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(54) Title: METHODS AND SYSTEMS FOR CONTROLLED LATERAL SOLIDIFICATION

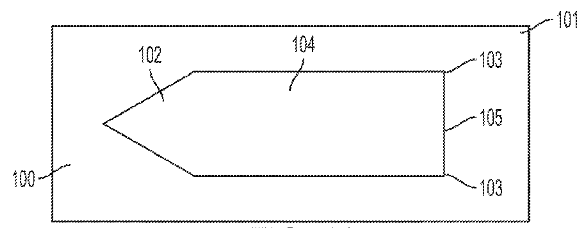


FIG. 1A

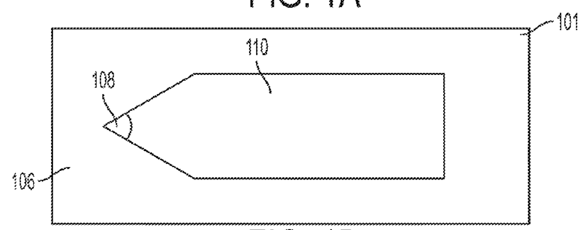


FIG. 1B

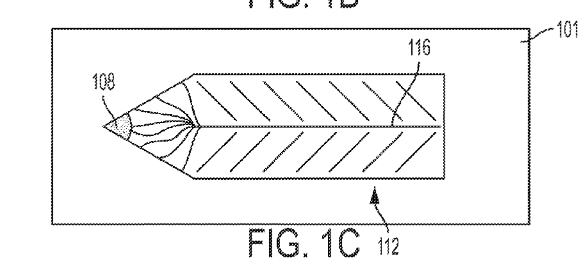


FIG. 1C

(57) **Abstract**: The present disclosure is directed to methods and systems for processing a thin film. An exemplary method can include providing the thin film on a non-absorbing substrate, patterning the thin film to form a patterned region comprising a plurality of sides, and irradiating the patterned region with a first laser pulse having a fluence that is sufficient to melt a first sub-region of the patterned region without melting a second sub-region of the patterned region proximal to a first side of the patterned region.

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# METHODS AND SYSTEMS FOR CONTROLLED LATERAL SOLIDIFICATION

## CROSS-REFERENCE TO RELATED APPLICATIONS

**[0001]** This application claims the benefit under 35 U.S.C. 119(e) to U.S. Provisional Application No. 61/941,824, entitled "METHODS AND SYSTEMS FOR CONTROLLED LATERAL SOLIDIFICATION," filed on February 19, 2014, the contents of which are incorporated by reference herein in their entirety.

## TECHNICAL FIELD

**[0002]** The present disclosure relates to systems and methods for thin film processing.

## BACKGROUND

**[0003]** Excimer laser annealing ("ELA") is a technique for processing thin films by partially melting portions of the film using laser radiation. ELA systems are described in United States Patent No. 8,479,681 entitled "Single-Shot Semiconductor Processing System and Method Having Various Irradiation Patterns," the entire contents of which are incorporated by reference.

**[0004]** Advanced Excimer Laser Annealing ("AELA") is a relatively new ELA technique whereby portions, e.g., target areas, of a large area thin film can be irradiated and partially melted to induce crystallization. AELA differs from ELA in that AELA requires less irradiations per target area of film. AELA systems are described in PCT Publication Number WO2013172965 entitled "Advanced Excimer Laser Annealing for Thin Films." These AELA systems can eliminate many of the "edge issues" experienced in ELA systems.

## SUMMARY

**[0005]** According to aspects of the disclosure, a method of processing a thin film is provided. The method can include the steps of providing the thin film on a non-absorbing substrate, patterning the thin film to form a patterned region comprising a plurality of sides, and irradiating the patterned region with a first laser pulse having a fluence that is sufficient to melt a first sub-region of the patterned region without melting a second sub-region of the patterned region proximal to a first side of the patterned region.

**[0006]** According to aspects of the disclosure, a system for processing a film can include a laser source, a non-absorbing substrate for depositing the film, and memory having a set of instructions. The instructions can include patterning the thin film to form a patterned region comprising a plurality of sides and irradiating the patterned region with a first laser pulse having a fluence that is

sufficient to melt a first sub-region of the patterned region without melting a second sub-region of the patterned region proximal to a first side of the patterned region.

BRIEF DESCRIPTION OF FIGURES

**[0007]** FIG. 1A-C are exemplary depictions of irradiation regions processed according to aspects of the present disclosure.

**[0008]** FIG. 2 is an exemplary depiction of a patterned film according to some aspects of the present disclosure.

**[0009]** FIG. 3 is an exemplary depiction of a patterned film according to some aspects of the present disclosure.

**[0010]** FIG. 4 is an exemplary depiction of a patterned region according to some aspects of the present disclosure.

**[0011]** FIG. 5 is an exemplary depiction of a patterned region according to some aspects of the present disclosure.

**[0012]** FIG. 6 is a flow chart depicting an exemplary process for irradiating a thin film according to some aspects of the present disclosure.

