

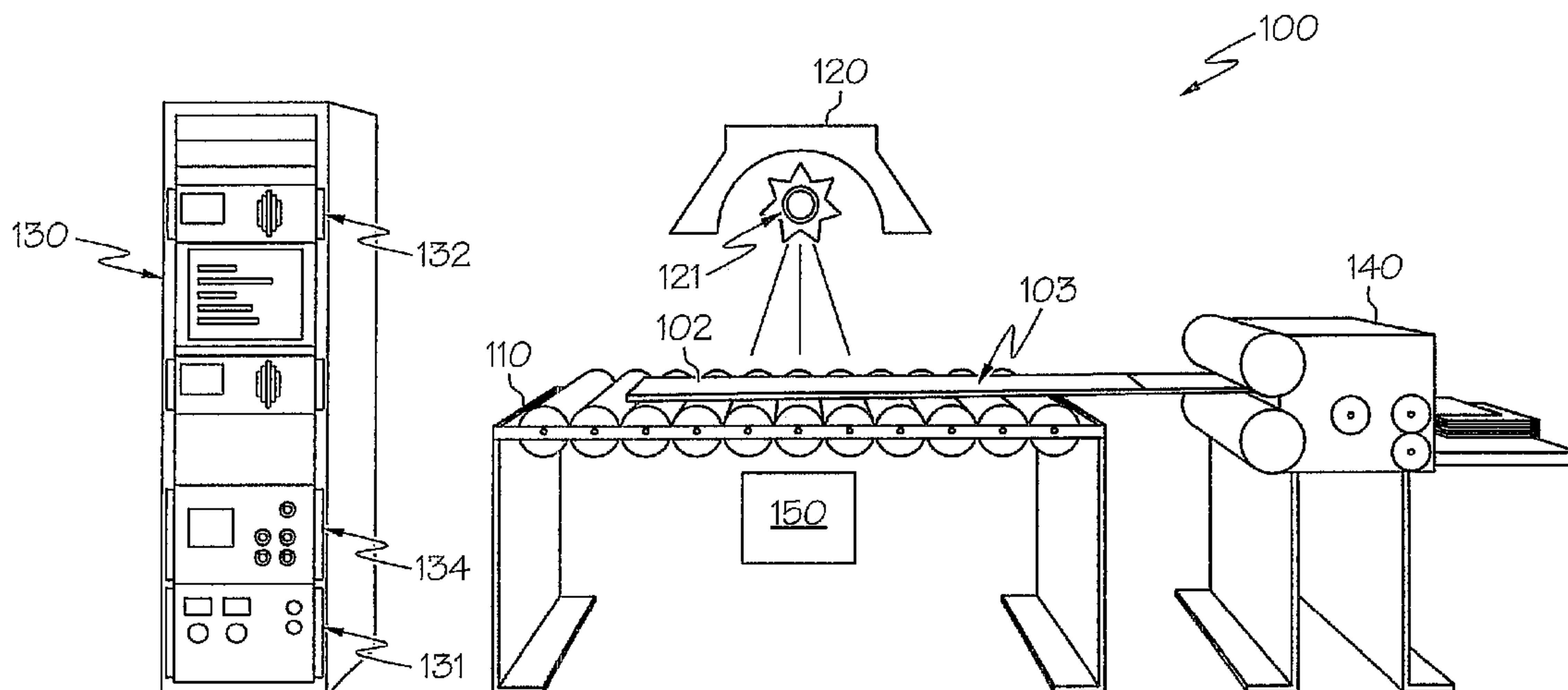


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(54) **Titre : PROCÉDE ET APPAREIL DE VULCANISATION DE FILM MINCE SUR DES SUBSTRATS DE BASSE TEMPERATURE A DES VITESSES ELEVEES**

(54) **Title: METHOD AND APPARATUS FOR CURING THIN FILMS ON LOW-TEMPERATURE SUBSTRATES AT HIGH SPEEDS**



(57) **Abrégé/Abstract:**

A curing apparatus for thermally processing thin films on low-temperature substrates at high speeds is disclosed. The curing apparatus includes a strobe head, a strobe control module and a conveyor control module. The strobe control module controls the power, duration and repetition rate of a set of pulses generated by a flash lamp on the strobe head. The conveyor control module along with the strobe control module provide real-time synchronization between the repetition rate of the set of pulses and the speed at which the substrate is being moved under the strobe head, according to the speed information.

