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Sampayan et al.

(54) **MULTI-SIDED OPTICAL WAVEGUIDE-FED PHOTOCONDUCTIVE SWITCHES**

(71) Applicants: **Stephen E. Sampayan**, Manteca, CA (US); **Hoang T. Nguyen**, Livermore, CA (US); **Scott D. Nelson**, Patterson, CA (US)

(72) Inventors: **Stephen E. Sampayan**, Manteca, CA (US); **Hoang T. Nguyen**, Livermore, CA (US); **Scott D. Nelson**, Patterson, CA (US)

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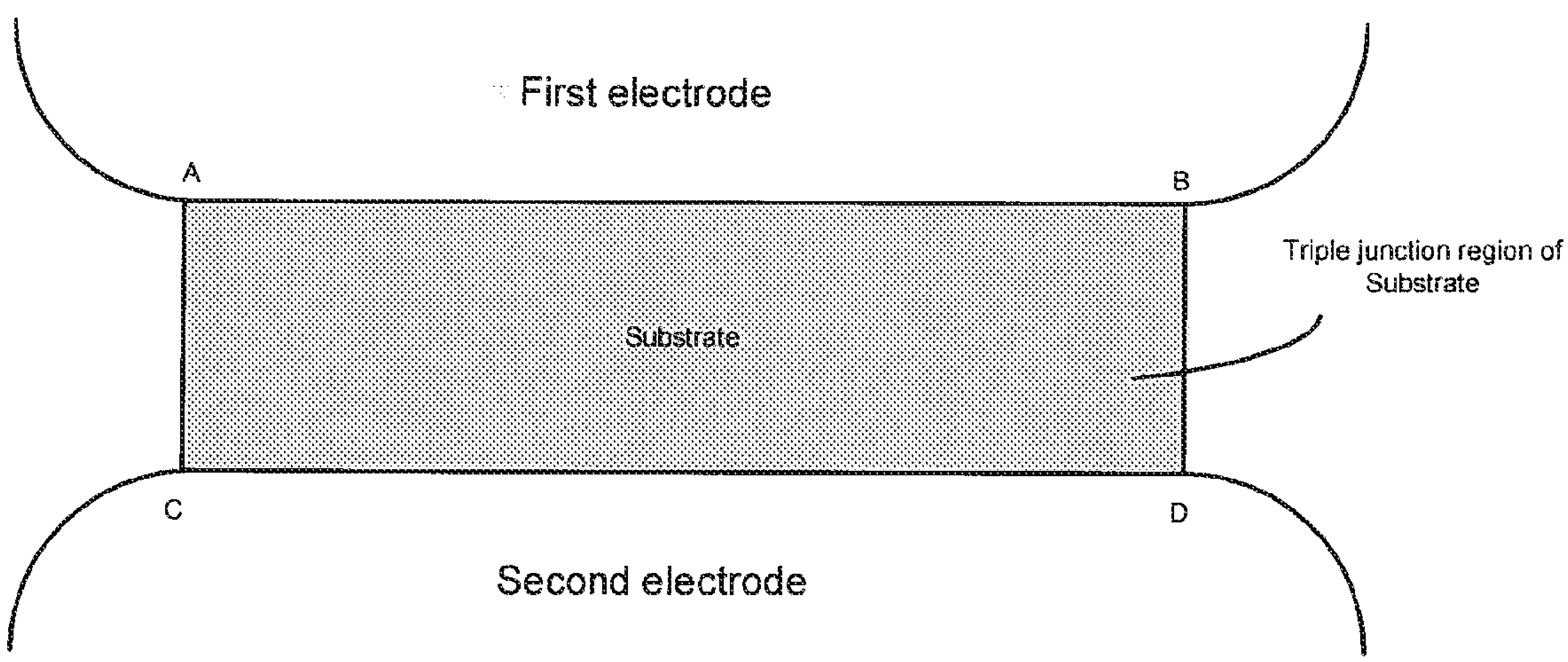
(57) **ABSTRACT**

A photoconductive switch and optical transconductance varistor having a photoconductive region e.g. a wide bandgap semiconductor material substrate between opposing electrodes. An optical waveguide is arranged to surround the photoconductive region for directing conduction-inducing radiation into the photoconductive region. And an optical diffusion element is arranged to diffuse/disperse the radiation prior to entering the optical waveguide and into the substrate, for uniformly illuminating the substrate for conduction.



