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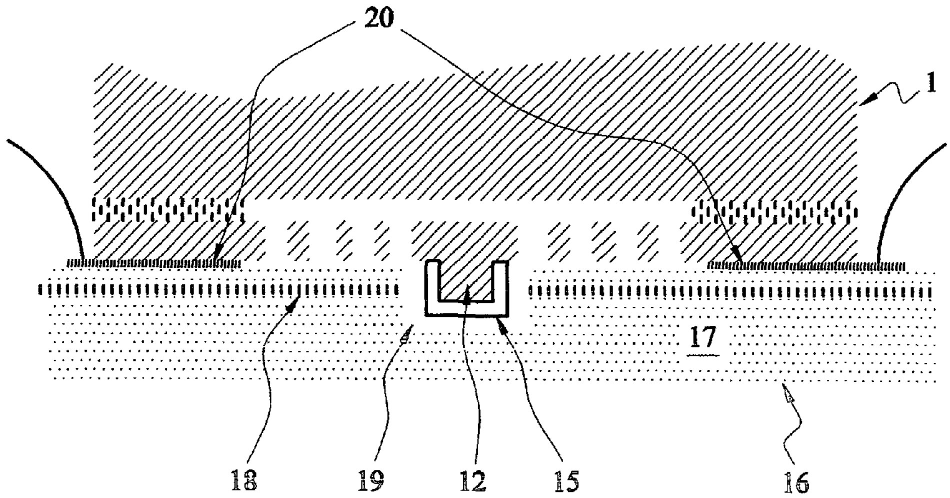
(54) Title: AN OPTICAL ACTUATOR



(57) Abstract: A method of manufacture of an optical actuator comprising an optically interacting element and an integral actuator, the method comprising the steps of (a) providing a wafer comprising a substrate, an insulating layer on the substrate and upper layer on the insulating layer; (b) depositing a first mask layer on the upper layer; (c) depositing a second mask layer on the upper layer; (d) etching the remaining exposed upper layer to a depth less than the thickness of the upper layer to reveal an actuator and a coplanar optically interacting element base portion; (e) removing the second mask layer; (f) further etching the upper layer to the depth of the insulating layer to reveal an optically interacting element upper portion extending upwardly from the optionally interacting element base portion out of the plane of the actuator; (g) etching the insulating layer beneath the upper layer so separating the optically interacting element and a rotor portion of the actuator from the insulating layer.

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AN OPTICAL ACTUATOR

The present invention relates to an optical actuator and a method of manufacture of the same. More particularly, but not exclusively, the present invention relates to an optical actuator comprising an actuator and an optically interacting element such as a shutter or mirror, a portion of the optically interacting element extending out of the plane of the actuator and also a method for manufacture of such an optical actuator.

US 6 315 462 discloses a fibre optic circuit switch. The elements of the switch are constructed entirely from a coating layer of a substrate. The same substrate also includes lightguides. These lightguides are fibres inserted into grooves formed in the substrate. Because the fibres and the switch lie within the same plane this considerably restricts the degree to which fibres can be packed on the substrate and results in an inefficient use of the substrate real estate.

EP 1 164 404A1 discloses a switch in which the actuator lies out of the plane of the lightguides. The optically interacting element lies in a plane perpendicular to the plane of the lightguides and in use is moved in and out of a slot in one or more of the lightguides by the actuator. Since the optically interacting element and actuator are not coplanar with the lightguides the optically interacting element/actuator combination has only a small footprint in the lightguide substrate. This enables the lightguides to be more closely packed resulting in a more efficient use of substrate real estate. However, the actuator of this switch is manufactured as a separate element to the lightguides and optically interacting element. During manufacture the actuator must be aligned with the optically interacting element and then glued in place. This increases the complexity of the manufacturing process and also reduces the reliability of the resulting device.

Thus, the need exists for an optical actuator comprising integral optically interacting element and actuator elements but having at least a portion of the optically interacting element extending out of the actuator plane for interaction with a lightguide circuit. There also exists a need for a simple and reliable method of manufacture of such a device.

Accordingly, in a first aspect, the present invention provides a method of manufacture of an optical actuator comprising an optically interacting element and an integral actuator, the method comprising the steps of

(a) providing a wafer comprising a substrate, an insulating layer on the substrate and an upper layer on the insulating layer;
(b) depositing a first mask layer on the upper layer;
(c) depositing a second mask layer on the upper layer;
(d) etching the remaining exposed upper layer to a depth less than the thickness of the upper layer to reveal an actuator and a coplanar optically interacting element base portion;
(e) removing the second mask layer;

(f) further etching the upper layer to the depth of the insulating layer to reveal an optically interacting element upper portion extending upwardly from the optically interacting element base portion out of the plane of the actuator;

g) etching the insulating layer beneath the upper layer so separating the optically interacting element and a rotor portion of the actuator from the insulating layer.