**[0013]** FIGS. 7A-E are depictions of a process for crystallizing an irradiation region, according to embodiments of the present disclosure.

DETAILED DESCRIPTION

**[0014]** The present disclosure relates to systems and methods for flood irradiation of thin films. According to embodiments of the present disclosure, a patterned film is irradiated using flood irradiation. The patterning of the film results in areas of the film being partially melted while other areas of the film are completely melted. Accordingly, the melting characteristics of the film can be controlled. The flood irradiation can be performed using excimer lasers, for example the same kind of excimer laser used for ELA or AELA. In some embodiments, a solid state laser may also be used.

**[0015]** According to aspects of the present disclosure, systems and methods perform controlled lateral solidification on a thin film using an AELA system and a patterned film. This controlled lateral solidification process can selectively completely melt or partially melt areas of the film using a flood irradiation process without adding steps to the process, e.g., additional deposition or patterning steps. For example, the thin film patterns can be produced during masked deposition, e.g., masked $SiO_2$ or other material deposition, in the photolithography process.

**[0016]** The areas targeted for irradiation in AELA can be patterned before irradiation to control the lateral growth of crystal grains. Prior art techniques require additional photolithography steps, e.g., additional etching steps, after depositing the thin film to form the patterned regions. According to aspects of the disclosure, the thin film material can be patterned during any deposition step, e.g., masked $SiO_2$ or other material deposition, in the photolithography process.

**[0017]** FIG. 1A depicts a patterned irradiation region 100 on a thin film. The thin film can be a semiconductor film, for example, a silicon film. Alternatively, the film can be an oxide or a metal film. An exemplary patterned irradiation region 100 is shown in FIG. 1. Region 100 can be shaped, for example, like the profile of a pencil with a tapered end 102 a center region 104, two square corners 103 and an end 105. Patterned irradiation region 100 is formed on substrate 101 using standard pattering techniques. For example, irradiation region 100 can correspond to a region where the thin film material has not been removed from the substrate 101. Substrate 101 is typically a non-absorbing material. As used herein, the term "non-absorbing" means that substrate 101 absorbs substantially less energy from the subsequent laser irradiation than the thin film material does. For example, substrate 101 can be glass, however other non-absorbing materials can be used. In some embodiments, there is a layer of, e.g., silicon oxide between substrate 101 and patterned irradiation region 100. Patterned irradiation region 100 can be formed using standard lithography techniques.

**[0018]** Because substrate 101 has different thermal properties from the patterned irradiation region 100, certain regions of patterned irradiation region 100 will not melt or will not melt completely upon irradiation if the fluence is sufficiently low. For example, tapered end 102, square corners 103, and end 105, will not melt at all or as completely as center region 104, because they are adjacent to the non-absorbing substrate, which is at a lower temperature than the center region. Substrate 101 can be made, for example, of glass or quartz. The patterning enables controlling which areas of patterned irradiation region 100 become hot under irradiation and therefore melt or completely melt, as opposed to other regions that remain relatively cold and do not melt or do not completely melt. In some embodiments, region 100 can have a length from about 10 microns to about 100 microns and a width in the range of about one micron to about five microns.

**[0019]** FIG. 1B depicts a patterned region 106 immediately after being irradiated using an AELA system. In some embodiments, the film can be irradiated with an excimer laser having an energy density between about 350 mJ per square centimeter to about 500 mJ per square centimeter. These exemplary energy densities generally correspond to energy densities that result in complete melting of a 50 nanometer film on a glass substrate. The pulse duration can be about 30 nanoseconds or more. Region 106 is irradiated and a seed region 108 of the tapered end 102 either partially melts or does not melt while the remainder of the region (melted region 110) completely melts. Seed region 108 acts as a seed to propagate the crystal structure of seed region 108 throughout the remainder of melted region 110. In some embodiments, melted region 110 can be partially melted instead of completely melted.

**[0020]** FIG. 1C depicts a crystallized region 112 after it has cooled. Seed region 108 remains and melted region 110 cools to form crystallized region 112. Crystallized region 112 can have a crystal structure that can provide a suitable material for formation of transistors. This process can produce, for example, a laterally grown single crystal with few defects and one centrally located grain boundary 116.

**[0021]** In some embodiments, the film is irradiated once. In other embodiments, the film can be irradiated two or more times to obtain the desired crystal structure. For example, one irradiation or "shot" should be sufficient for creating a crystal structure for high mobility, uniform thin film transistors. Additionally, because this process can be performed in a single "shot," this process can have higher throughput than prior processes.

**[0022]** FIG. 2 depicts a patterned film have a plurality of patterned irradiation regions 202, 204, 206 on a substrate 200. The irradiation process described in reference to FIG. 1 can also be applied to the patterned film of FIG. 2.