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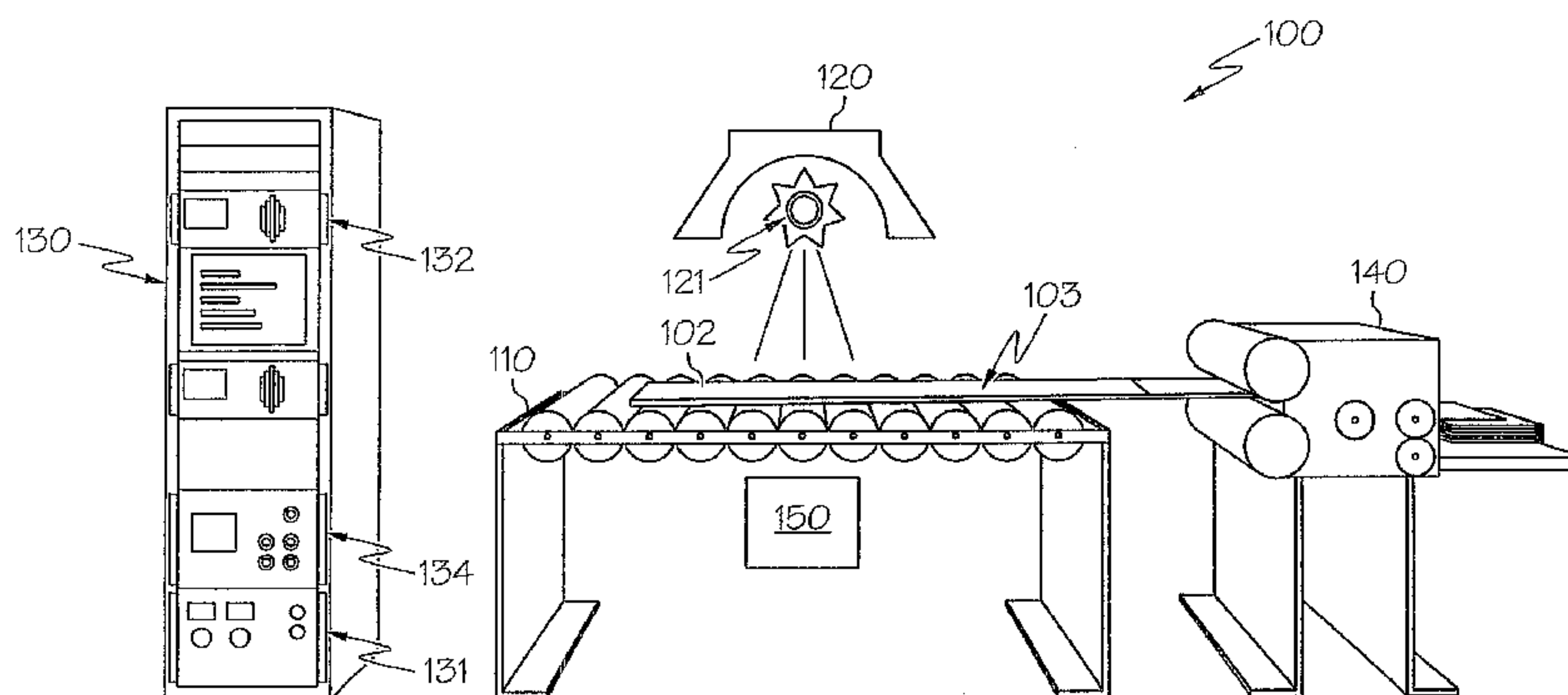


FIG. 1

(57) Abstract: A curing apparatus for thermally processing thin films on low-temperature substrates at high speeds is disclosed. The curing apparatus includes a strobe head, a strobe control module and a conveyor control module. The strobe control module controls the power, duration and repetition rate of a set of pulses generated by a flash lamp on the strobe head. The conveyor control module along with the strobe control module provide real-time synchronization between the repetition rate of the set of pulses and the speed at which the substrate is being moved under the strobe head, according to the speed information.

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1           **METHOD AND APPARATUS FOR CURING THIN FILMS ON LOW-**  
2           **TEMPERATURE SUBSTRATES AT HIGH SPEEDS**

3  
4           **BACKGROUND OF THE INVENTION**

5  
6       **1.     Technical Field**

7  
8           The present invention relates to curing systems in general, and, in particular, to a  
9       method for curing thin films on substrates at low temperatures.

10  
11       **2.     Description of Related Art**

12  
13           Printed electronics is the convergence of the semiconductor industry and the  
14       printing industry. The notion of printing electronic circuits instead of printing reading  
15       materials is seductive to printers as they can see the potential for doing "high value" print  
16       jobs without making major changes to their equipment. Similarly, electronic circuit  
17       manufacturers view the notion of printing electronic circuits as equally seductive because  
18       it allows them to fabricate electronic circuits in large volumes at a relatively low cost.

19  
20           During the manufacturing of electronic circuits, most thin film coatings need to be  
21       thermally processed, and the effectiveness of most thermal curing processes is related to  
22       the product of temperature and time. For example, the typical approach to curing a thin  
23       film is placing the thin film in an oven set to the maximum working temperature of a



1 substrate on which the thin film is disposed, and allowing the thin film to be cured within  
2 some reasonable amount of time.

3  
4 Since printed electronic circuits are typically associated with high volume  
5 and low cost, the substrates for the printed electronic circuits need to be made of relatively  
6 cheap materials such as paper or polymer instead of traditional substrate materials such as  
7 silicon, quartz, glass, ceramic, FR4, etc. However, paper or polymer has a much lower  
8 temperature of decomposition than silicon, quartz, glass, ceramic, FR4, etc., and the much  
9 lower temperature necessitates a longer cure time for thin films. For example, the  
10 maximum working temperature of polyethylene terephthalate (PET) is 150 °C, and a typical  
11 curing time for a silver based conductive film at this temperature is in the order of minutes.  
12 Such a long curing time makes the proposition of printing electronic circuits on paper on  
13 polymer much less economically attractive.

14  
15 Consequently, it would be desirable to provide a method and apparatus for  
16 thermally processing thin films on low-temperature substrates at a relatively high speed.

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## SUMMARY OF THE INVENTION

Certain exemplary embodiments can provide a curing apparatus comprising: a conveyor system for transporting a layer of thin film mounted on a low-temperature substrate; a strobe head having a flash lamp for providing a plurality of electromagnetic pulses to said layer of thin film; a strobe control module for controlling power, duration and repetition rate of said plurality of electromagnetic pulses generated by said flash lamp; a conveyor control module, in conjunction with said strobe control module, for synchronizing in real-time said repetition rate of said plurality of electromagnetic pulses with the speed at which said low-temperature substrate is being moved past said strobe head; and means for blowing air to cool said thin film after said thin film has been exposed to one of said electromagnetic pulses.

