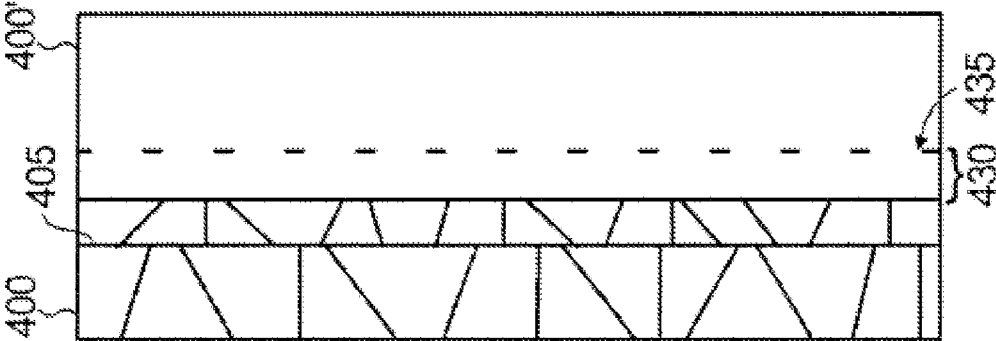


Fig. 2C

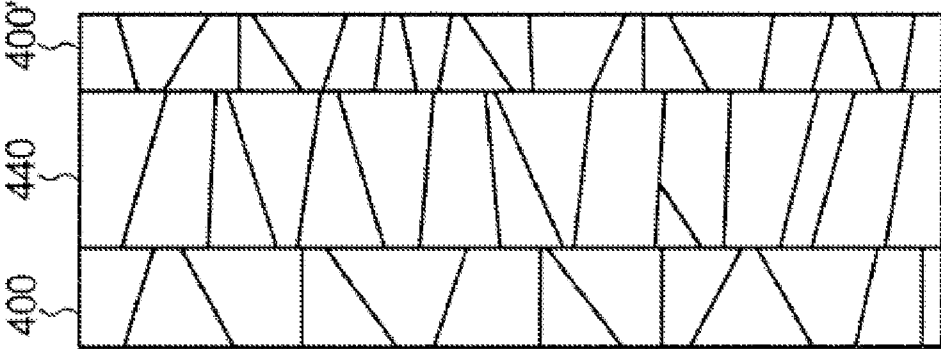
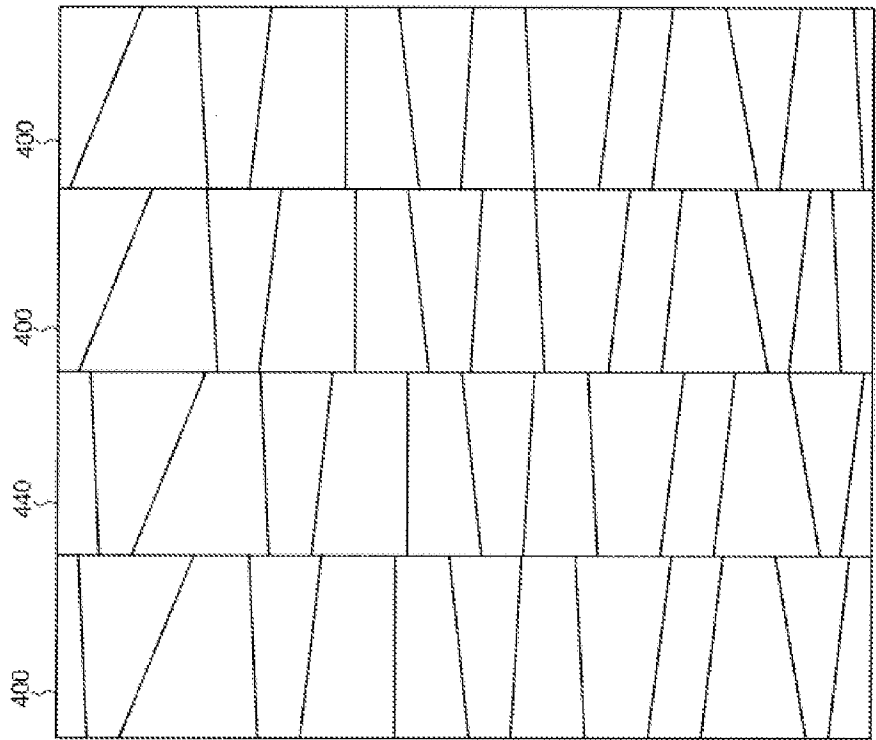