The method according to the invention has the advantage that it results in an optical actuator having integral actuator and non-coplanar optically interacting element. The optical actuator therefore has a small "footprint" in the plane of a substrate to which it is to be attached so allowing optimisation of the spacing of lightguides in the substrate.

In addition, since the optically interacting element and actuator are integrated, there is no need to align them during the manufacture of the composite optical activator/planar lightguide circuit. This simplifies manufacture and also increases reliability of the resulting device.

Further, since the upper (optical interacting)portion of the optically interacting element is created during the second etching step, this is a shallower etch than will be required to reveal an optically interacting element to the full height of the upper layer. This allows the etch quality and so the optical quality of the optically interacting element to be maximised.

Further, manufacture of the optically interacting element by a two stage process allows greater flexibility in the design of the shape of the optically interacting element and actuator components. This allows greater flexibility in the tuning of the mechanical actuator performance parameters.

As a further advantage, since the upper portion of the optically interacting element is upstanding from the actuator it is easy to post-process, for example by coating with gold.

Preferably, at least a portion of the second mask layer covers at least a portion of the first mask layer.

Preferably, the method further comprises a step of removing the first mask layer after the second etching step, preferably before etching the insulating layer.

The method can further comprise the step of coating at least part of the upper portion of the optically interacting element to promote optical interaction with the light beam.

The method can further comprise the step of bonding the optical actuator to a lightguide substrate, the substrate comprising a slot in a wave guide, at least part of the upper portion of the optically interacting element being arranged within the slot.

At least one of the substrate and upper layer can be silicon. The insulating layer can be SiO_2. At least one of the first and second mask layers can be SiO_2.

Preferably the resulting rotor portion is adapted to be displaced in the plane of the actuator. Alternatively, the resulting rotor portion can be adapted to pivot the optically interacting element about an axis perpendicular to the substrate.

In an alternate embodiment of the invention the first layer is not deposited until after the second mask is removed but before the second etching step.

In a further aspect of the invention there is provided a method of manufacture of an optical actuator comprising an optically interacting element and integral actuator, the method comprising the steps of:

providing a wafer comprising a substrate, an insulating layer on the substrate and an upper layer on the insulating layer, the upper layer comprising a bottom layer of a first material on the substrate and a top layer of a second material on the bottom layer;

depositing a first mask layer on the upper layer;

depositing a second mask layer on the upper layer;

etching the remaining exposed upper layer to the depth of the insulating layer to reveal an actuator and a coplanar optically interacting element base portion;

removing the second mask layer to reveal a further portion of the upper layer;

etching the top layer of the upper layer to reveal a optically interacting element portion extending upwardly from the optically interacting element base portion out of the plane of the actuator;

etching the insulating layer beneath the upper layer so separating the optically interacting element and a rotor portion of the actuator from the insulating layer.

Alternatively, the first mask layer is not deposited until after the second mask layer is removed.

In a further aspect of the invention there is provided an optical actuator comprising:

a substrate;

an insulating layer coating a portion of the substrate;

an actuator comprising stator and rotor portions, the stator portion attached to the insulating layer and the rotor portion free of the insulating layer, and an optically interacting element free of the insulating layer, the optically interacting element being arranged to be displaced in response to displacement of the rotor portion;

the optically interacting element comprising a base portion in the plane of the actuator and an integral upper portion upstanding from the base portion out of the plane of the actuator.

The optical actuator of the invention has the advantage that no post processing of the optically interacting element is required to manouvre its upper portion into an operational position.

The rotor can be adapted to displace the optically interacting element in the plane of the actuator. Alternatively, the rotor can be adapted to rotate the optically interacting element about an axis perpendicular to the substrate.

The present invention will now be described by way of example only, and not in any limitative sense, with the reference to the accompanying in drawings in which

> Figures 1 to 11 show a wafer in cross section at various steps of manufacture of an optical actuator according to the invention;
>
> Figures 12 to 14 show an optical actuator according to the invention bonded to planar lightguide circuits;
>
> Figure 15 shows, in perspective view, a hybrid device including an optical actuator according to the invention.

Shown in cross section in figure 1 is a wafer 1 comprising a silicon substrate 2, a thin SiO_2 insulating layer 3 on the substrate 2 and an upper silicon layer 4 on the insulating layer 3.

In a first embodiment of a method according to the invention a first SiO_2 mask layer 5 is deposited on the upper silicon layer 4 as shown in figure 2. SiO_2 is chosen for its high etch ratio compared to silicon, although other mask materials are possible. The first mask layer 5 is then patterned so exposing areas 6 of the upper layer as shown in figure 3.