**[0023]** FIG. 3 depicts a patterned film 300, having a plurality of irradiation regions 302, 304, 306, 308, 310, and 312. Regions 302, 308 and 310 are shaped similarly to the regions in FIGS. 1 and 2. Regions 304, 306 and 312 can have a square-like configuration. The entire film 300 can be irradiated and the most preferred crystalline structure can be formed in region 314. This region can melt and form crystal grains seeded by the cooler tapered ends. Accordingly, region 314 can be used for device formation, e.g., formation of thin film transistors. Regions 304, 306, and 312 are formed to regulate the temperature of irradiated regions 302, 308 and 310 to facilitate the melting of those regions without having, for example, un-melted regions on edges 303, 305, and 307. In some embodiments, the distance between region 312 and edge 309 can be sufficient to allow the semiconductor material adjacent to edge 309 to completely melt. In some embodiments, the distance can be a few microns.

**[0024]** FIGS. 4 and 5 provide some additional irradiation pattern designs that can be used with the methods of the present disclosure. FIG. 4 has an irradiation region 400 and a U-shaped temperature control region 402. Region 402 can be made from a material that can absorb light. Therefore, when region 402 is irradiated, its temperature will increase. The U-shaped temperature control region 402 heats up the edge areas 403 of the irradiation region 400, so that a main portion 404 of the irradiation region 400 completely melts. The U-shaped region 402 absorbs radiant energy from the beam source and diffuses that energy to irradiation region 400. FIG. 5 depicts another irradiation region 500 having a rectangular body 502 and a protruding tip 504. Upon irradiation, the protruding tip 504 remains colder than the rectangular body 502. Accordingly, the rectangular body 502 can completely melt, while the protruding tip 504 remains solid or only partially melts, serving as a seed region upon crystallization. The structure depicted in FIG. 5 is generally easier for photolithography systems to create than the pencil-like shape in FIGs. 1-4.

**[0025]** FIG. 6 is a flow chart depicting an exemplary process for irradiating a thin film 600 of the present disclosure. The process can include patterning a thin film 602, as described above, to generate patterned regions according to patterns such as those depicted in FIGS. 1–5. The process can also include irradiating the film to at least partially melt patterned regions 604, as also described above, and forming devices in the patterned regions 606.

**[0026]** FIG. 7 depicts a process for crystallizing an irradiation region, according to embodiments of the present disclosure. FIG. 7A depicts a top view of a film having a plurality of pre-patterned irradiation regions 702, 704, 706 on a substrate 700. Pre-patterned irradiation regions 702, 704, and 706, can correspond to regions where semiconductor material, e.g., silicon, has not been removed from the glass substrate. Pre-patterned irradiation regions 702, 704, 706, can be sized to fit devices, e.g., pixel composed of thin film transistors ("TFTs"). In some embodiments, pre-patterned irradiation regions 702, 704, 706, can be about 10 to 100 microns in length and can be about 1 to 10 microns in width.

**[0027]** FIG. 7B depicts a magnified view of pre-patterned irradiation region 702. Pre-patterned irradiation region 702 is shown having four regions: region 1 in the center; region 2, on a top edge; region 3, a side edge; and region 4, a corner. In general, during the heating/melting period, that is, when the beam is on, the temperature of region 1 is the greatest, followed by the temperature of region 2, followed by the temperature of region 3, and then the temperature of region 4.

**[0028]** FIG. 7C depicts a plot of temperature, shown on the y-axis, versus time, shown on the x-axis, for each of regions 1-4. The complete melting threshold of pre-irradiated region 702 is shown at 706. According to disclosed methods of irradiating thin films, regions 1-3 all experience complete melting at some point during the irradiation process. However, the temperature of region 4 does not exceed the complete melting threshold 706 and therefore does not melt if the fluence is sufficiently low. Accordingly, as shown in FIG. 7D, when irradiated, irradiation region 708 completely melts in central region 710 and leaves corner regions 712 as un-melted solid seed regions.

**[0029]** FIG. 7E depicts a crystallized region 710 having laterally solidified high mobility enabling grains in region 722. FIG. 7E depicts irradiation region 708 in FIG. 7D after it has crystallized. As can be seen in FIG. 7E, crystallized region has four sub-regions 714, 716, 718, and 720, each of these sub-regions corresponding to distinct crystal grains, delineated by grain boundaries 724, 726. TFTs for use in display devices can be formed in region 722 having laterally solidified high mobility enabling grains. In some embodiments, an active channel of a TFT can be formed in a region spanning all four sub-regions 714, 716, 718, and 720. In other embodiments, two TFTs can be formed in region 722 by having a first active channel of a TFT in regions 714 and 718 and a second active channel of a TFT on regions 716 and 720.

**[0030]** Although the disclosed subject matter has been described and illustrated in the foregoing exemplary embodiments, it is understood that the present disclosure has been made only by way of example, and that numerous changes in the details of implementation of the disclosed subject matter may be made without departing from the spirit and scope of the disclosed subject matter.

## CLAIMS

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

providing the thin film on a non-absorbing substrate;

patterning the thin film to form a patterned region comprising a plurality of sides; and

irradiating the patterned region with a first laser pulse having a fluence that is sufficient to melt a first sub-region of the patterned region without melting a second sub-region of the patterned region proximal to a first side of the patterned region.