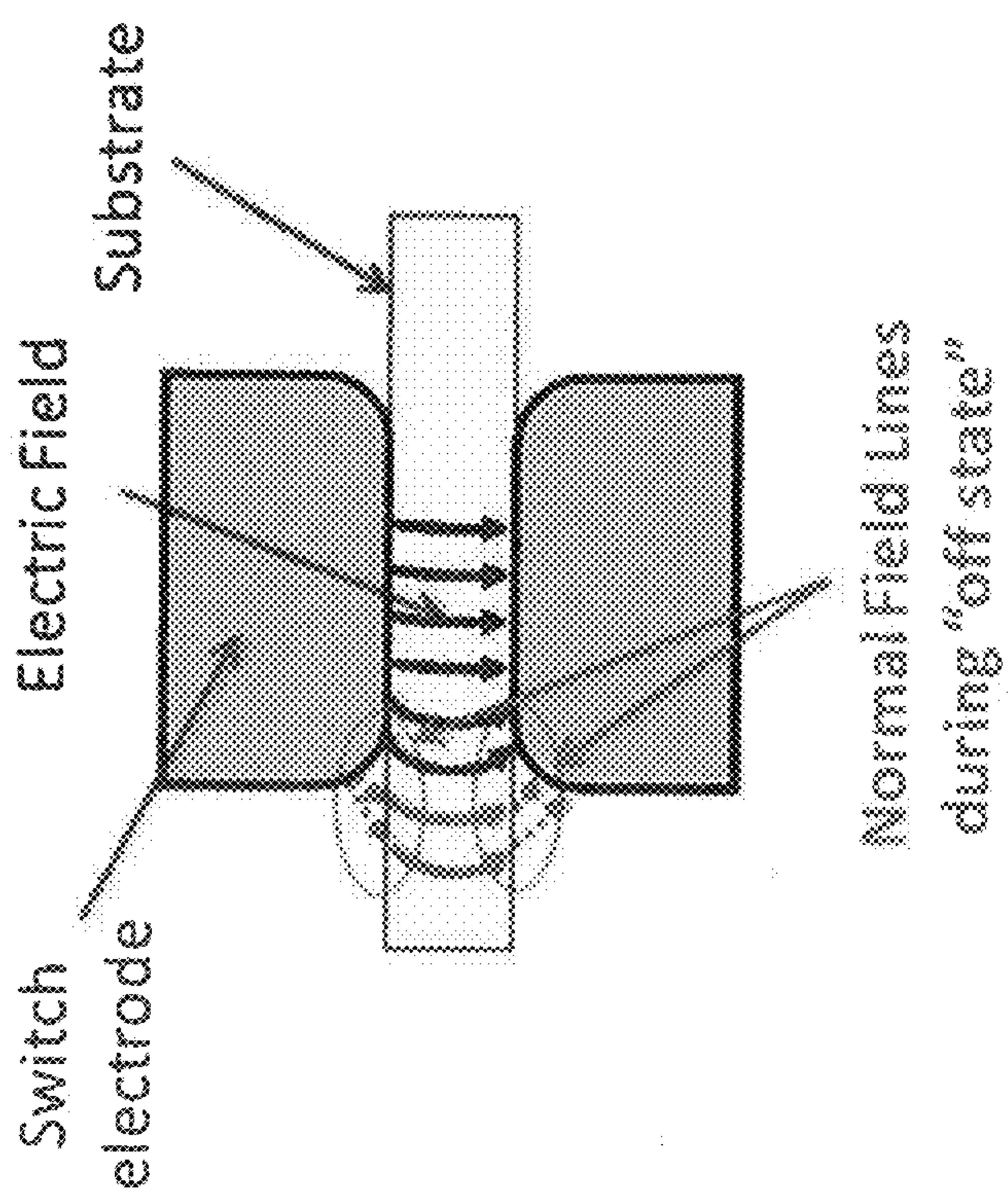

Switch electrode
Electric Field
Substrate
Normal Field Lines during "off state"

Fig. 1

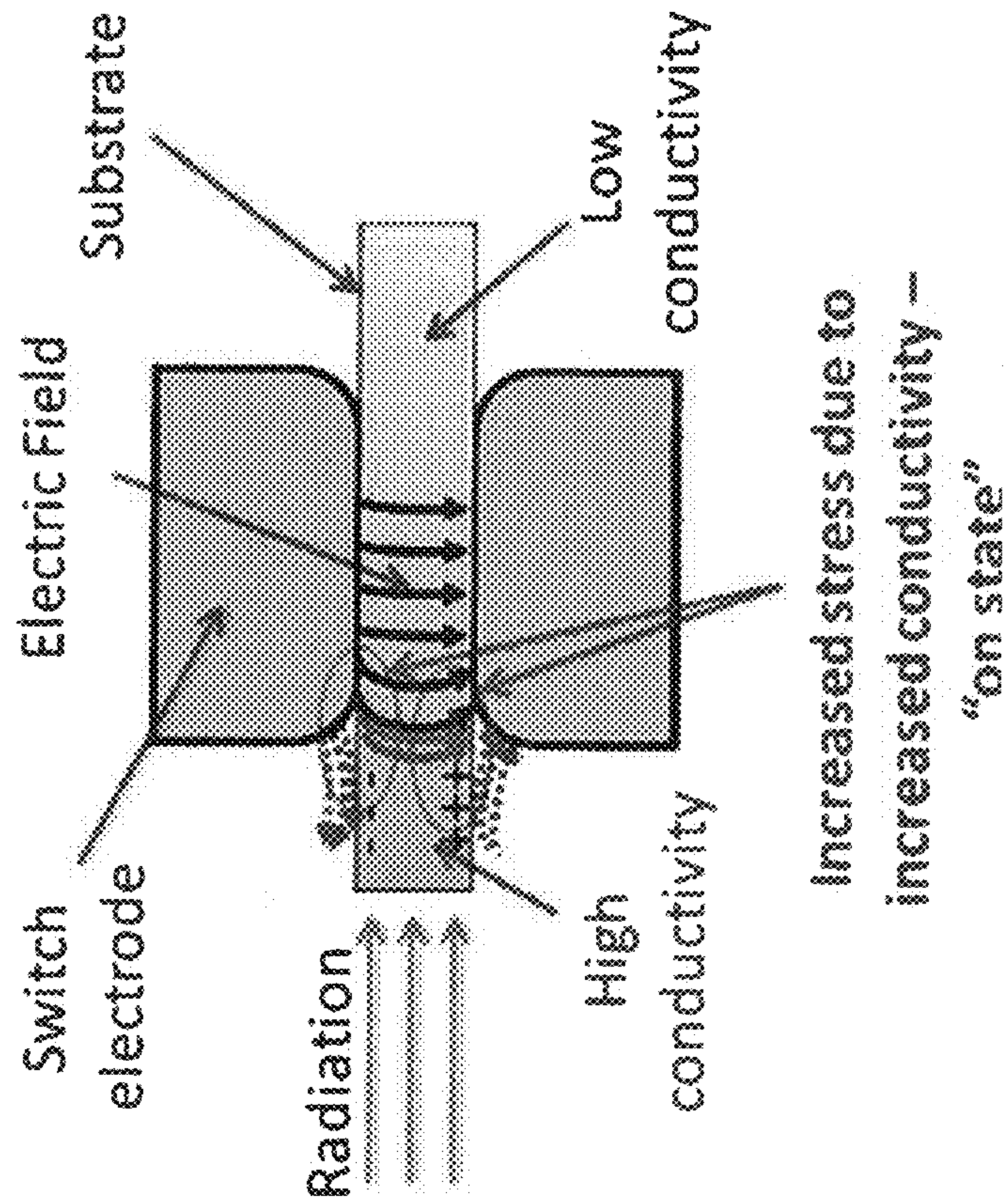

Switch electrode
Electric Field
Substrate
Low conductivity
Radiation
High conductivity
Increased stress due to increased conductivity – "on state"