Certain exemplary embodiments can provide a curing apparatus comprising: a strobe head having a flash lamp for providing a plurality of electromagnetic pulses to a layer of thin film mounted on a low-temperature substrate; a strobe control module for controlling power, duration and repetition rate of said plurality of electromagnetic pulses generated by said flash lamp; means for moving said low-temperature substrate past said strobe head; a control module for providing real-time synchronization of said repetition rate of said plurality of electromagnetic pulses with a speed at which said low-temperature substrate is being moved past said strobe head; and means for blowing air to cool said thin film after said thin film has been exposed to one of said electromagnetic pulses.

Certain exemplary embodiments can provide a curing apparatus comprising: a conveyor system for transporting a layer of thin film mounted on a low-temperature substrate; a strobe head having a flash lamp for providing a plurality of electromagnetic pulses to said layer of thin film; a strobe control module for controlling power, duration and repetition rate of said plurality of electromagnetic pulses generated by said flash lamp; a conveyor

1 control module, in conjunction with said strobe control module, for synchronizing in real-  
2 time said repetition rate of said plurality of electromagnetic pulses with the speed at  
3 which said low-temperature substrate is being moved past said strobe head; and means  
4 for cooling said thin film by removing heat from said substrate via conduction after said  
5 thin film has been exposed to one of said electromagnetic pulses.

6

7 Certain exemplary embodiments can provide a curing apparatus comprising: a strobe  
8 head having a flash lamp for providing a plurality of electromagnetic pulses to a layer of  
9 thin film mounted on a low-temperature substrate; a strobe control module for controlling  
10 power, duration and repetition rate of said plurality of electromagnetic pulses generated  
11 by said flash lamp; means for moving said low-temperature substrate past said strobe  
12 head; a control module for providing real-time synchronization of said repetition rate of  
13 said plurality of electromagnetic pulses with a speed at which said low-temperature  
14 substrate is being moved past said strobe head; and means for cooling said thin film by  
15 removing heat from said substrate via conduction after said thin film has been exposed to  
16 one of said electromagnetic pulses.

17

18 All features and advantages of the present invention will become apparent in the  
19 following detailed written description.



1                                   **BRIEF DESCRIPTION OF THE DRAWINGS**

2

3                   The invention itself, as well as a preferred mode of use, further objects, and

4 advantages thereof, will best be understood by reference to the following detailed

5 description of an illustrative embodiment when read in conjunction with the accompanying

6 drawings, wherein:

7

8                   Figure 1 is a diagram of a curing apparatus, in accordance with a preferred

9 embodiment of the present invention;

10

11                  Figure 2 is a diagram of a thermal barrier layer on a low-temperature

12 substrate, in accordance with a preferred embodiment of the present invention;

13

14                  Figure 3 is a diagram of an air knife within the curing apparatus from Figure

15 1, in accordance with a preferred embodiment of the present invention; and

16

17                  Figure 4 is a diagram of a cooling roller within the curing apparatus from

18 Figure 1, in accordance with a preferred embodiment of the present invention.

## DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

For the present invention, *curing* is defined as thermal processing, which includes drying (driving off solvent), particle sintering, densification, chemical reaction initiation, phase transformation, grain growth, annealing, heat treating, etc. When curing materials on a low-temperature substrate, such as polymer or paper, one limiting factor in attaining a good cure is the decomposition of the substrate because a thin film (which is defined as a layer of material of less than 100 microns thick) often needs to be processed at temperatures close to or even beyond the decomposition temperature of the substrate. Furthermore, even if the thin films can be cured at a low temperature, the low decomposition temperature of the substrate increases the amount of time to thermally cure the material on the substrate. The above-mentioned problems can be overcome by the curing apparatus of the present invention.

Referring now to the drawings and in particular to Figure 1, there is depicted a diagram of a curing apparatus, in accordance with a preferred embodiment of the present invention. As shown, a curing apparatus 100 includes a conveyor belt system 110, a strobe head 120, a relay rack 130 and a reel-to-reel feeding system 140. Curing apparatus 100 is capable of curing a thin film 102 mounted on a low-temperature substrate 103 situated on a web or individual sheets being moved across a conveyor belt at a relatively high speed. Conveyor belt system 110 can operate at speeds from 2 to 1000 ft/min, for example, to move substrate 103. Curing apparatus 100 can accommodate a web of any width in 6-inch increments. Thin film 102 can be added on substrate 103 by one or combinations of existing technologies such as screen printing, inkjet printing, gravure, laser printing, xerography, pad printing, painting, dip-pen, syringe, airbrush, flexographic, chemical vapor deposition (CVD), PECVD, evaporation, sputtering, etc.

Strobe head 120, which is preferably water cooled, includes a high-intensity pulsed xenon flash lamp 121 for curing thin film 102 located on substrate 103. Pulsed xenon flash lamp 121 can provide light pulses of different intensity, pulse length and pulse



1 repetition frequency. For example, pulsed xenon flash lamp 121 can provide 10  $\mu$ s to 10  
2 ms pulses with a 3" by 6" wide beam pattern at a pulse repetition rate of up to 1 kHz. The  
3 spectral content of the emissions from pulsed xenon flash lamp 121 ranges from 200 nm  
4 to 2,500 nm. The spectrum can be adjusted by replacing the quartz lamp with a cerium  
5 doped quartz lamp to remove most of the emission below 350 nm. The quartz lamp can  
6 also be replaced with a sapphire lamp to extend the emission from approximately 140 nm  
7 to approximately 4,500 nm. Filters may also be added to remove other portions of the  
8 spectrum. Flash lamp 121 can also be a water wall flash lamp that is sometimes referred  
9 to as a Directed Plasma Arc (DPA) arc lamp.