A second mask layer 7 again having a high relative etch ratio to silicon (for example a photoresist) is deposited on the first mask layer and the exposed upper layer as shown in figure 4. The second mask layer 7 is then patterned so exposing areas 8 of the upper layer 4 as shown in figure 5.

The upper layer 4 is then etched to a depth h less than the thickness of the upper layer 4 as shown in figure 6. This etching defines an actuator structure 9 and also a base portion 10 of a optically interacting element 11.

The second mask layer 7 is then removed (as shown in figure 7) so leaving the first mask layer 5 and also revealing un-etched portions of the upper layer 4. The upper layer 4 is further etched to the thickness of the upper layer 4 revealing the insulating layer 3. The second etch continues to transfer the second mask layer pattern into the silicon upper layer 4 except where the silicon layer is protected by the first mask pattern as shown in figure 8. The first mask pattern is arranged such that this further etching reveals an upper portion 12 of the optically interacting element 11 extending upwardly from the base portion 10 and out of the plane of the actuator 9.

The first mask layer 5 is then removed as shown in figure 9. The underlying SiO_2 is etched away to produce an optical actuator 9 according to the invention as shown in figure 10. This etching releases a rotor 13 component of the actuator 9 and also the optically interacting element 11 from the underlying insulating layer 3. The stator 14 component of the actuator 9 remains fixed to the insulating layer 3.

In the above described method according to the invention the second mask layer 7 is shown covering the first mask layer 5 and also areas of the upper layer 4. In an alternative embodiment the second mask layer 7 only partially covers the first mask layer 5 i.e. it may cover some areas of the first mask layer 5 but not others. In a further embodiment of the method the second mask layer 7 does not cover any portion of the first mask layer 5.

In an alternative embodiment of the invention the first mask layer 5 is not deposited until after the second mask layer 7 is removed. In this embodiment the second mask layer 7 is deposited and the upper layer 4 etched to reveal the actuator 9 and coplanar optically interacting element base portion 10. The second mask layer 7 is then removed and replaced with a first mask layer 5. The upper layer 4 is then further etched to the depth of the insulating layer 3 to reveal a optically interacting element upper portion 12 extending upwardly from the optically interacting element base portion 10 out of the plane of the actuator 9.

In a further embodiment of the method according to the invention, the optical actuator can be post-processed after the second etching step. As shown in figure 11 the upper portion 12 of the optically interacting element 11 could be coated with a reflective material, for example gold 15.

This post-processing is simplified since the upper portion 12 of the optically interacting element 11 stands out of the plane of the actuator 9. This portion of the optically interacting element 11 could be processed in other ways to promote interaction depending on the nature of the interaction required.

In a further embodiment of the method according to the invention the upper layer 4 of the provided wafer 1 is split into a bottom layer on the insulating layer and a top layer on the bottom layer (not shown). In this embodiment the top and bottom layers are made of different materials. In alternative embodiments the top and bottom layers are made of the same material but doped in different ways, for example by the inclusion of different dopants or different dopant concentrations.

In this embodiment a mask layer is applied to the upper layer 4. The upper layer 4 is then etched down through both top and bottom layers to the insulating layer 3 to reveal an actuator 9 and base portion 10 of a optically interacting element 11.

The mask layer is then removed and replaced with a further mask layer. The top layer is selectively etched so as to form the upper parts of the optically interacting element 11 out of the plane of the actuator 9.

In all of the above embodiments of the method according to the invention the optically interacting upper portion 12 of the optically interacting element 11 is revealed in the second etching step and not the first etching step. There are two reasons for this: firstly this ensures that due to misalignment or under etching the optically interacting element 11 does not become degraded. Secondly, an etched surface can be formed from a second etch in such a way that the surface quality is better than after the first etch.

After formation of the optical actuator it is typically bonded to a planar lightguide circuit 16. Such a composite actuator/lightguide circuit 16 is shown in figure 12. The planar lightguide circuit 16 comprises a substrate 17 with at least one waveguide 18 having a slot 19 therein. Bonding pads 20 on the substrate 17 provide adhesion for the optical actuator and electrical contact for the planar lightguide circuit 16. The optical actuator is arranged such that the upper portion 12 of the optically interacting element 11 enters the slot 19 and so interrupts the lightguide optical field. In figure 12 the optically interacting element 11 is arranged to move in a plane perpendicular to the plane of the page, so moving in and out of the field of the lightguide.

Figure 13 shows the composite of figure 12 rotated through 90 degrees so that the optically interacting element 11 is now displaced in the plane of the page.