Fig. 2

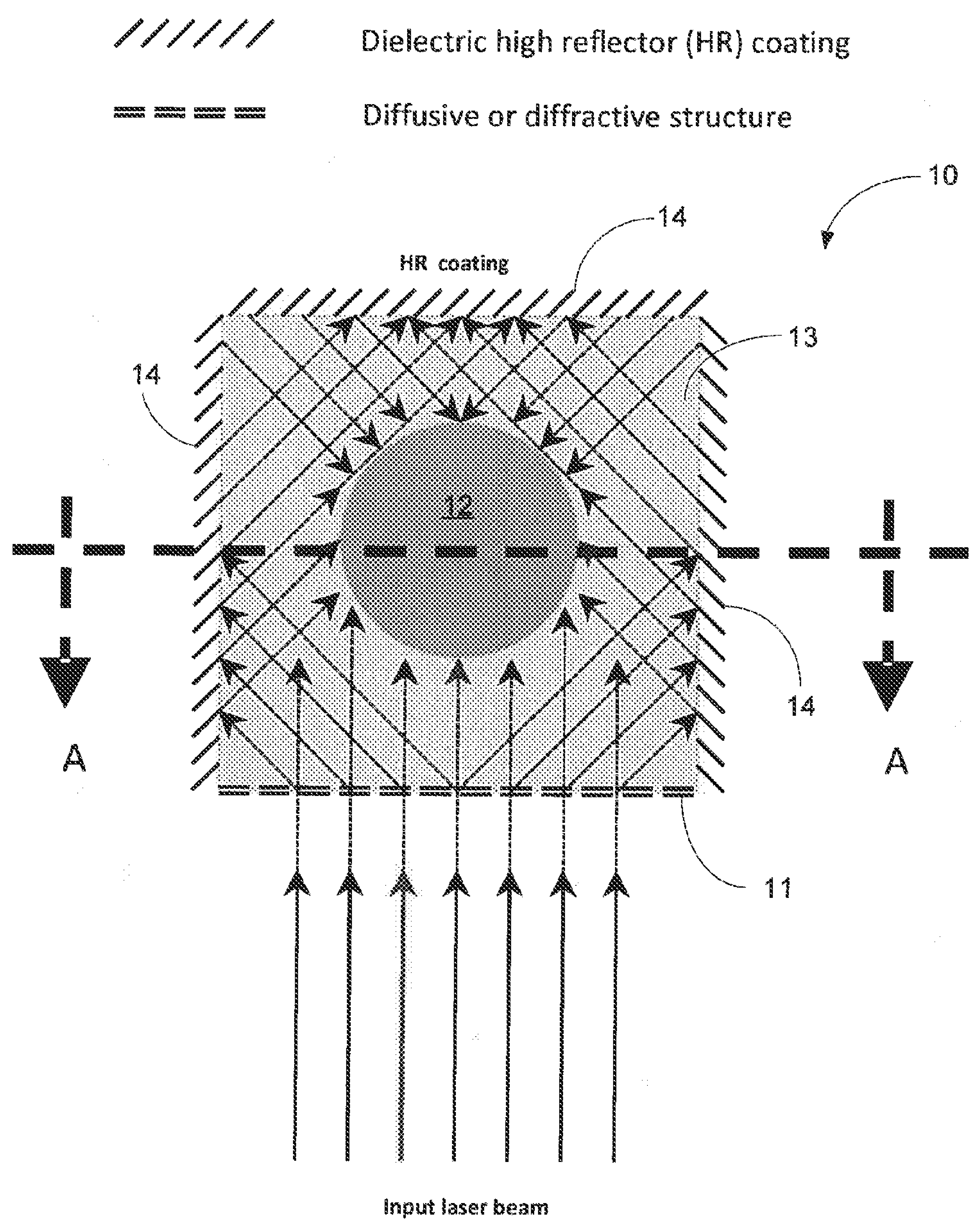

Dielectric high reflector (HR) coating
Diffusive or diffractive structure
10
14
HR coating
13
14
12
A
A
14
11
Input laser beam

Fig. 3

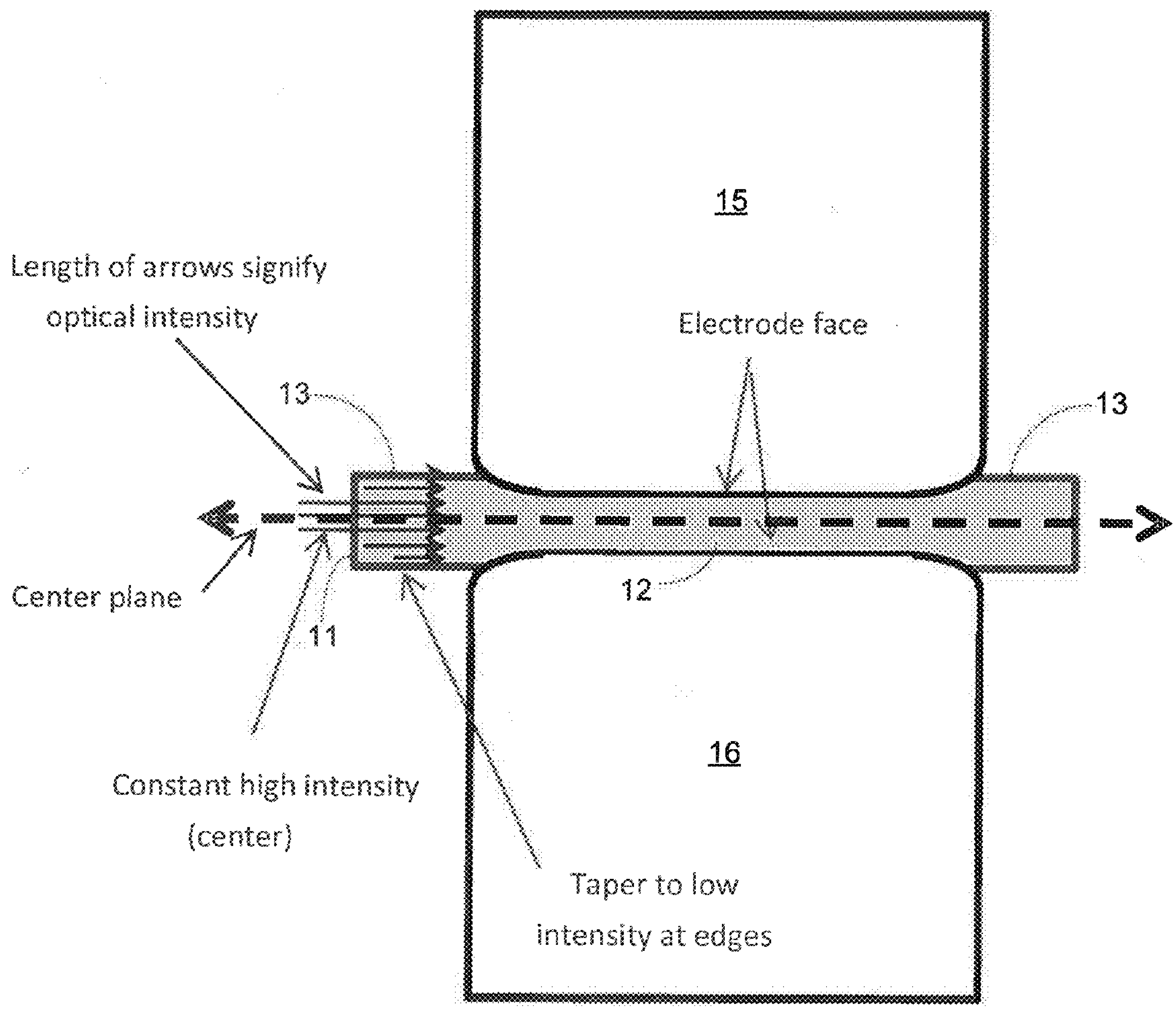

15
Length of arrows signify optical intensity
Electrode face
13
13
Center plane
12
11
16
Constant high intensity (center)
Taper to low intensity at edges