10  
11 Relay rack 130 includes an adjustable power supply 131, a conveyor control  
12 module 132, and a strobe control module 134. Adjustable power supply 131 can produce  
13 pulses with an energy of up to 4 kiloJoules per pulse. Adjustable power supply 131 is  
14 connected to pulsed xenon flash lamp 121, and the intensity of the emission from pulsed  
15 xenon flash lamp 121 can be varied by controlling the amount of current passing through  
16 pulsed xenon flash lamp 121.

17  
18 Adjustable power supply 131 controls the emission intensity of pulsed xenon  
19 flash lamp 121. The power, pulse duration and pulse repetition frequency of the emission  
20 from pulsed xenon flash lamp 121 are electronically adjusted and synchronized to the web  
21 speed to allow optimum curing of thin film 102 without damaging substrate 103, depending  
22 on the optical, thermal and geometric properties of thin film 102 and substrate 103.

23  
24 During curing operation, substrate 103 as well as thin film 102 are being  
25 moved onto conveyor belt system 110. Conveyor belt system 110 moves thin film 102  
26 under strobe head 120 where thin film 102 is cured by rapid pulses from pulsed xenon flash  
27 lamp 121. The power, duration and repetition rate of the emissions from pulsed xenon  
28 flash lamp 121 are controlled by strobe control module 134, and the speed at which  
29 substrate 103 is being moved past strobe head 120 is determined by conveyor control  
30 module 132.

1 A sensor **150**, which can be a mechanical, electrical or optical sensor, is  
 2 utilized to sense the speed of the conveyor belt of conveyor belt system **110**. For example,  
 3 the conveyor belt speed of conveyor belt system **110** can be sensed by detecting a signal  
 4 from a shaft encoder connected to a wheel that made contact with the moving conveyor  
 5 belt. In turn, the pulse repetition rate can be synchronized with the conveyor belt speed  
 6 of conveyor belt system **110** accordingly. The synchronization of the strobe pulse rate  $f$   
 7 is given by:

$$f = \frac{0.2 * S * O}{W}$$

11 *where*  $f =$  strobe pulse rate [Hz]  
 12  $S =$  web speed [ft/min]  
 13  $O =$  overlap factor (*i.e.*, the average number of strobe pulses that are  
 14 received by the substrate)  
 15  $W =$  curing head width [in]

16  
 17 For example, with a web speed of 200 ft/min, an overlap factor of 5, and a curing head  
 18 width of 2.75 inches, the pulse rate of the strobe lamp is 72.7 Hz.

19  
 20 By combining a rapid pulse train with moving substrate **103**, a uniform cure  
 21 can be attained over an arbitrarily large area as each section of thin film **102** is exposed to  
 22 multiple pulses, which approximates a continuous curing system such as an oven.

23  
 24 When thin film **102** is in direct contact with substrate **103**, its heating is  
 25 limited by the decomposition temperature of substrate **103** at the interface of thin film **102**.  
 26 This effect can be alleviated and better curing can be attained by placing a layer of thermal  
 27 barrier material with a higher temperature of decomposition than substrate **103** between thin  
 28 film **102** and substrate **103**.



1 With reference now to Figure 2, there is depicted a diagram of a thermal  
2 barrier layer added onto a low-temperature substrate, in accordance with a preferred  
3 embodiment of the present invention. As shown, a thermal barrier layer **201** is inserted  
4 between thin film **102** and substrate **103**. Thermal barrier layer **201** enables a higher power  
5 radiation pulse to more deeply cure thin film **102** on substrate **103** that is thermally fragile.  
6 The usage of thermal barrier layer **201** enables a higher power irradiation and a slightly  
7 higher total energy, which results in a pulse having a shorter pulse length. When multiple  
8 rapid pulses are used, the time scale of curing is increased to a level that allows heat to be  
9 removed from substrate **103** during the curing process.

10  
11 Thermal barrier layer **201** is preferably a higher temperature material than  
12 substrate **103** yet with a lower thermal conductivity than substrate **103**. Thermal barrier  
13 layer **201** can be made of, for example, a layer of silicon dioxide ( $\text{SiO}_2$ ). Other materials  
14 include silica particles or ceramic particles. Silane derivatives make excellent high  
15 temperature binders for these particles. A particularly convenient barrier layer is spin-on-  
16 glass (SOG), which is widely used in the semiconductor industry for wafer planarization  
17 as it can easily be applied to a large area with standard coating techniques. SOG allows  
18 thermal barrier layer **201** to be applied in-line in a reel-to-reel process at a high processing  
19 rate.

20  
21 Referring now to Figure 3, there is depicted a diagram of an air knife within  
22 curing apparatus **100** from Figure 1, in accordance with a preferred embodiment of the  
23 present invention. As shown, an air knife **301** is utilized to cool substrate **103** before,  
24 during, and/or after curing of thin film **102**. Air knife **301** is applied from the top or  
25 bottom of substrate **103**. When applied from the top, air knife **301** may also aid in  
26 removing additional solvent from thin film **102** during the curing process. Although there  
27 can be little convective cooling during a single pulse (~1 ms), this technique can provide  
28 substantive cooling during a rapid pulse train that may be greater than 100 ms.