Fig. 2D



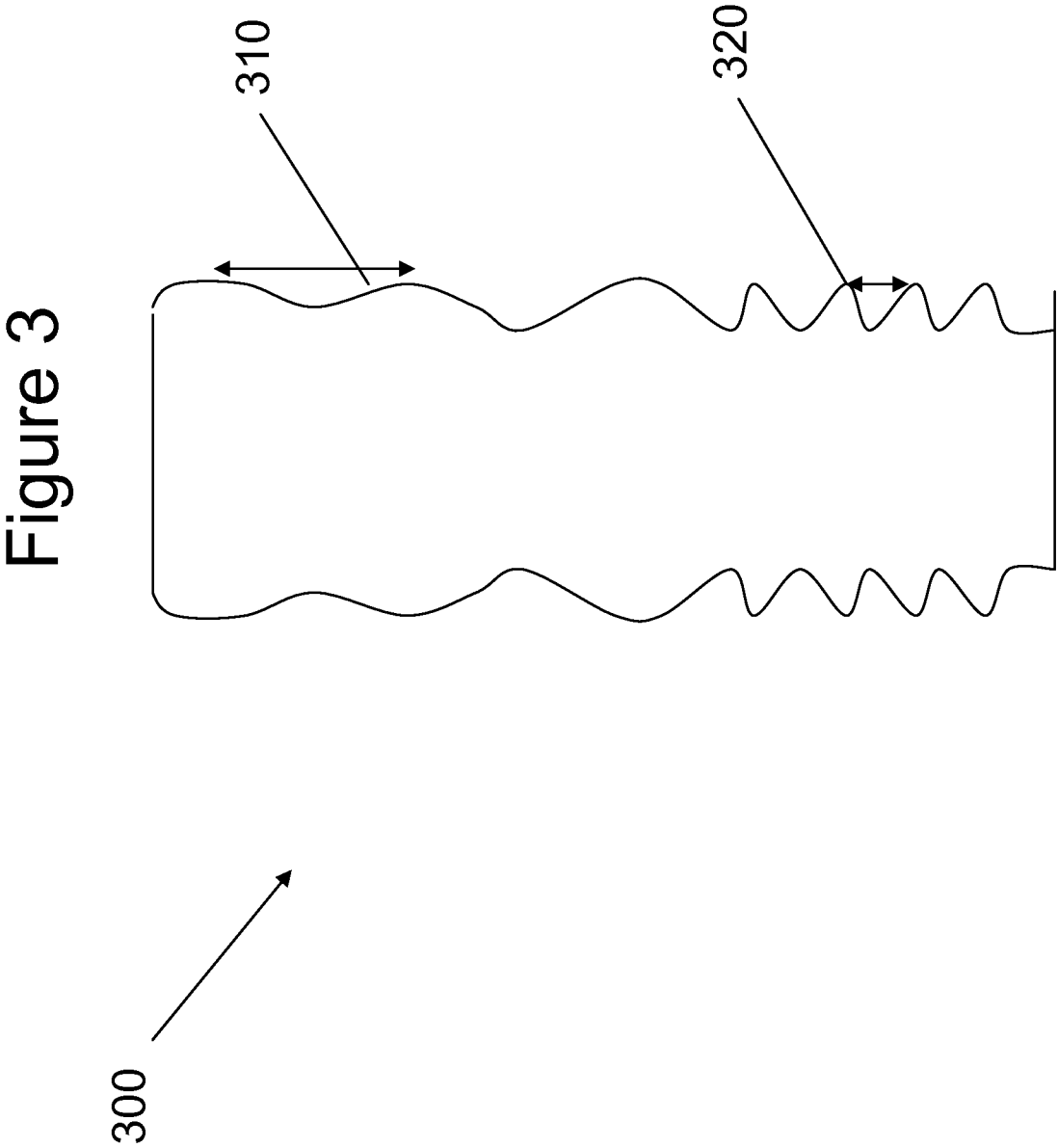


Figure 4

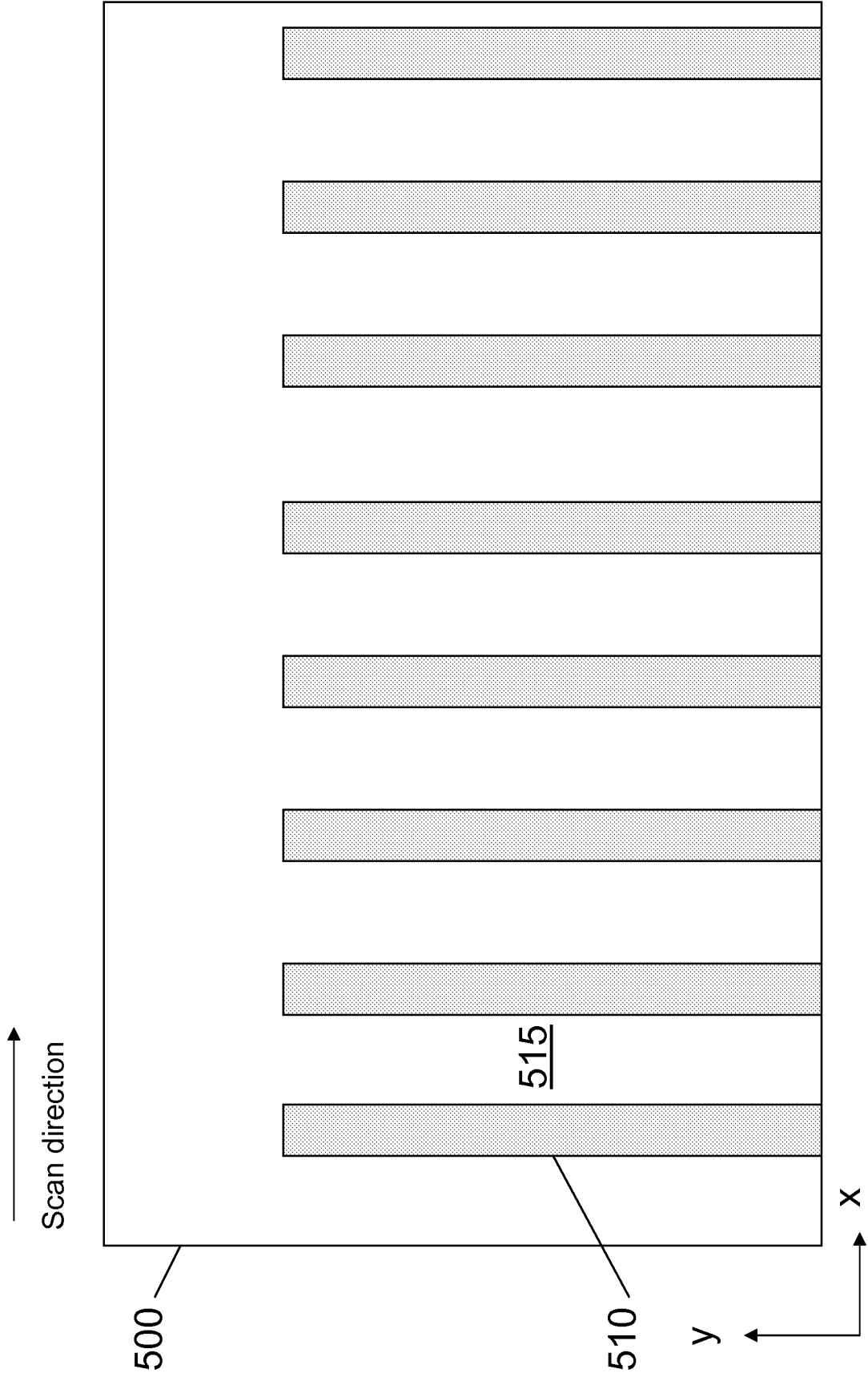


Figure 5

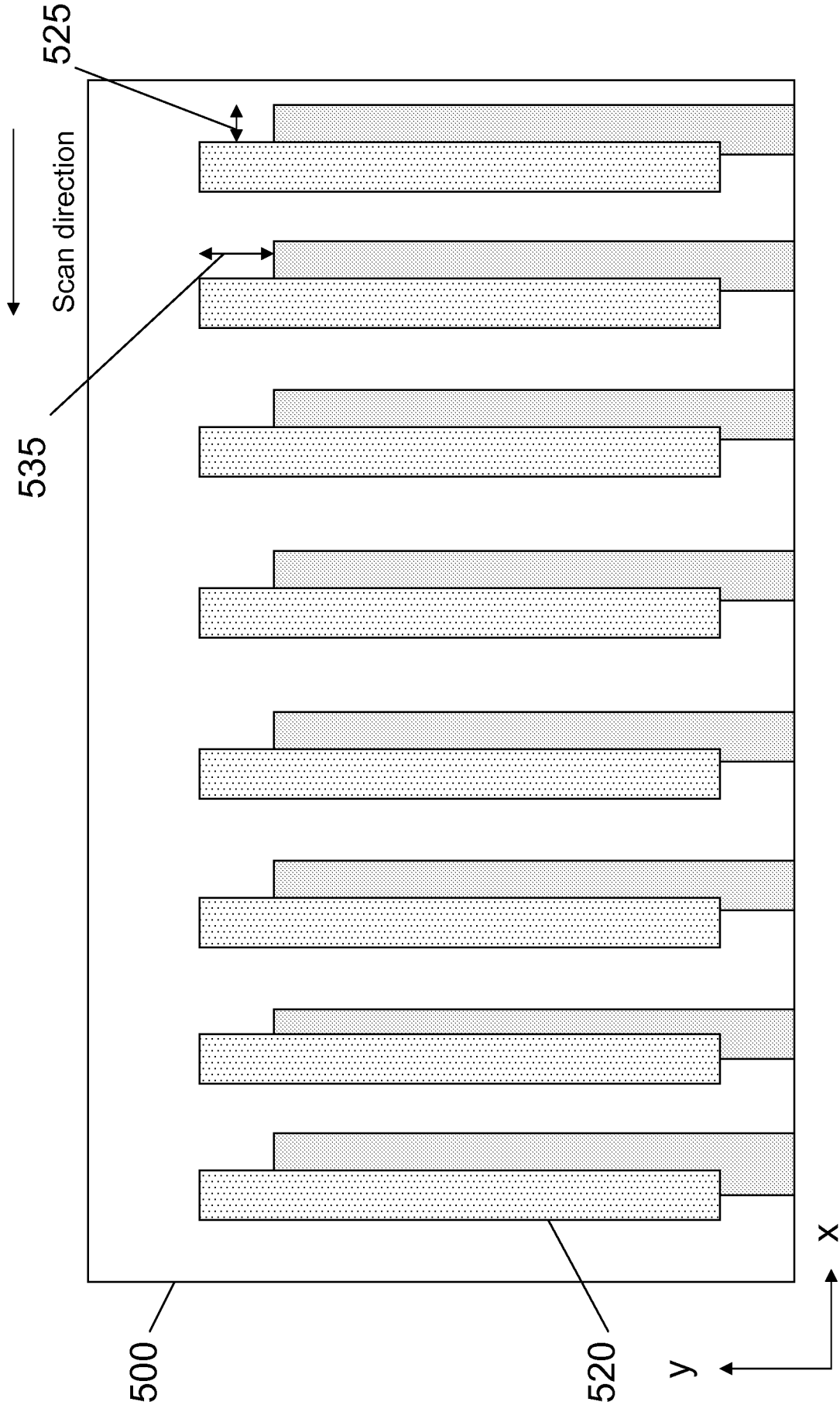


Figure 6

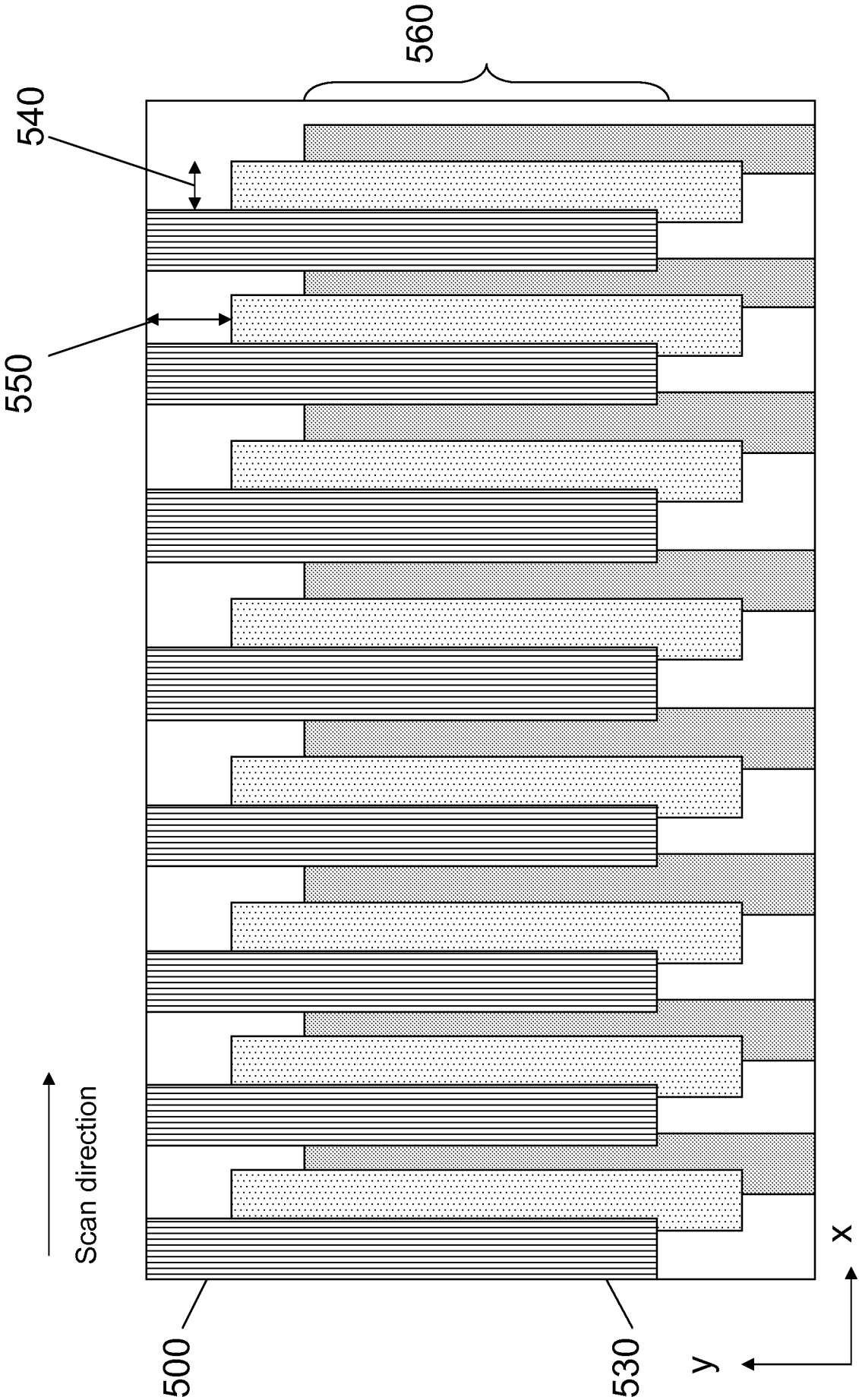


Figure 7A

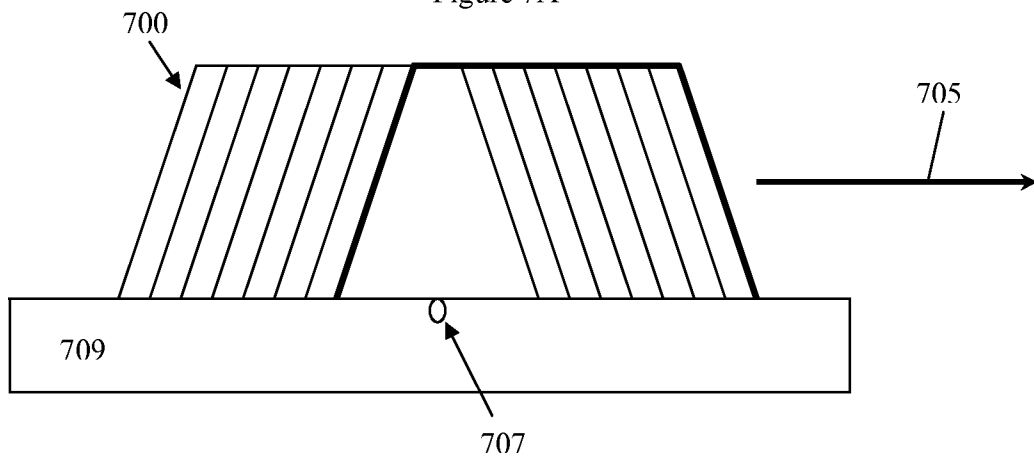


Figure 7B

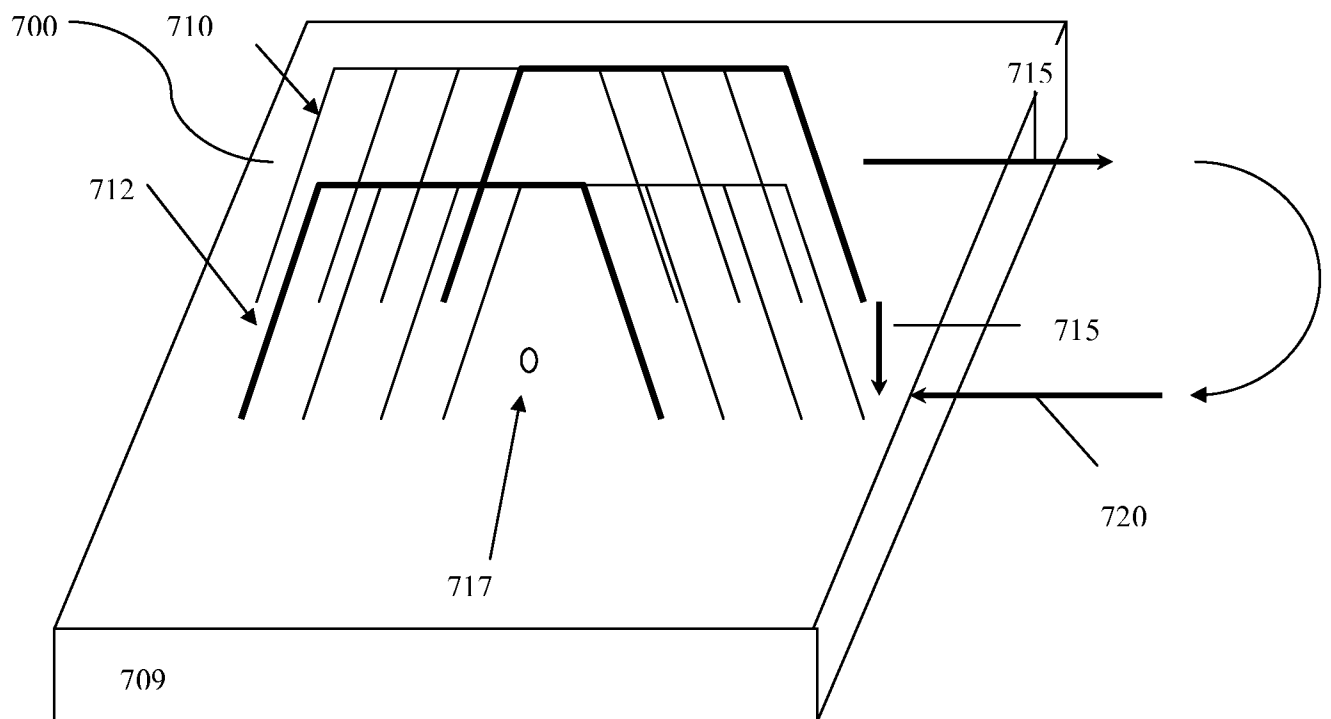