Fig. 4

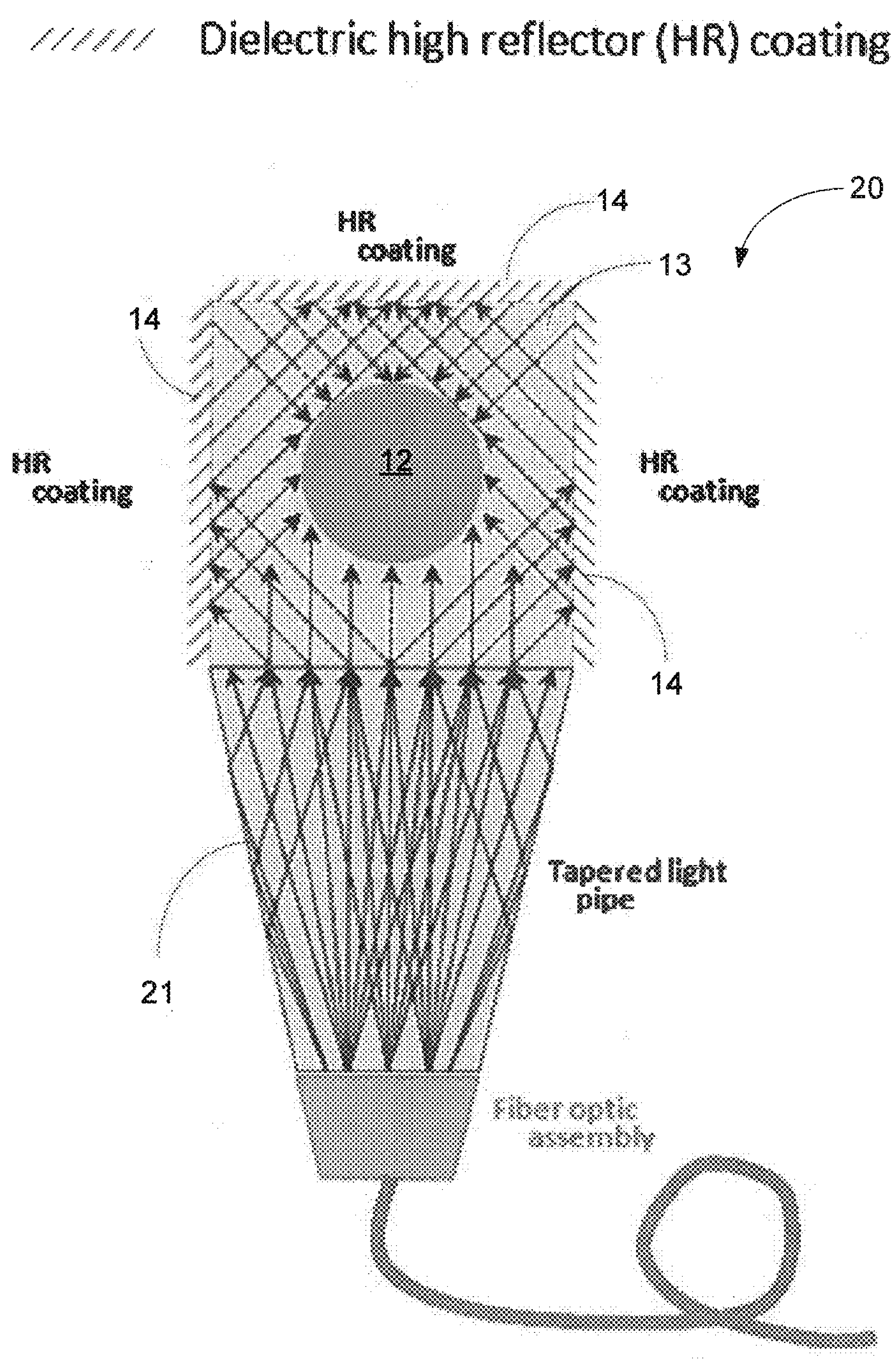

Dielectric high reflector (HR) coating
20
14
HR coating
13
14
12
HR coating
HR coating
14
Tapered light pipe
21
Fiber optic assembly

Fig. 5

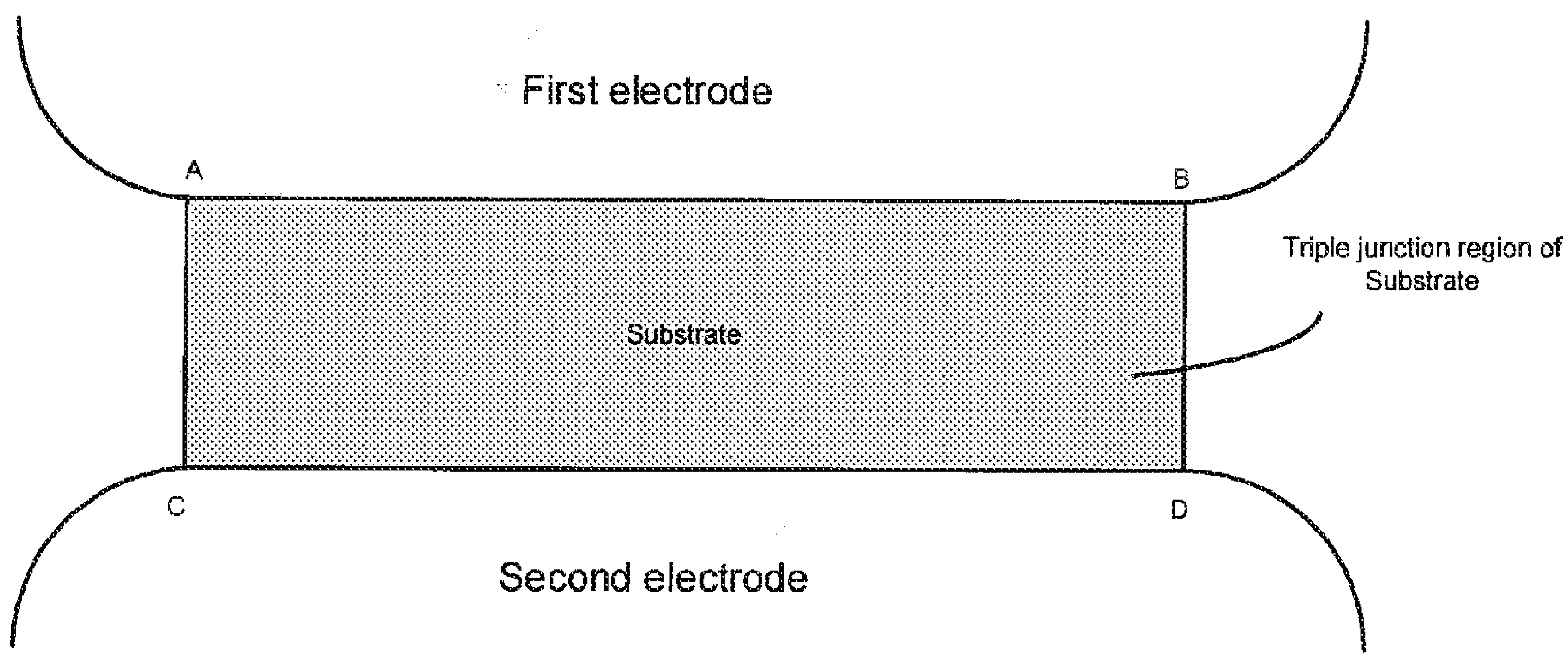

First electrode
A
B
Triple junction region of Substrate
Substrate
C
D
Second electrode