2. The method of claim 1, further comprising:

defining a third sub-region of the patterned region proximal to a first corner defined by two sides of the patterned region.

3. The method of claim 2, wherein the first corner has an acute angle.

4. The method of claim 3, wherein the third sub-region remains unmolten during irradiation of the patterned region.

5. The method of claim 2, wherein the third sub-region comprises a seed grain.

6. The method of claim 5, wherein later crystal growth from the seed grain initiates from the third sub-region and extends to other sub-regions of the patterned region.

7. The method of claim 1, further comprising:

patterning a temperature control region on the non-absorbing substrate; and

controlling the temperature of a side of the patterned region proximal to the temperature control region during irradiation of the patterned region.

8. The method of claim 1, further comprising:

defining a third sub-region of the patterned region proximal to a first corner defined by two sides of the patterned region;

defining a fourth sub-region of the patterned region proximal to a second corner defined by two other sides of the patterned region, the second corner having a wider angle than the first corner;

wherein a temperature of the third sub-region during irradiation of the patterned region is lower than a temperature of the fourth sub-region.

9. A system for processing a film, the system comprising:

a laser source;

a non-absorbing substrate for depositing the film; and

memory having a set of instructions, the instructions comprising:

patterning the thin film to form a patterned region comprising a plurality of sides; and

irradiating the patterned region with a first laser pulse having a fluence that is sufficient to melt a first sub-region of the patterned region without melting a second sub-region of the patterned region proximal to a first side of the patterned region.

10. The system of claim 9, the instructions further comprising:

defining a third sub-region of the patterned region proximal to a first corner defined by two sides of the patterned region.

11. The system of claim 10, wherein the first corner has an acute angle.

12. The system of claim 11, wherein the third sub-region remains unmolten during irradiation of the patterned region.

13. The system of claim 10, wherein the third sub-region comprises a seed grain.

14. The system of claim 13, wherein later crystal growth from the seed grain initiates from the third sub-region and extends to other sub-regions of the patterned region.

15. The system of claim 9, the instructions further comprising:

patterning a temperature control region on the non-absorbing substrate; and

controlling the temperature of a side of the patterned region proximal to the temperature control region during irradiation of the patterned region.

16. The system of claim 9, the instructions further comprising:

defining a third sub-region of the patterned region proximal to a first corner defined by two sides of the patterned region;

defining a fourth sub-region of the patterned region proximal to a second corner defined by two other sides of the patterned region, the second corner having a wider angle than the first corner;

wherein a temperature of the third sub-region during irradiation of the patterned region is lower than a temperature of the fourth sub-region.