Shown in figure 14 is a further embodiment of a composite planar lightguide circuit. In this embodiment the rotor portion 13 is adapted to rotate the optically interacting element 11 about an axis perpendicular to the plane of the substrate 17, to deflect the beam from the waveguide 18.

Shown in figure 15 is a hybrid device comprising an optical actuator according to the invention and also fibre retaining walls 21 and end stops 22. The second mask layer defines the rotor and stator portions 13, 14 of the actuator. The first mask layer defines the upper portion of this shutter 12 and the fibre retaining walls 21 and end stops 22. In contrast with single etched apparatus the double etch reveals an optical surface which is substantially higher than the actuator 9 and as such is relatively easy to post-process.

In all of the above embodiments the optically interacting element is a shutter. In alternative embodiments the optically interacting element is a mirror.

Claims

1. A method of manufacture of an optical actuator comprising an optically interacting element and an integral actuator, the method comprising the steps of

   (a) providing a wafer comprising a substrate, an insulating layer on the substrate and an upper layer on the insulating layer;
   (b) depositing a first mask layer on the upper layer;
   (c) depositing a second mask layer on the upper layer;
   (d) etching the remaining exposed upper layer to a depth less than the thickness of the upper layer to reveal an actuator and a coplanar optically interacting element base portion;
   (e) removing the second mask layer;
   (f) further etching the upper layer to the depth of the insulating layer to reveal an optically interacting element upper portion extending upwardly from the optically interacting element base portion out of the plane of the actuator;
   (g) etching the insulating layer beneath the upper layer so separating the optically interacting element and a rotor portion of the actuator from the insulating layer.

2. A method as claimed in claim 1 wherein at least a portion of the second mask layer covers at least a portion of the first mask layer.

3. A method as claimed in either of claims 1 or 2, further comprising the step of removing the first mask layer after the second etching step, preferably before etching the insulating layer.

4. A method as claimed in any of claims 1 to 3, further comprising the step of coating part of the upper portion of the optically interacting element to promote optical interaction with an incident light beam.

5. A method as claimed in any one of claims 1 to 4, further comprising the step of bonding the optical actuator to a waveguide substrate, the substrate comprising a slot in a waveguide, at least part of the upper portion of the optically interacting element being arranged within the slot.

6. A method as claimed in any one of claims 1 to 5, wherein at least one of the substrate and upper layer is silicon.

7. A method as claimed in any one of claims 1 to 6, wherein the insulating layer is SiO_2.

8. A method as claimed in any one of claims 1 to 7, wherein at least one of the first and second mask layers is SiO_2.

9. A method as claimed in any one of claims 1 to 8, wherein the resulting rotor portion is adapted to displace the optically interacting element in the plane of the actuator.

10. A method as claimed in any one of claims 1 to 9, wherein the resulting rotor portion is adapted to pivot the optically interacting element about an axis perpendicular to the substrate.

11. A method as claimed in claim 1, wherein the first mask layer is not deposited until after the second mask is removed but before the second etching step.

12. A method of manufacture of an optical actuator comprising an optically interacting element and integral actuator, the method comprising the steps of:

(a) providing a wafer comprising a substrate, an insulating layer on the substrate and an upper layer or the insulating layer, the upper layer comprising a bottom layer of a first material on the substrate and a top layer of a second material on the bottom layer;

(b) depositing a first mask layer on the upper layer;

(c) depositing a second mask layer on the upper layer;

(d) etching the remaining exposed upper layer to the depth of the insulating layer to reveal an actuator and a coplanar optically interacting element base portion;

(e) removing the second mask layer to reveal a further portion of the upper layer;

(f) etching the top layer of the upper layer to reveal an optically interacting element portion extending upwardly from the optically interacting element base portion out of the plane of the actuator;

(g) etching the insulating layer beneath the upper layer so separating the optically interacting element and a rotor portion of the actuator from the insulating layer.

13. A method as claimed in claim 12 wherein the first mask layer is not deposited until after the second mask layer is removed.

14. An optical actuator manufactured by a method according to any one of claims 1 to 13.

15. An optical actuator comprising:
a substrate;
an insulating layer coating a portion of the substrate;
an actuator comprising stator and rotor portions, the stator portion attached to the insulating layer and the rotor portion free of the insulating layer, and an optically interacting element free of the insulating layer, the optically interacting element being arranged to be displaced in response to displacement of the rotor portion;
the optically interacting element comprising a base portion in the plane of the actuator and an integral upper portion upstanding from the base portion out of the plane of the actuator.

16. An optical actuator as claimed in claim 15, wherein the rotor is adapted to displace the

optically interacting element in the plane of the actuator.