Fig. 6

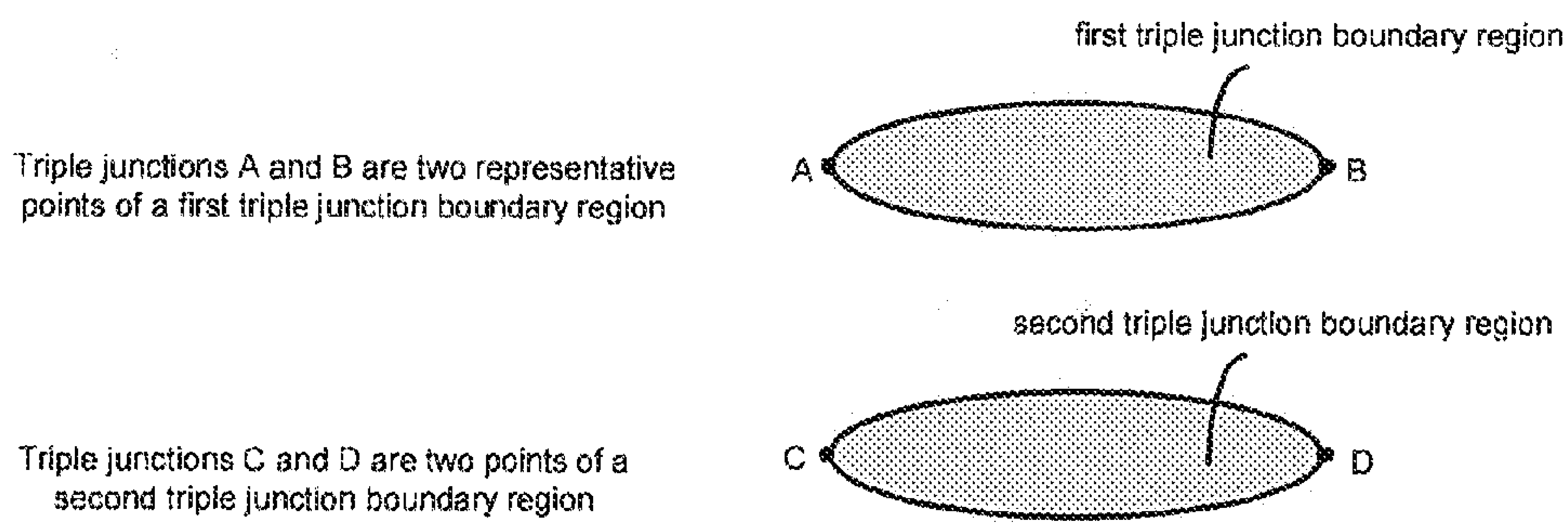


Fig. 7

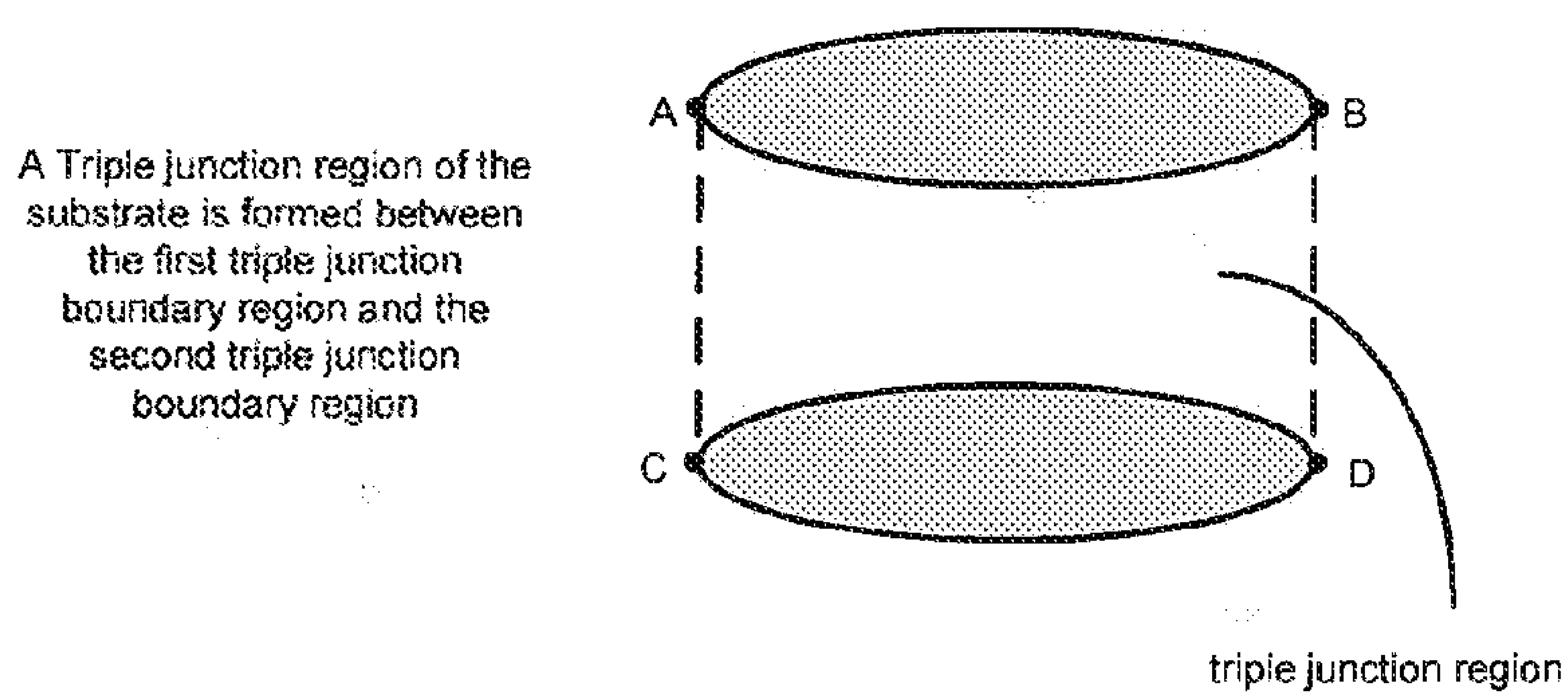


Fig. 8

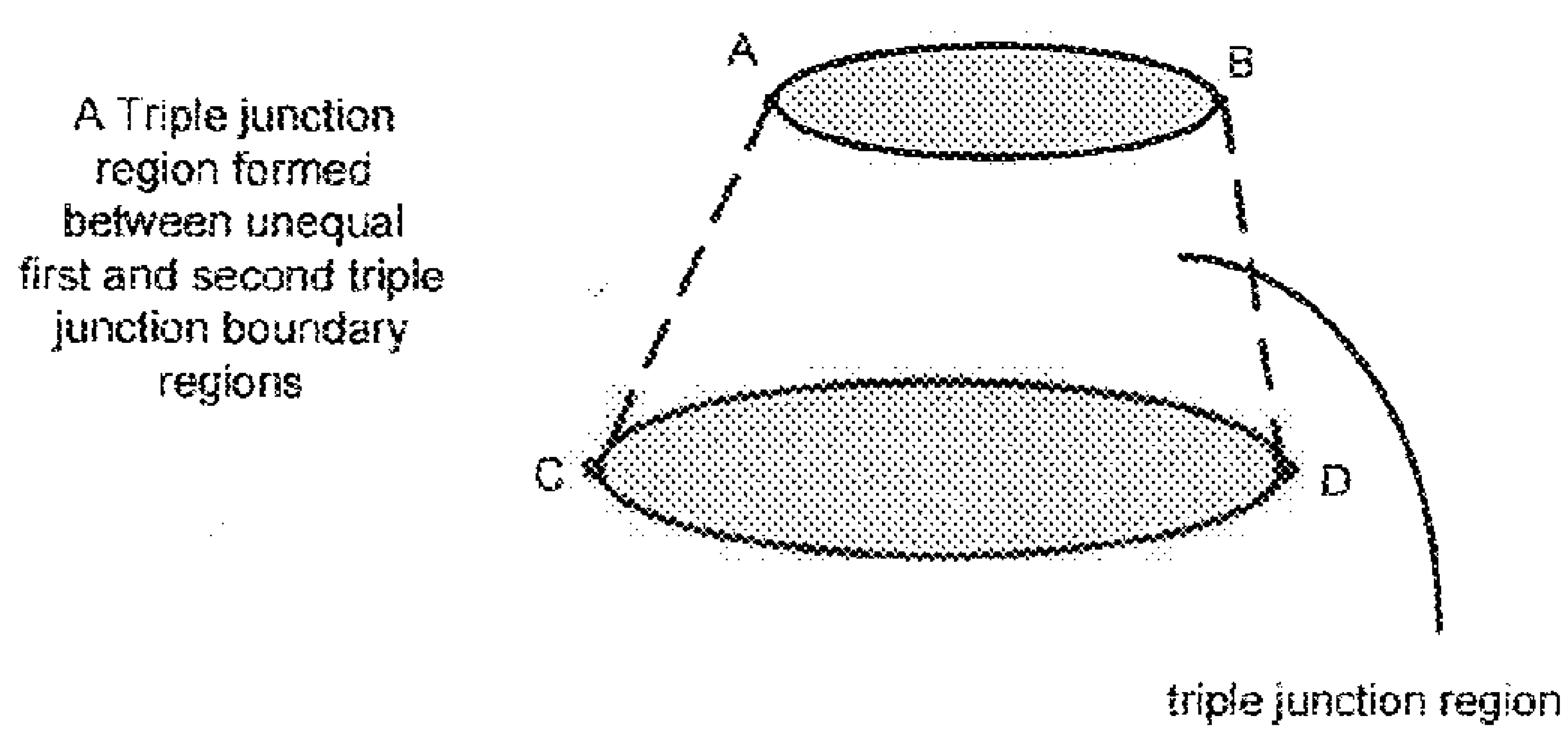


Fig. 9

MULTI-SIDED OPTICAL WAVEGUIDE-FED PHOTOCONDUCTIVE SWITCHES

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation of prior application Ser. No. 13/912,162, filed Jun. 6, 2013, which claims the benefit and priorities of U.S. Provisional Application No. 61/656,467, filed on Jun. 6, 2012, U.S. Provisional Application No. 61/656,470, filed on Jun. 6, 2012, and U.S. Provisional Application No. 61/801,483, filed on Mar. 15, 2013, all of which are hereby incorporated by reference herein.

FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] The United States Government has rights in this invention pursuant to Contract No. DE-AC52-07NA27344 between the United States Department of Energy and Lawrence Livermore National Security, LLC for the operation of Lawrence Livermore National Laboratory.

TECHNICAL FIELD

[0003] This patent document relates to photoconductive switches, and in particular to a multi-sided optical waveguide-fed photoconductive switch having an optical diffusion structure for smoothing and homogenizing light to uniform illuminate the switch material for conduction.

BACKGROUND

[0004] Photoconductive switches and switch packages typically consist of a wide bandgap photoconductive material (such as GaN, ZnO, diamond, AlN, SiC, BN, etc.), a source for energetic photons (e.g. a laser), a method to couple the laser into the switch, and a method for high voltage to enter and leave the switch package such as via electrodes positioned on opposite sides of the substrate. Arranged as such, the photoconductive switch package may be characterized as a three terminal device similar to transistors; with one of the terminals being a laser input or the voltage input to the laser system. When the photoconductive switch material is illuminated such as by a laser, the laser photons change the conductivity of the photoconductive material and make it viable as an optically controlled switch. Various package configurations and methods are known for feeding the high voltage into the switch package (while maintaining low capacitance and inductance), reducing detrimental electric field effects, optical coupling methods, and extracting high voltage and high current from the switch package.

[0005] Traditional photoconductive switch (PCS) illumination techniques, such as bulk free-space optics or fiber optic assemblies, rely on the intrinsic laser beam shape for uniform illumination of the PCS. However, these approaches may not adequately illuminate the entire switch volume. In order to illuminate the entire switch volume, the laser beam shape would need to be enlarged to bigger than the switch dimensions, which in turn results in inefficiencies due to unused laser light.

SUMMARY

[0006] In one example implementation, the present invention includes a photoconductive switch comprising: a wide bandgap semiconductor material substrate; first and second electrodes in contact with said substrate; an optical waveguide surrounding exposed facets of the substrate for directing conduction-inducing radiation into said exposed facets of the substrate; and an optical diffusion element arranged to diffuse/disperse said radiation prior to entering the optical waveguide and into the substrate.