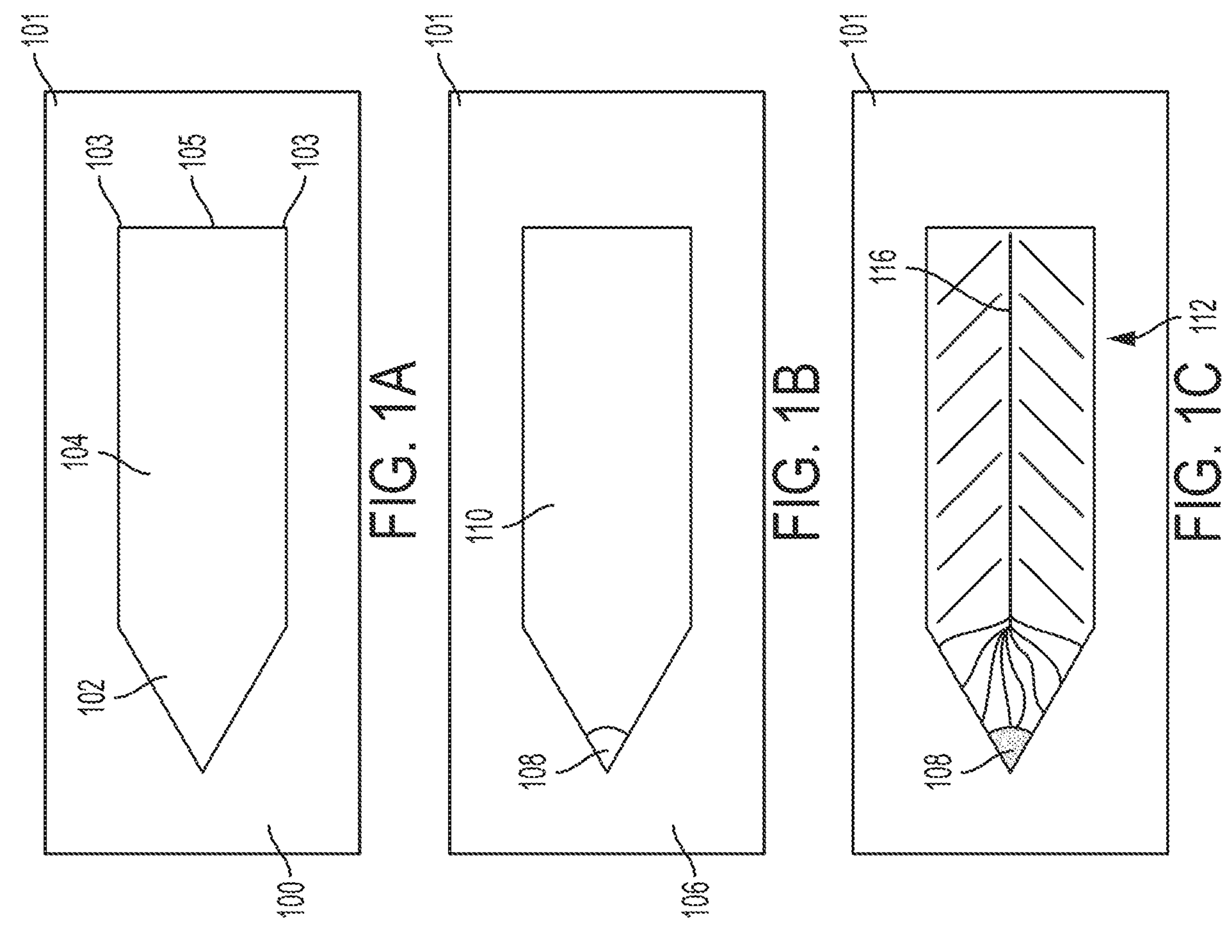


FIG. 1A

FIG. 1B

FIG. 1C

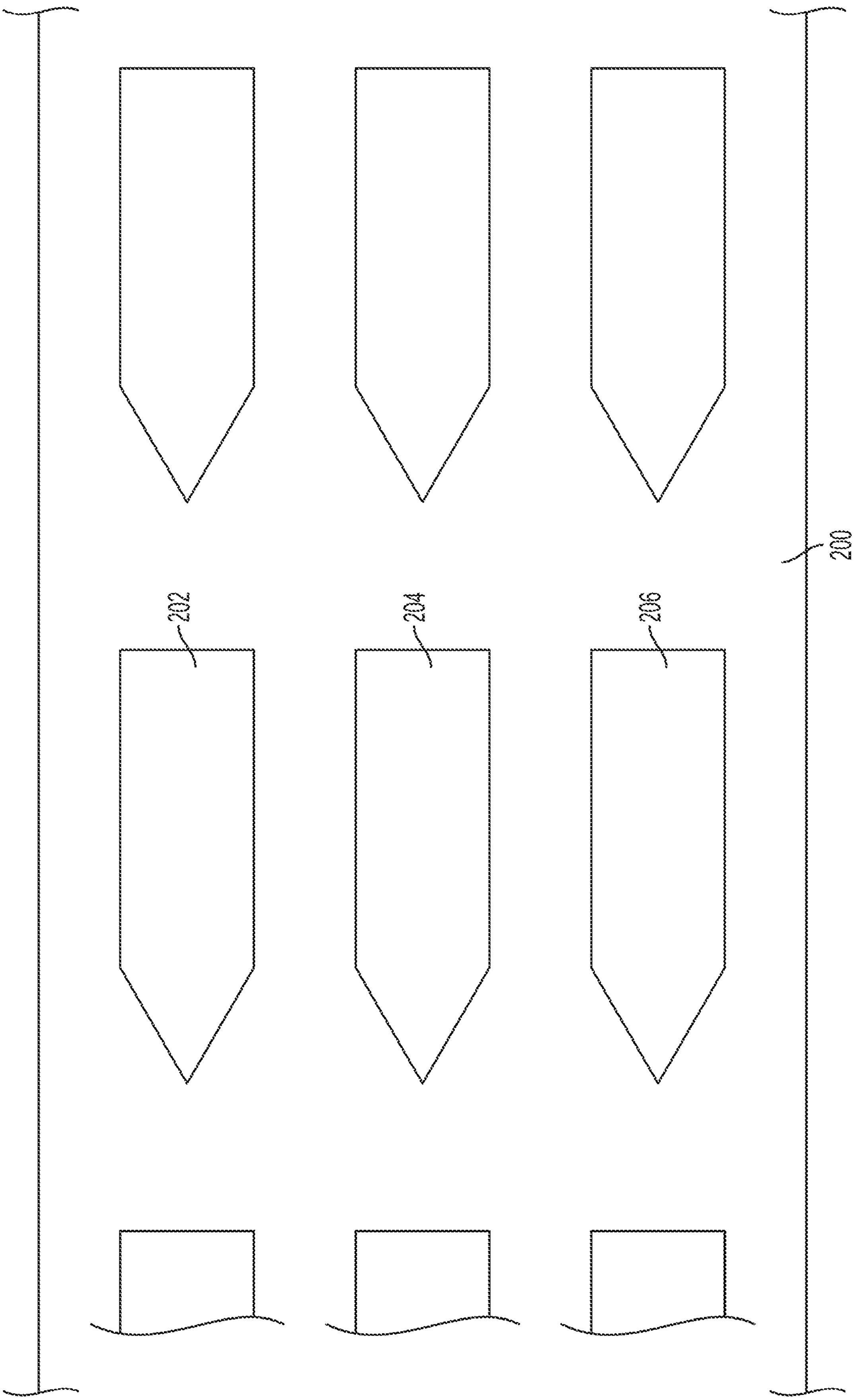


FIG. 2