17. An optical actuator as claimed in claim 16, wherein the rotor is adapted to rotate the optically interacting element about an axis perpendicular to the substrate.

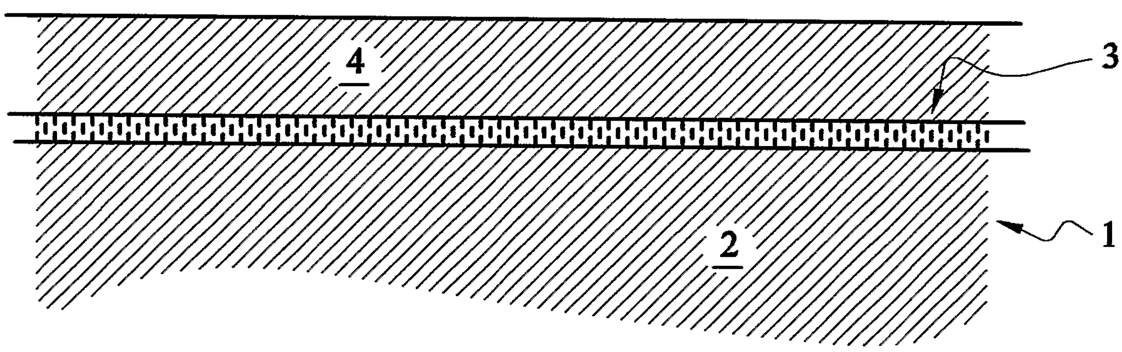

FIG. 1

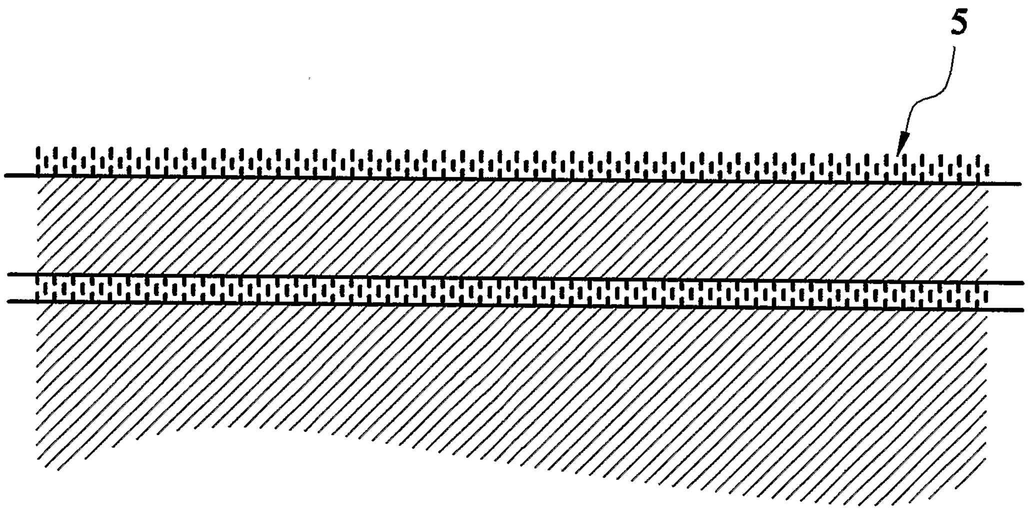

FIG. 2

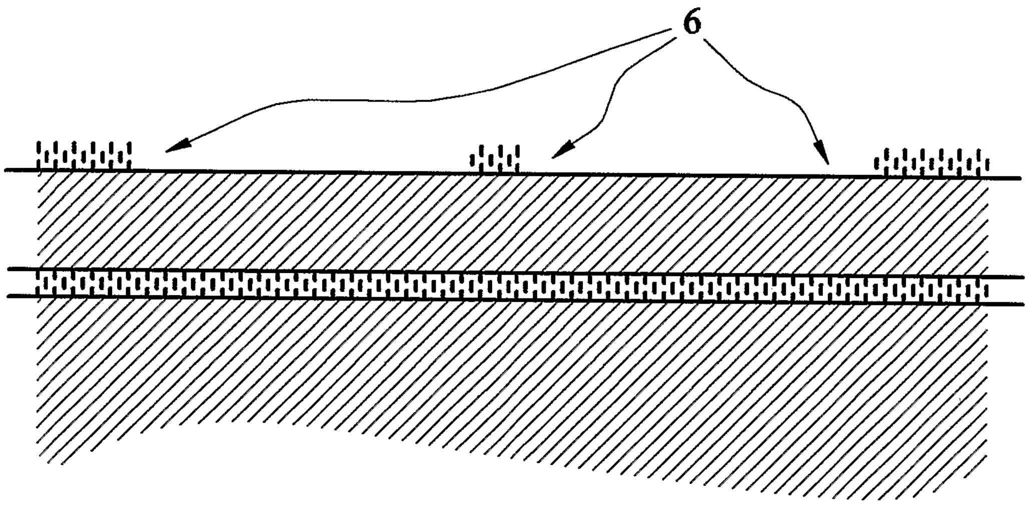

FIG. 3

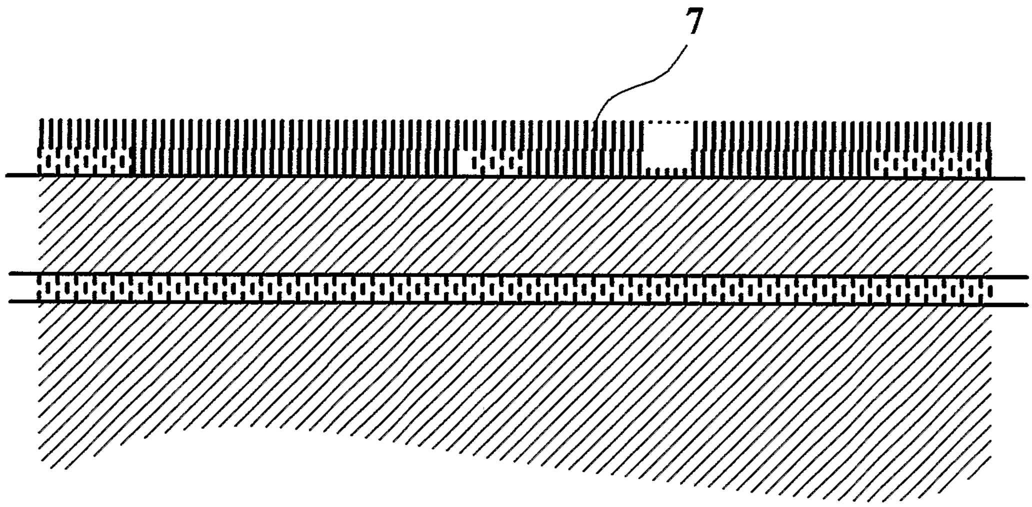