1 With reference now to Figure 4, there is depicted a diagram of a cooling  
2 roller within curing apparatus 100 from Figure 1, in accordance with a preferred  
3 embodiment of the present invention. As shown, a cooling roller 401 is utilized to cool  
4 substrate 103. Substrate 103 is drawn over roller 401 before, during, or after the curing  
5 process. Roller 401 functions to remove heat via conduction from substrate 103 after the  
6 curing process. Active cooling may be applied to roller 401 in order to maintain roller 401  
7 at a constant temperature. Aside from pre-cooling substrate 103, though there can be little  
8 external conductive cooling during a single pulse (~1 ms), this technique can provide  
9 additional substantive cooling during a rapid pulse train that may be greater than 100 ms.  
10

11 As has been described, the present invention provides a curing apparatus and  
12 method for thermally processing thin films on low-temperature substrates at relatively high  
13 speeds.  
14

15 The following is an example of curing using the curing apparatus of the  
16 present invention with a sheet fed conveyor. A silver nanoparticle, aqueous-based ink,  
17 which is available commercially from Novacentrix Corporation, was loaded into an ink jet  
18 cartridge and printed onto a photopaper at approximately 300 nm thick. After printing, the  
19 ink layer had a sheet resistance of approximately 20,000 ohm/square. The photopaper (*i.e.*,  
20 substrate) was clamped onto a 1/4" thick aluminum plate maintained at 27 °C and placed  
21 on a conveyor belt moving at 100 feet per minute. The curing region of the curing lamp  
22 was 2.75" wide in the web conveyance direction and 6" wide perpendicular to the web  
23 conveyance direction resulting in a beam area of 106 cm<sup>2</sup>. The strobe lamp was activated  
24 to provide multiple pulses at a frequency of 14.6 Hz with a pulse width of 450  
25 microseconds, delivering 1.0 J/cm<sup>2</sup> per pulse and an average radiant power of 2.2 KW/cm<sup>2</sup>.  
26 Each portion of the substrate received 2 overlapping pulses for a total of 2.0 J/cm<sup>2</sup> of total  
27 energy. The total time of curing was approximately 0.15 seconds. After curing, the sheet  
28 resistance of the ink layer was reduced to 0.25 ohms per square. This corresponded to a  
29 resistivity of 8 micro-ohm-cm or five times the resistivity of bulk silver. The area of the  
30 ink layer was larger than the curing head, but the overlapping pulses resulting from the

1 combination of rapid pulsing and a moving substrate allowed a uniform cure for an  
2 arbitrarily long pattern. In contrast, with conventional oven curing, an identical  
3 film/substrate can be placed in an oven at 100 °C (which is the highest working  
4 temperature of the substrate). After 30 minutes of curing, the resulting sheet resistance  
5 reached only 1.8 ohms/square.

6

7           While the invention has been particularly shown and described with reference to a  
8 preferred embodiment, it will be understood by those skilled in the art that various  
9 changes in form and detail may be made therein.

1    **CLAIMS**2  
3    1.    A curing apparatus comprising:4           a conveyor system for transporting a layer of thin film mounted on a low-  
5 temperature substrate;6           a strobe head having a flash lamp for providing a plurality of electromagnetic  
7 pulses to said layer of thin film;8           a strobe control module for controlling power, duration and repetition rate of said  
9 plurality of electromagnetic pulses generated by said flash lamp;10          a conveyor control module, in conjunction with said strobe control module, for  
11 synchronizing in real-time said repetition rate of said plurality of electromagnetic pulses  
12 with the speed at which said low-temperature substrate is being moved past said strobe  
13 head; and14          means for blowing air to cool said thin film after said thin film has been exposed  
15 to one of said electromagnetic pulses.  
16

17    2.    A curing apparatus comprising:

18           a strobe head having a flash lamp for providing a plurality of electromagnetic  
19 pulses to a layer of thin film mounted on a low-temperature substrate;20           a strobe control module for controlling power, duration and repetition rate of  
21 said plurality of electromagnetic pulses generated by said flash lamp;

22           means for moving said low-temperature substrate past said strobe head;

23           a control module for providing real-time synchronization of said repetition rate of  
24 said plurality of electromagnetic pulses with a speed at which said low-temperature  
25 substrate is being moved past said strobe head; and26          means for blowing air to cool said thin film after said thin film has been  
27 exposed to one of said electromagnetic pulses.  
28



- 1 3. The curing apparatus of Claim 1 or 2, wherein said flash lamp is a xenon flash  
2 lamp.  
3
- 4 4. The curing apparatus of Claim 3, wherein said xenon flash lamp is operable to  
5 generate pulses from 10  $\mu$ s to 10 ms at a pulse repetition rate of up to 1 kHz.  
6
- 7 5. The curing apparatus of Claim 3, wherein the spectral content of said xenon flash  
8 lamp ranges from 200 nm to 2,500 nm.  
9
- 10 6. The curing apparatus of Claim 1 or 2, wherein said means for blowing air is an air  
11 knife.  
12
- 13 7. The curing apparatus of Claim 1 or 2, wherein said curing apparatus comprises a  
14 roller for removing heat from said substrate via conduction.  
15
- 16 8. The curing apparatus of Claim 1 or 2, wherein said flash lamp is a Directed  
17 Plasma Arc lamp.  
18
- 19 9. The curing apparatus of Claim 1 or 2, wherein said speed synchronization is given  
20 by:  
21

$$f = \frac{0.2 * S * O}{W}$$

22

23 wherein

24 f = pulse repetition rate [Hz]

25 S = speed at which said low-temperature substrate is being moved [ft/min]

26 O = overlap factor

27 W = width of said strobe head [in].

28

1 10. The curing apparatus of Claim 1 or 2, wherein said curing apparatus comprises a  
2 feeder for feeding said substrate to said means for moving said low-temperature substrate  
3 past said strobe head.

4  
5 11. The curing apparatus of Claim 1 or 2, wherein said curing apparatus comprises a  
6 sensor for sensing the speed at which the substrate is being moved under said strobe head.

7  
8 12. A curing apparatus comprising:

9 a conveyor system for transporting a layer of thin film mounted on a low-  
10 temperature substrate;

11 a strobe head having a flash lamp for providing a plurality of electromagnetic  
12 pulses to said layer of thin film;

13 a strobe control module for controlling power, duration and repetition rate of said  
14 plurality of electromagnetic pulses generated by said flash lamp;

15 a conveyor control module, in conjunction with said strobe control module, for  
16 synchronizing in real-time said repetition rate of said plurality of electromagnetic pulses  
17 with the speed at which said low-temperature substrate is being moved past said strobe  
18 head; and

19 means for cooling said thin film by removing heat from said substrate via  
20 conduction after said thin film has been exposed to one of said electromagnetic pulses.