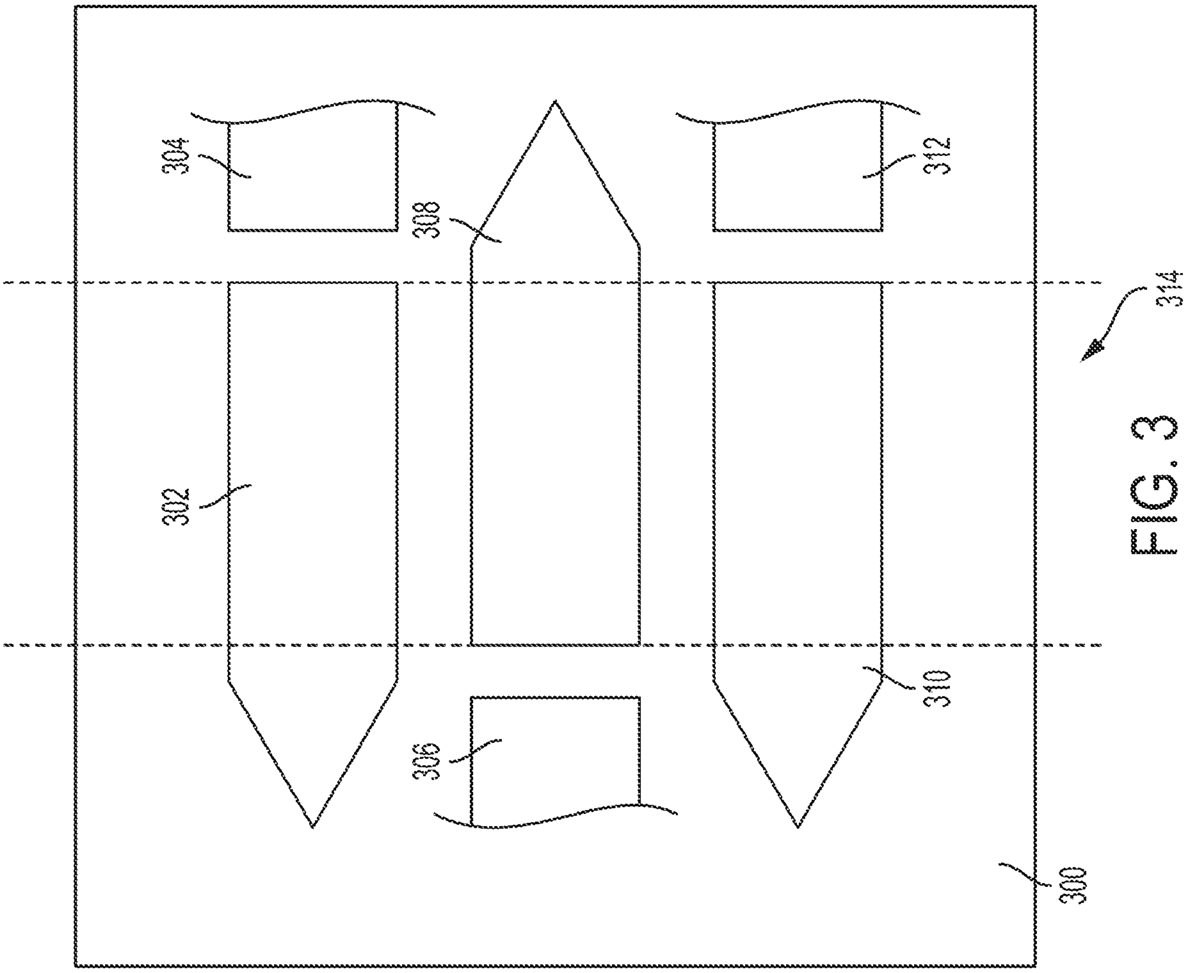


FIG. 3

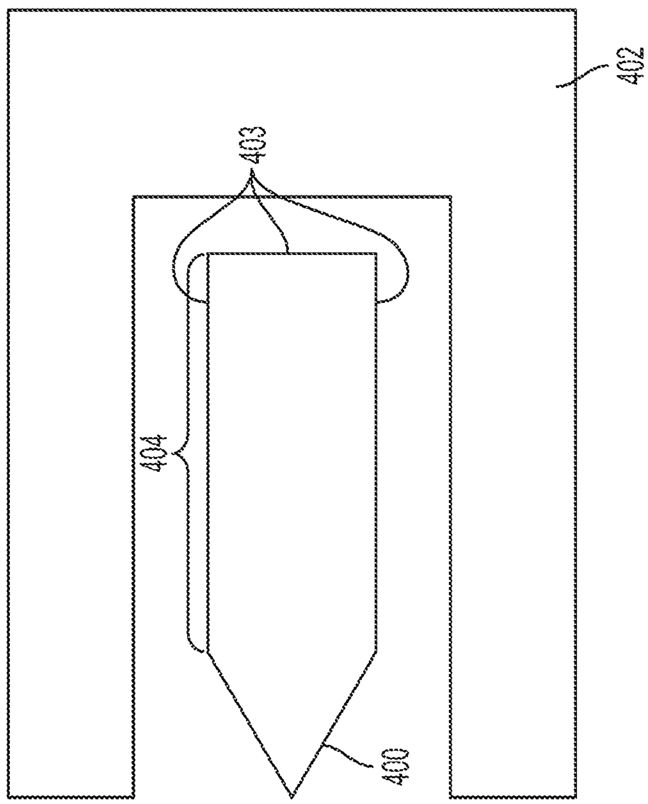


FIG. 4

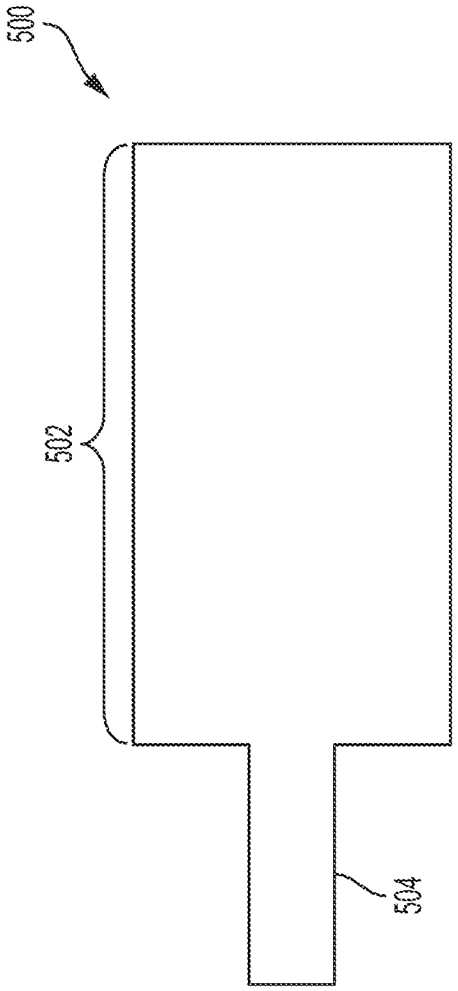


FIG. 5