FIG. 4

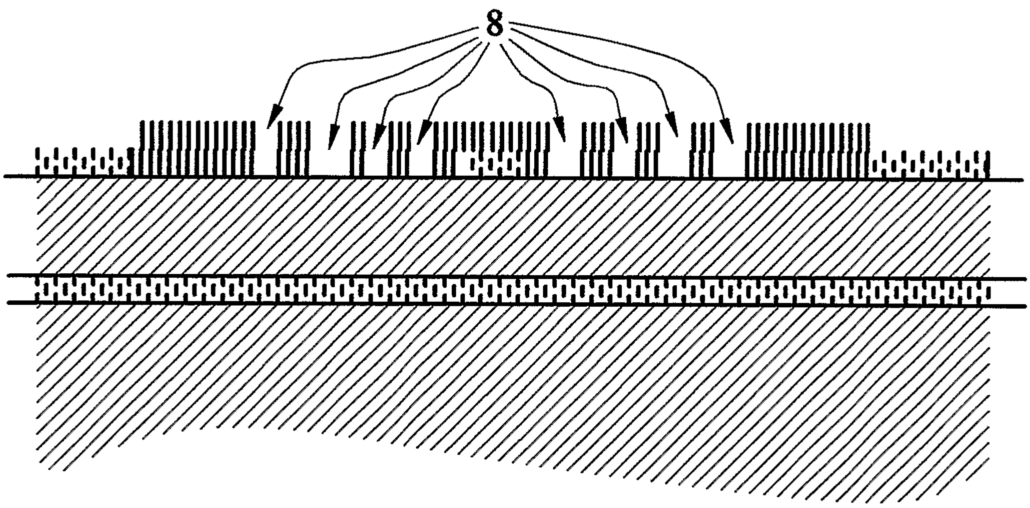

FIG. 5

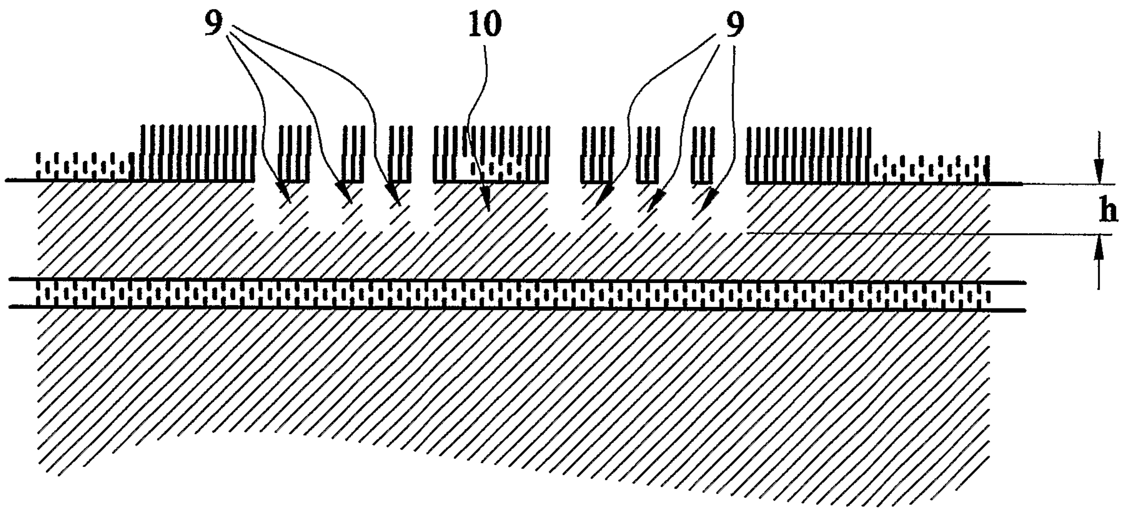

FIG. 6

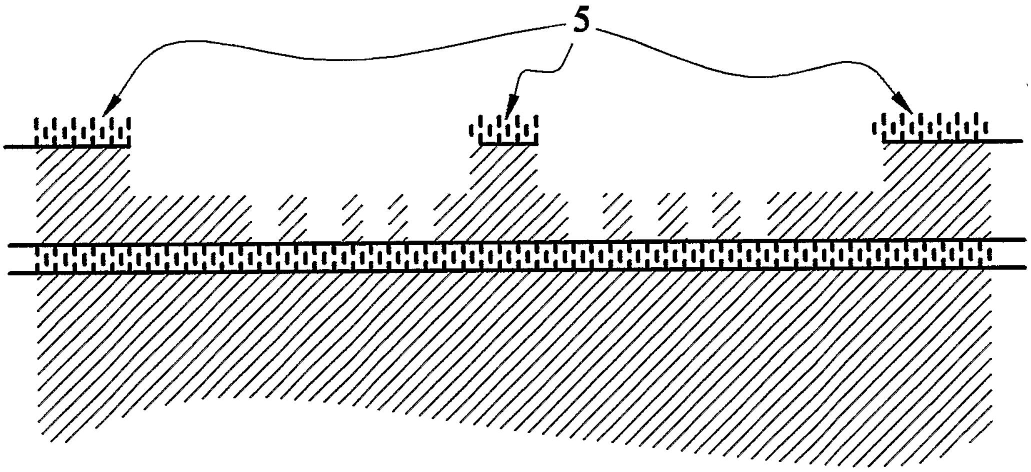

FIG. 7

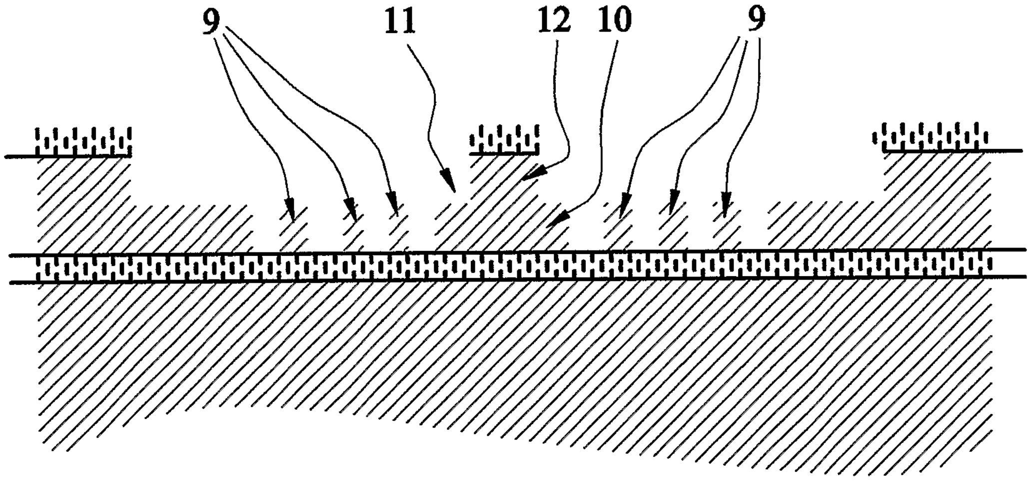