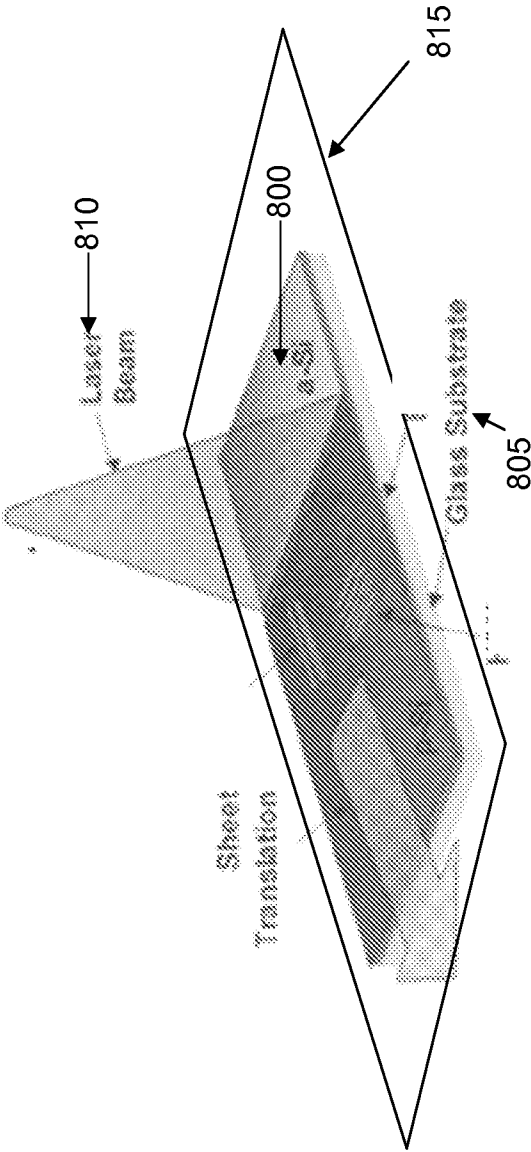


Figure 8



INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 09/64381

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - H01L 21/02 (2010.01)

USPC - 438/487; 257/70; 257/E21.134

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC(8) - H01L 21/02 (2010.01)

USPC - 438/487; 257/70; 257/E21.134

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

IPC(8) - H01L 21/02 (2010.01)

USPC - 438/487; 257/70; 257/E21.134 (text search)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

PubWEST (PGPB,USPT,EPAB,JPAB), Google

Search terms used: film, process, irradiate, line, beam, laser, pulse, crystallization, sequential, lateral, solidification, excimer, anneal, overlap, scan, rotate, liquid, crystal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2006/0254500 A1 (Im et al.) 16 November 2006 (16.11.2006), para [0033], [0051]-[0070], [0076]-[0079], [0086], [0098]	1-36
Y	US 2008/0035863 A1 (Im et al.) 14 February 2008 (14.02.2008), para [0039]-[0063], [0077]	1-36

☐ Further documents are listed in the continuation of Box C.


* Special categories of cited documents:

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"P" document published prior to the international filing date but later than the priority date claimed

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

29 December 2009 (29.12.2009)

Date of mailing of the international search report

14 JAN 2010

Name and mailing address of the ISA/US

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