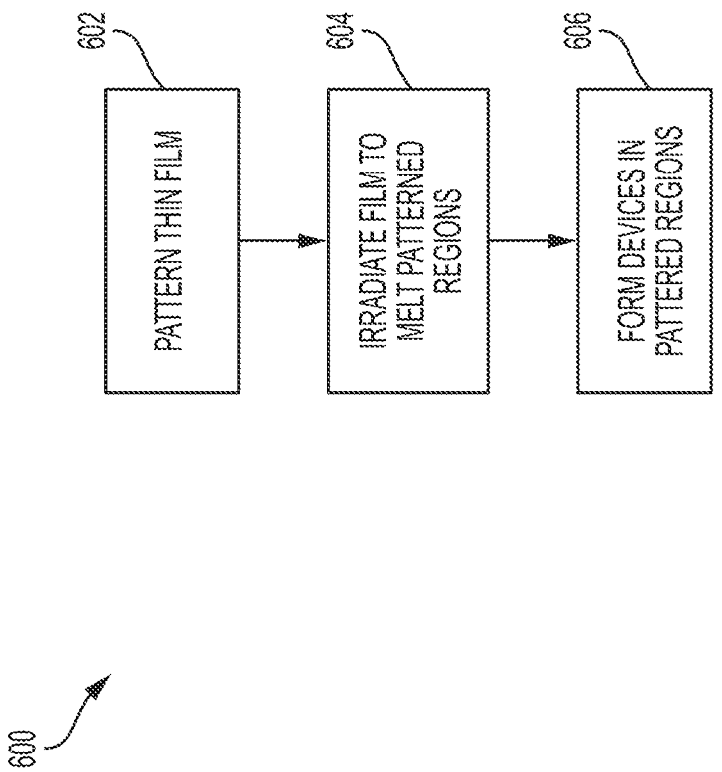
600
602
PATTERN THIN FILM
604
IRRADIATE FILM TO MELT PATTERNED REGIONS
606
FORM DEVICES IN PATTERED REGIONS