21  
22 13. A curing apparatus comprising:

23 a strobe head having a flash lamp for providing a plurality of electromagnetic  
24 pulses to a layer of thin film mounted on a low-temperature substrate;

25 a strobe control module for controlling power, duration and repetition rate of said  
26 plurality of electromagnetic pulses generated by said flash lamp;

27 means for moving said low-temperature substrate past said strobe head;

28

1 a control module for providing real-time synchronization of said repetition rate of  
2 said plurality of electromagnetic pulses with a speed at which said low-temperature  
3 substrate is being moved past said strobe head; and

4 means for cooling said thin film by removing heat from said substrate via  
5 conduction after said thin film has been exposed to one of said electromagnetic pulses.  
6

7 14. The curing apparatus of Claim 12 or 13, wherein said means for cooling  
8 comprises a roller.

9  
10 15. The curing apparatus of Claim 12 or 13, wherein said flash lamp is a xenon flash  
11 lamp.

12  
13 16. The curing apparatus of Claim 12 or 13, wherein said xenon flash lamp generates  
14 pulses from 10  $\mu$ s to 10 ms at a pulse repetition rate of up to 1 kHz.

15  
16 17. The curing apparatus of Claim 14, wherein the spectral content of said xenon  
17 flash lamp ranges from 200 nm to 2,500 nm.

18  
19 18. The curing apparatus of Claim 12 or 13, wherein said flash lamp is a Directed  
20 Plasma Arc lamp.

21  
22 19. The curing apparatus of Claim 12 or 13, wherein said curing apparatus comprises  
23 a feeder for feeding said low-temperature substrate to said conveyor system.

24  
25 20. The curing apparatus of Claim 12 or 13, wherein said curing apparatus comprises  
26 a sensor for sensing the speed at which said low-temperature substrate is being moved  
27 past said flash lamp.  
28



1 21. The curing apparatus of Claim 12 or 13, wherein said speed synchronization is  
2 given by:

$$f = \frac{0.2 * S * O}{W}$$

4  
5 wherein

6 f = pulse repetition rate [Hz]