[0007] In another example implementation, the present invention includes an optical transconductance varistor comprising: a wide bandgap semiconductor material substrate, whose conduction response to changes in amplitude of incident radiation that is substantially linear throughout a non-saturation region thereof, whereby the substrate is operable in non-avalanche mode as a variable resistor; first and second electrodes in contact with said substrate; an optical waveguide surrounding exposed facets of the substrate for directing conduction-inducing radiation into said exposed facets of the substrate; and an optical diffusion element arranged to diffuse/disperse said radiation prior to entering the optical waveguide and into the substrate.

[0008] In another example implementation, the present invention includes a photoconductive switch comprising: a wide bandgap semiconductor material substrate; first and second electrodes in contact with said substrate and defining a triple junction region therebetween, with all remaining surfaces of the substrate having a reflective coating to internally reflect conduction-inducing radiation; and an optical diffusion element arranged to diffuse/disperse said conduction-inducing radiation into the substrate so that the triple junction region may be uniformly illuminated and made conductive.

[0009] Various other aspects of the present invention may include one or more of the following aspects to the above example implementations, including wherein the optical waveguide is coated with a reflective coating to reflect radiation into the exposed facets of the substrate, and wherein the optical diffusion element is a tapered light pipe connected to the optical waveguide, wherein the first and second electrodes are in contact with said material so that a first triple junction boundary region is formed between the substrate and the first electrode and a second triple junction boundary region is formed between the substrate and the second electrode, and the substrate is located completely within a triple junction region formed between the first and second triple junction boundary regions.

[0010] These and other implementations and various features and operations are described in greater detail in the drawings, the description and the claims.

[0011] The present invention is generally directed to a multi-sided optical waveguide fed photoconductive switch configuration which distributes radiation to all sides of a material substrate e.g. a photoconductive, semi-insulating, or semi-conducting material, hereinafter collectively referred to as photoconductive material for convenience, located between opposing electrodes so that the substrate is rendered conductive. As such the induced conductivity of the substrate may be uniformly produced in the substrate material. A diffusive or diffractive element or a mask at one or more facets of the substrate may also be used to control light distribution along the height of the switch substrate. In particular, it may be used to keep light intensity highest along a center region (at or near the center plane) of the substrate and keep it high to reach the electrode faces, while light intensity is tapered down towards the top and bottom boundaries of the substrate, so as to taper the resistivity around the triple junction and thereby minimize field enhancement at the triple junction.

[0012] Photoconductive switches have typically been illuminated (fed) from the side or edge of the photoconductive material, i.e. along a longitudinal direction of a planar switch, with electrodes transversely positioned on either side of the switch material. As shown in FIGS. **1** and **2**, it can be seen that the region of the semiconductor that does not have physical electrode attachment cannot be excited by the radiation that renders the bulk of the crystal conductive. When the switch is in the "off state" as shown in FIG. **1**, the normal field lines can terminate on the surface of the substrate. Under these conditions, the field lines obey the normal boundary conditions specified by Maxwell's equations. When the substrate is rendered conductive by the radiation source, as shown in FIG. **2**, the condition of "Ohms Law" in general form must be fulfilled. That is J=E, where J is the current density and E is the applied electric field. In this case, an electric field line that does terminate on an electrode supplies current to that electrode. A field line that does not terminate on an electrode will generate a surface charge at the boundary interface between the substrate and the non-conductive surrounding media. That net charge will distort the applied electric field as to enhance the fields at the point where the electrode ends and cause catastrophic breakdown. The present invention is intended to mitigate this issue by transversely illuminating the triple junction region of the photoconductive material (i.e. substrate) directly between opposing electrodes so that no portion outside the triple junction region is activated to conduct.

[0013] As used herein and in the claims, the triple junction region is that region of the substrate located between a first triple junction boundary region defined between the substrate and a first electrode, and a second triple junction boundary region defined between the substrate and a second electrode. In particular, FIGS. **6-9** illustrate and define the triple junction region formed between a first triple junction boundary region and a second triple junction boundary region. The switch material may be photoconductive, or semi-insulating or semiconducting, and may be induced to conduct by an electromagnetic radiation source, or a particle radiation source.

[0014] It is also appreciated that by optically exciting wide bandgap materials, the conductivity of bulk of the material is modulated. In such a device, the entirety of the crystal participates in the conduction process. For instance, a 100 micron thick crystal will have the capability approaching 40 kV and would replace ten equivalent junction devices. Thus, unlike junction devices, the wide bandgap material can be made arbitrarily thick to accommodate higher voltages in a single device. Furthermore, there is both a linear region and a saturation region as is with a typical transistor device. Thus, when the material is operated in the linear region, amplification of an applied modulation to the optical pulse will result in amplification of the applied signal. Such a device may consist of the modulation input to the radiation source (whether it be a laser, particle source, or x-ray source) and the wide bandgap semiconductor material. The terminals would then be the common electrode, the input to the modulation source, and the output terminal. Because this device is similar to a "transconductance varistor," or more commonly called a "transistor," such as device may be we characterized as an optical transconductance varistor, or "opticondistor."

BRIEF DESCRIPTION OF DRAWINGS

[0015] FIG. **1** shows a schematic side view of an example photoconductive switch showing normal electric field lines during an off state of the switch.

[0016] FIG. **2** shows a schematic side view of the example photoconductive switch of FIG. **1** showing increased stress due to increased conductivity during an on state of the switch due to illumination.

[0017] FIG. **3** shows a schematic view of an example embodiment of the photoconductive switch of the present invention.

[0018] FIG. **4** shows a cross-sectional view taken along line A-A of FIG. **3**.

[0019] FIG. **5** shows another example embodiment of the present invention using a tapered light pipe for diffusing light prior to entering the optical waveguide.

[0020] FIGS. **6-9** illustrate and define the triple junction region of the present invention in terms of first and second triple junction boundary regions.

DETAILED DESCRIPTION

[0021] Turning now to the drawings, FIG. **3** shows an example embodiment of the multi-sided optical waveguide-fed photoconductive switch, generally indicated at **10**, with an optical diffusion or diffraction structure (hereinafter referenced simply as optical diffusion structure) shown at **11** for diffusing radiation into an optical structure (shown together as an optical waveguide **13** surrounding a photoconductive region **12**) to uniformly illuminate the photoconductive region **12**. The diffusive structure operates to smooth and homogenize light sources while providing uniform light. Hotspots and uneven light distribution are common problems with fiber-optic and laser light sources. Homogenization provides a uniform pattern of light. It is notable that the diffusive structure does not need to be fabricated onto the input switch fact, but can also be a separate optical component that resides in front of the switch, with such configuration providing the same effect. The circular central region of the optical structure is the active photoconductive region **12** which may be a doped region of the optical structure, or a separate photoconductive material such as a wide bandgap semiconductor. Electrodes are provided on opposite sides of the photoconductive region **12** (see for example **15** and **16** in FIG. **4**). And the optical waveguide **13** surrounding the active photoconductive region **11** operates to guide light centrally to the active photoconductive region, and is of a type that cannot be rendered conductive by the radiation. Materials such as for example silicon dioxide would be a suitable material for the optical waveguide. In FIG. **3**, the diffusive diffraction structure **11** is arranged at an aperture of the optical waveguide **13**. And a high reflective (HR) coating **14** is shown formed on the optical waveguide (e.g. optical dielectric multi-layer thin films). Integrated together as a photoconductive switch (PCS) package, this configuration can enable illumination intensity uniformities and electrical conductive efficiencies. These enhancements results in a device illumination technique that utilizes minimal optical elements, thus greatly simplifying PCS assemblies.