FIG. 6

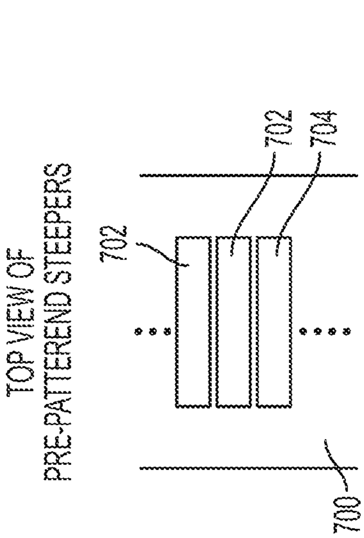


FIG. 7A

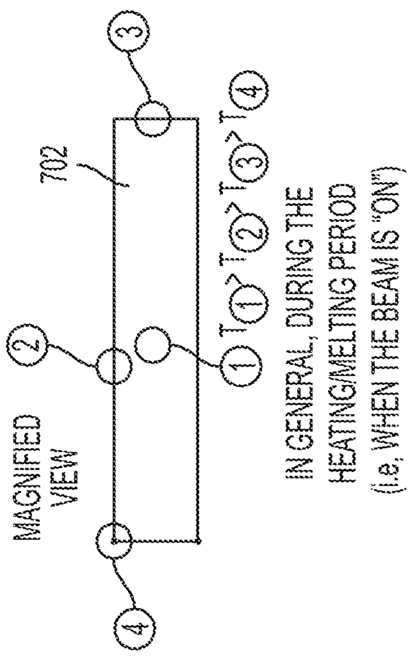


FIG. 7B

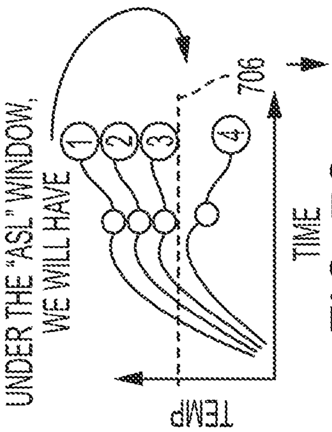


FIG. 7C

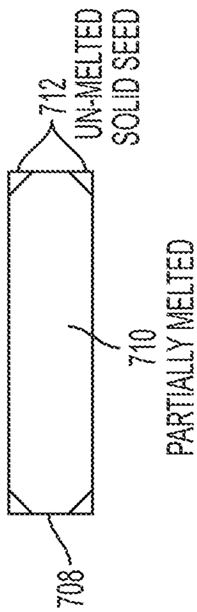


FIG. 7D

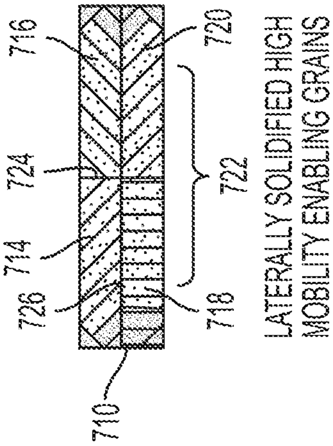


FIG. 7E

# INTERNATIONAL SEARCH REPORT

International application No.
PCT/US15/16559

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - B23K 26/354;C30B 13/24; H01L 21/266 (2015.01)
CPC - B23K 26/0081; C30B 13/24; H01L 21/268
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) - B23K 23/352, 26/354; C30B 13/24; H01L 21/00; 21/266, 21/268 (2015.01)
CPC - B23K 26/0081; C30B 13/24; H01L 21/00, 21/02, 21/268, 21/02675, 21/02686 USPC - 257/66, 75; 438/795

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

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PatSeer (US, EP, WO, JP, DE, GB, CN, FR, KR, ES, AU, IN, CA, INPADOC Data); Google/Google Scholar; Proquest; EBSCO; pattern, mask, masked deposition, laser, thin film, film, substrate, melt, temperature control, energy transfer layer, absorb, proximal, adjacent

C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| X<br>------<br>Y | JP 2004-281771A (THE SHARP CORP) October 7, 2004; paragraphs [0040], [0058], [0067], [0069], [0071], [0076], [0081]; claim 1; figures 2-3, 5, 9 | 1-2, 5-7<br>------<br>3-4, 9-15 |
| Y | US 2009/0242805 A1 (IM, JS) October 1, 2009; figure 4A; paragraphs [0028]-[0029]; claim 30 | 3-4, 9-15 |
| A | US 2010/0099268 A1 (TIMANS, PJ) April 22, 2010; entire document | 1-16 |
| A | WO 2009/111340 A2 (THE TRUSTEES OF COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK) September 11, 2009; entire document | 1-16 |
| A | US 2004/0053450 A1 (SPOSILI, RS et al.) March 18, 2004; entire document | 1-16 |

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
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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 | Date of mailing of the international search report |
|---|---|
| 23 April 2015 (23.04.2015) | 29 MAY 2015 |

| Name and mailing address of the ISA/ | Authorized officer |
|---|---|
| Mail Stop PCT, Attn: ISA/US, Commissioner for Patents<br>P.O. Box 1450, Alexandria, Virginia 22313-1450<br>Facsimile No. 571-273-8300 | Shane Thomas<br>PCT Helpdesk: 571-272-4300<br>PCT OSP: 571-272-7774 |