7 S = speed at which said low-temperature substrate is being moved [ft/min]

8 O = overlap factor

9 W = width of said strobe head [in].

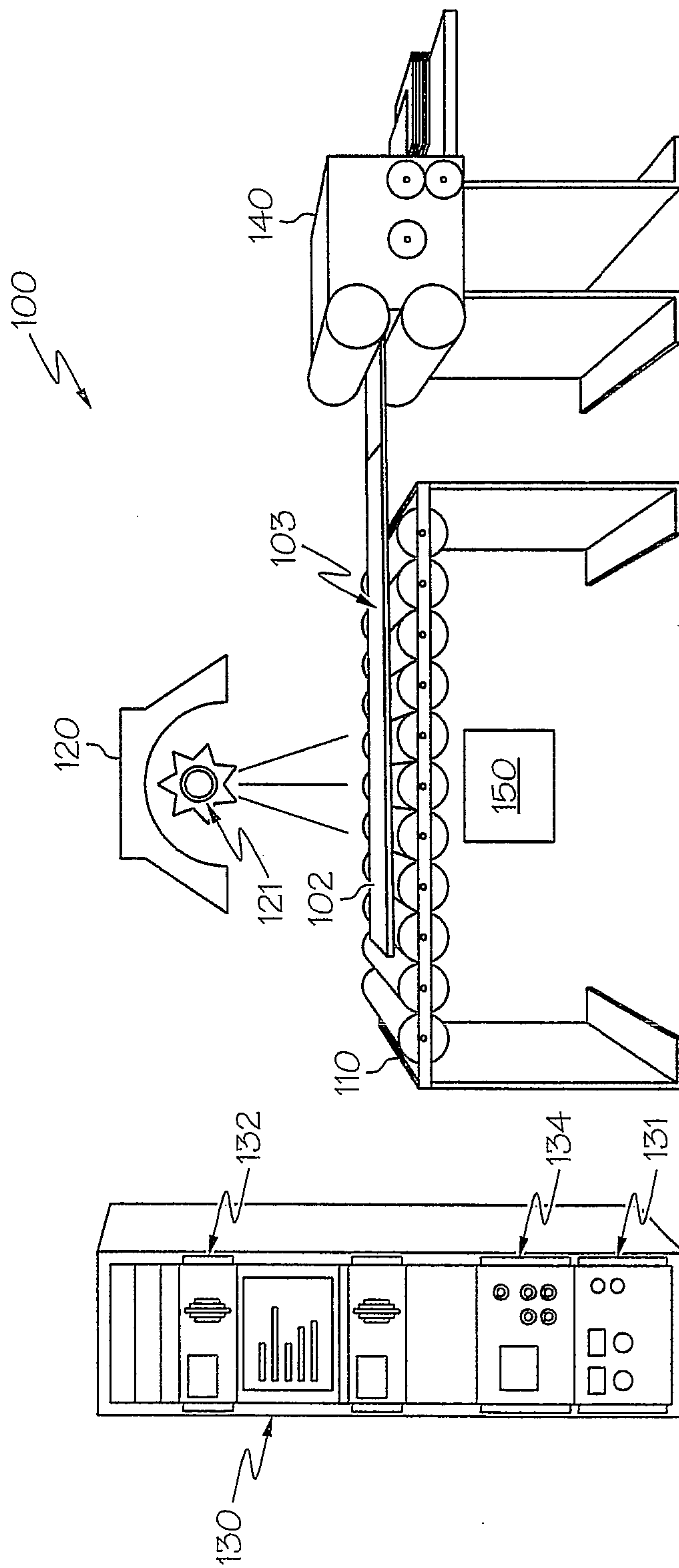