[0022] FIG. **4** shows a cross sectional view taken along line A-A of FIG. **3** showing how the optical diffusion structure **11** may be configured to shape the radiation so that it has a constant intensity near a center plane of the substrate, with intensity tapered lower near the opposing substrate surfaces. Optionally, edge masks may also be used to direct laser light along near the center plane of the substrate to target the triple point region. FIG. **4** also shows electrodes **15** and **16** abutting on opposite sides of the photoconductive region **12** of the optical structure, with the optical waveguide **14** surrounding the photoconductive region.

[0023] In FIG. **5**, another embodiment is shown, generally indicated at **20**, using a tapered light pipe **21** as the optical diffusion structure for diffusing radiation uniformly into the optical waveguide **14** and the photoconductive region **12**. Here too, a high reflective coating **14** (e.g. optical dielectric multi-layer thin films) is shown used to redirect leaked light back into the photoconductive region, and integrated onto a photoconductive switch (PCS) to improve illumination intensity uniformities and electrical conductive efficiencies.

[0024] Though not shown in the drawings, another embodiment of the photoconductive switch includes a wide bandgap semiconductor material substrate, and first and second electrodes are in contact with said substrate to define a triple junction region therebetween, with all remaining surfaces of the substrate having a reflective coating to internally reflect conduction-inducing radiation. An optical diffusion element, as described above, is then arranged to diffuse/disperse said conduction-inducing radiation into the substrate so that the triple junction region may be uniformly illuminated and made conductive. Here too, the optical diffusion element may be a tapered light pipe connected to a face of the substrate.

[0025] Although the description above contains many details and specifics, these should not be construed as limiting the scope of the invention but as merely providing illustrations of some of the presently preferred embodiments of this invention. Other implementations, enhancements and variations can be made based on what is described and illustrated in this patent document. The features of the embodiments described herein may be combined in all possible combinations of methods, apparatus, modules, systems, and computer program products. Certain features that are described in this patent document in the context of separate embodiments can also be implemented in combination in a single embodiment. Conversely, various features that are described in the context of a single embodiment can also be implemented in multiple embodiments separately or in any suitable subcombination. Moreover, although features may be described above as acting in certain combinations and even initially claimed as such; one or more features from a claimed combination can in some cases be excised from the combination, and the claimed combination may be directed to a subcombination or variation of a subcombination. Similarly, while operations are depicted in the drawings in a particular order, this should not be understood as requiring that such operations be performed in the particular order shown or in sequential order, or that all illustrated operations be performed, to achieve desirable results. Moreover, the separation of various system components in the embodiments described above should not be understood as requiring such separation in all embodiments.

[0026] Therefore, it will be appreciated that the scope of the present invention fully encompasses other embodiments which may become obvious to those skilled in the art. In the claims, reference to an element in the singular is not intended to mean "one and only one" unless explicitly so stated, but rather "one or more." All structural and functional equivalents to the elements of the above-described preferred embodiment that are known to those of ordinary skill in the art are expressly incorporated herein by reference and are intended to be encompassed by the present claims. Moreover, it is not necessary for a device to address each and every problem sought to be solved by the present invention, for it to be encompassed by the present claims. Furthermore, no element or component in the present disclosure is intended to be dedicated to the public regardless of whether the element or component is explicitly recited in the claims. No claim element herein is to be construed under the provisions of 35 U.S.C. 112, sixth paragraph, unless the element is expressly recited using the phrase "means for."

We claim:

1. A photoconductive switch comprising:

a wide bandgap semiconductor material substrate;

first and second electrodes in contact with said substrate;

an optical waveguide surrounding exposed facets of the substrate for directing conduction-inducing radiation into said exposed facets of the substrate; and

an optical diffusion element arranged to diffuse/disperse said radiation prior to entering the optical waveguide and into the substrate.

2. The photoconductive switch of claim **1**,

wherein the optical waveguide is coated with a reflective coating to reflect radiation into the exposed facets of the substrate.

3. The photoconductive switch of claim **2**,

wherein the optical diffusion element is a tapered light pipe connected to the optical waveguide.

4. The photoconductive switch of claim **1**,

wherein the first and second electrodes are in contact with said material so that a first triple junction boundary region is formed between the substrate and the first electrode and a second triple junction boundary region is formed between the substrate and the second electrode, and the substrate is located completely within a triple junction region formed between the first and second triple junction boundary regions.

5. An optical transconductance varistor comprising:

a wide bandgap semiconductor material substrate, whose conduction response to changes in amplitude of incident radiation that is substantially linear throughout a non-saturation region thereof, whereby the material is operable in non-avalanche mode as a variable resistor;

first and second electrodes in contact with said substrate;

an optical waveguide surrounding exposed facets of the substrate for directing conduction-inducing radiation into said exposed facets of the substrate; and

an optical diffusion element arranged to diffuse/disperse said radiation prior to entering the optical waveguide and into the substrate.

6. The optical transconductance varistor of claim **5**,

wherein the optical waveguide is coated with a reflective coating to reflect radiation into the exposed facets of the substrate.

7. The optical transconductance varistor of claim **6**,

wherein the optical diffusion element is a tapered light pipe connected to the optical waveguide.

8. The optical transconductance varistor of claim **5**,

wherein the first and second electrodes are in contact with said material so that a first triple junction boundary region is formed between the substrate and the first electrode and a second triple junction boundary region is formed between the substrate and the second electrode, and the substrate is located completely within a triple junction region formed between the first and second triple junction boundary regions.

9. A photoconductive switch comprising:
a wide bandgap semiconductor material substrate;
first and second electrodes in contact with said substrate and defining a triple junction region therebetween, with all remaining surfaces of the substrate having a reflective coating to internally reflect conduction-inducing radiation; and
an optical diffusion element arranged to diffuse/disperse said conduction-inducing radiation into the substrate so that the triple junction region may be uniformly illumated and made conductive.

10. The photoconductive switch of claim **9**,
wherein the optical diffusion element is a tapered light pipe connected to a face of the substrate.

* * * * *