FIG. 1

2 / 3

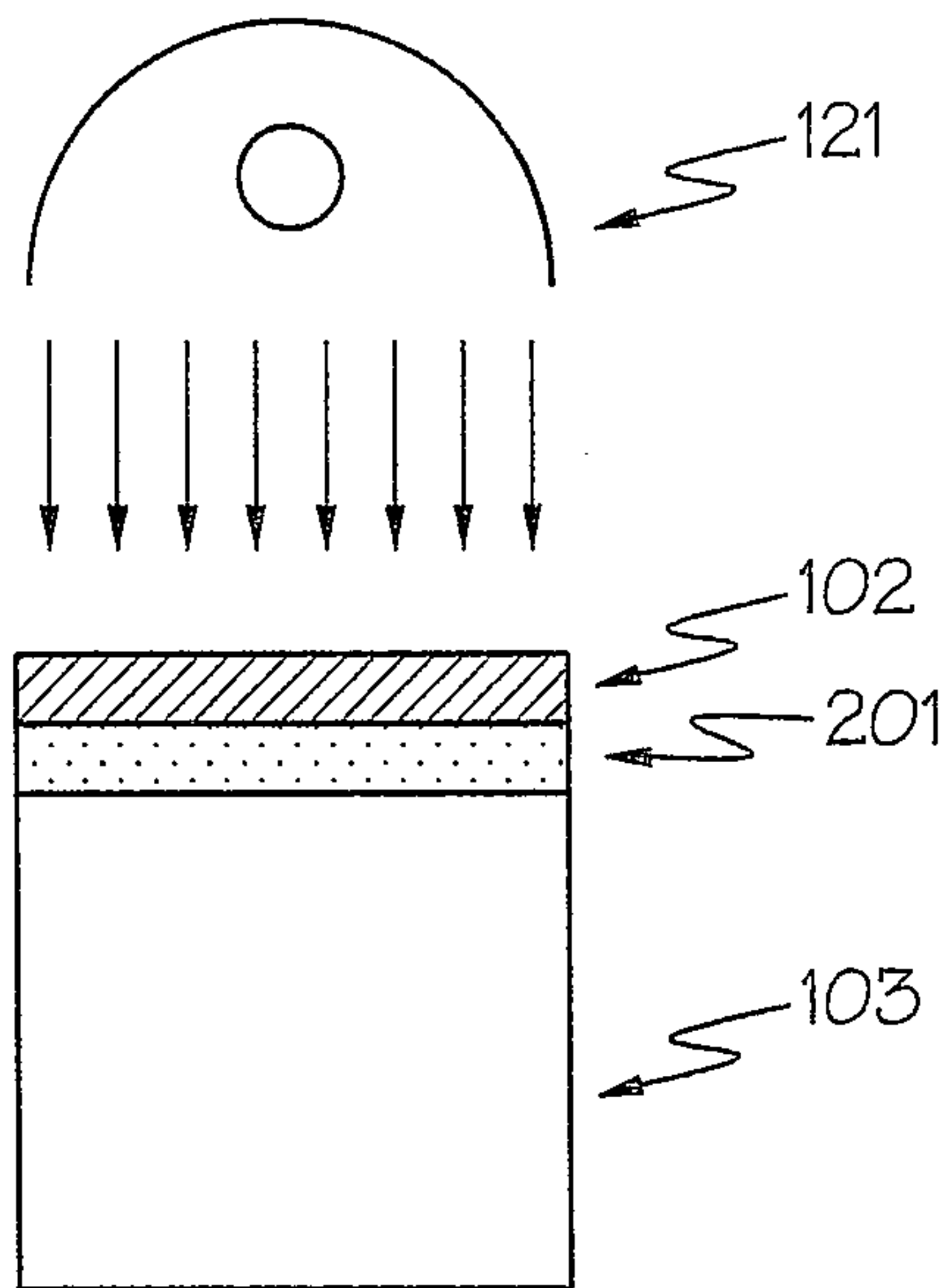


FIG. 2

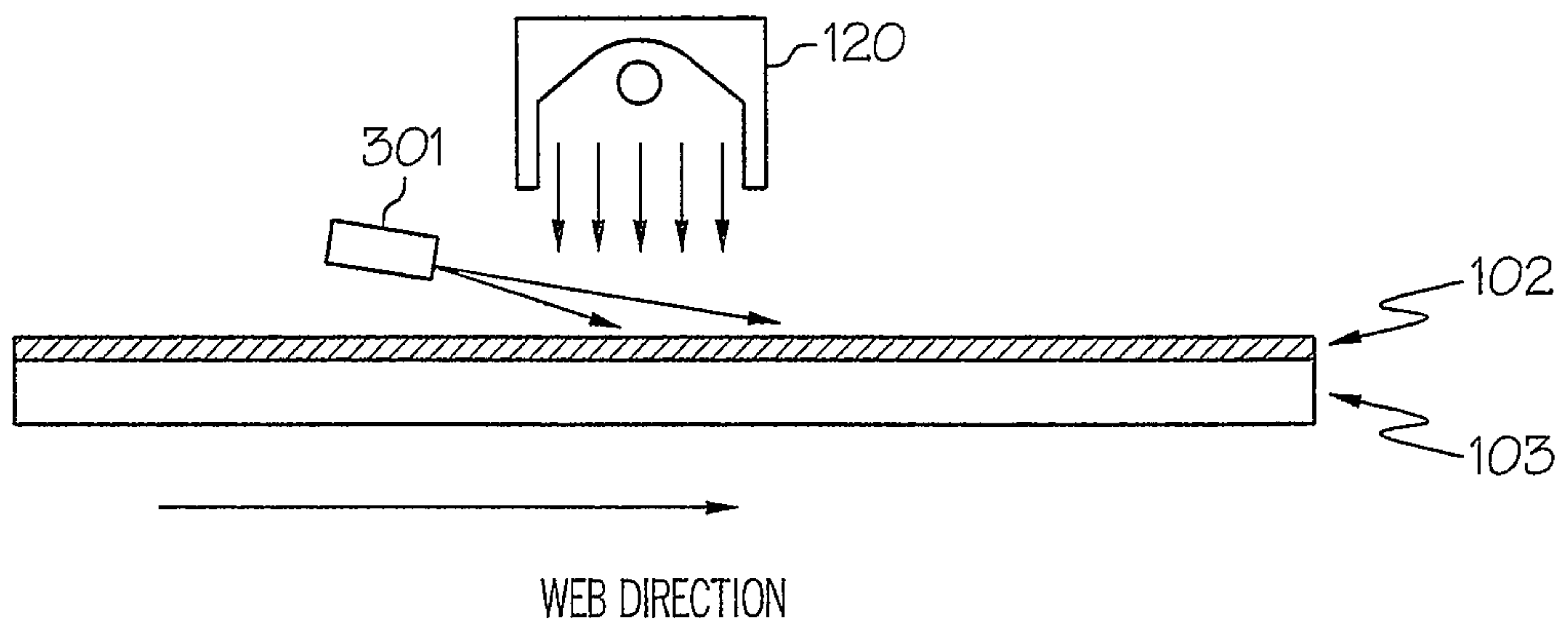


FIG. 3



3 / 3

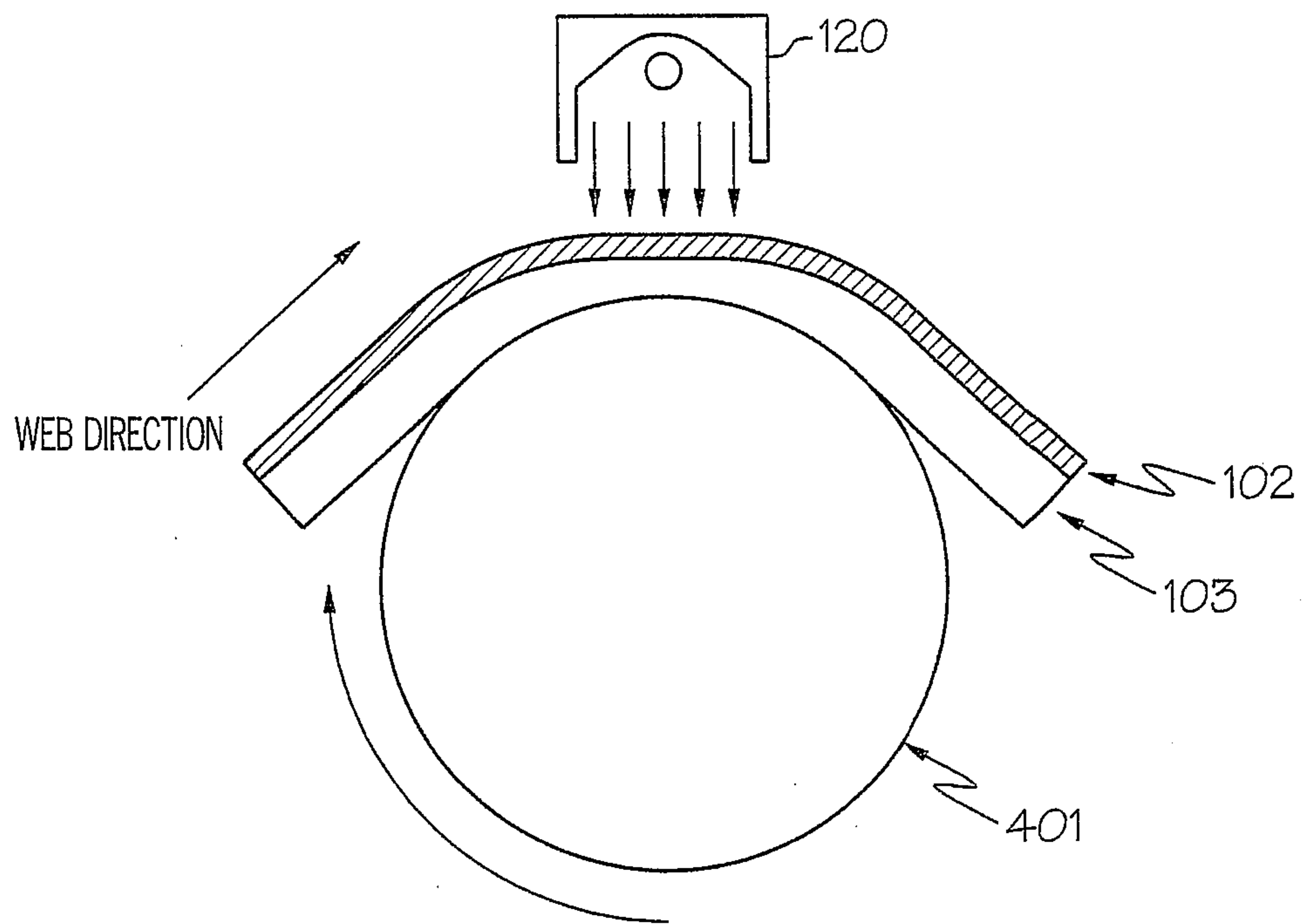


FIG. 4