FIG. 8

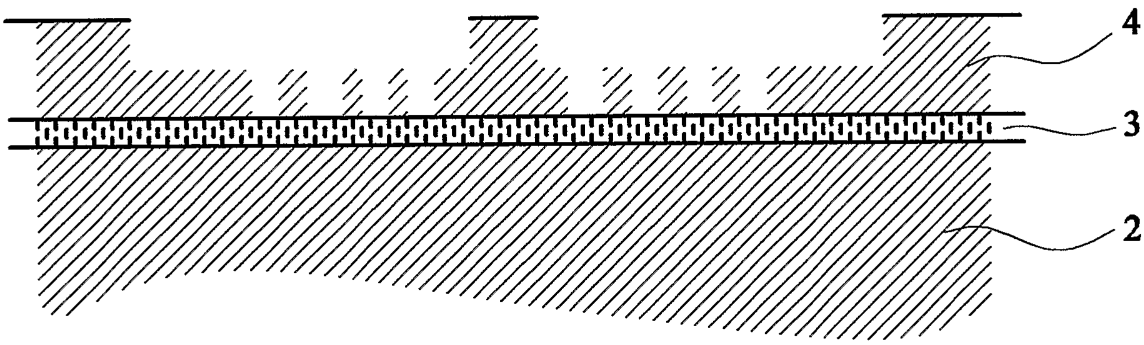

FIG. 9

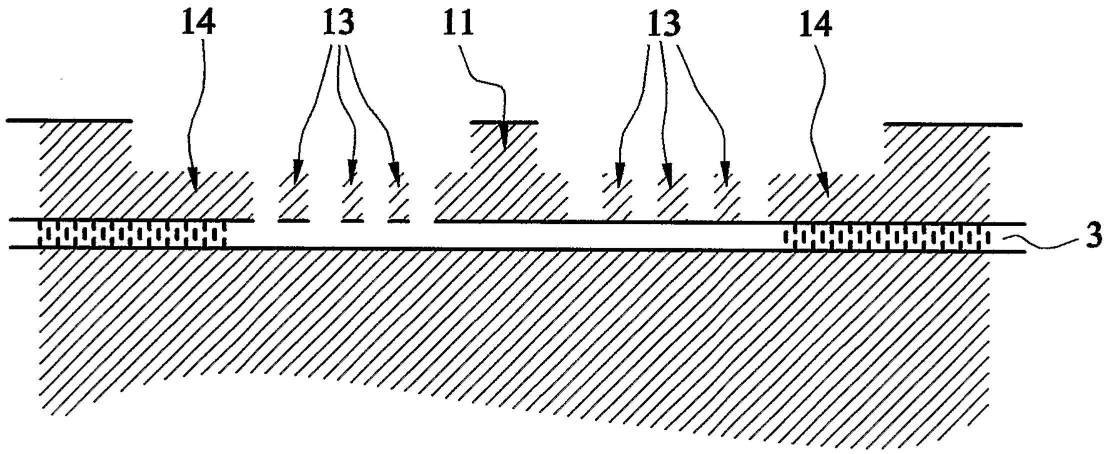

FIG. 10

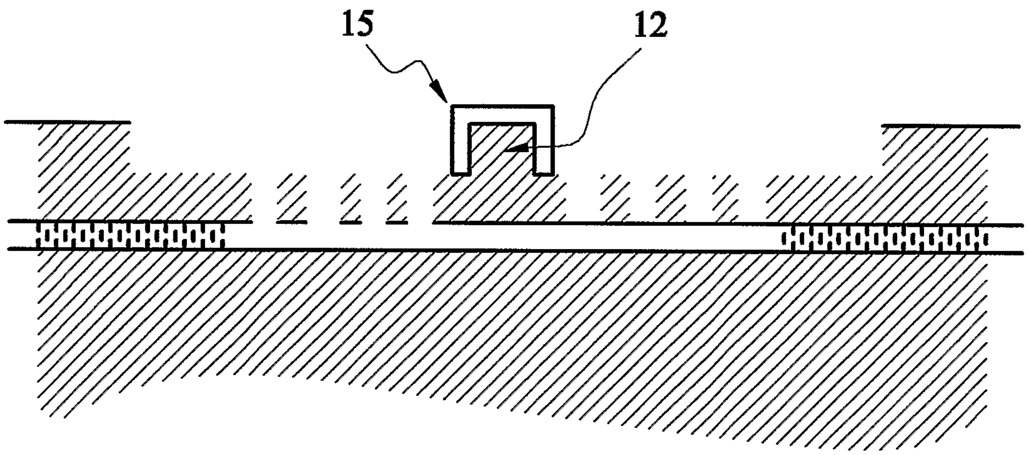

FIG. 11

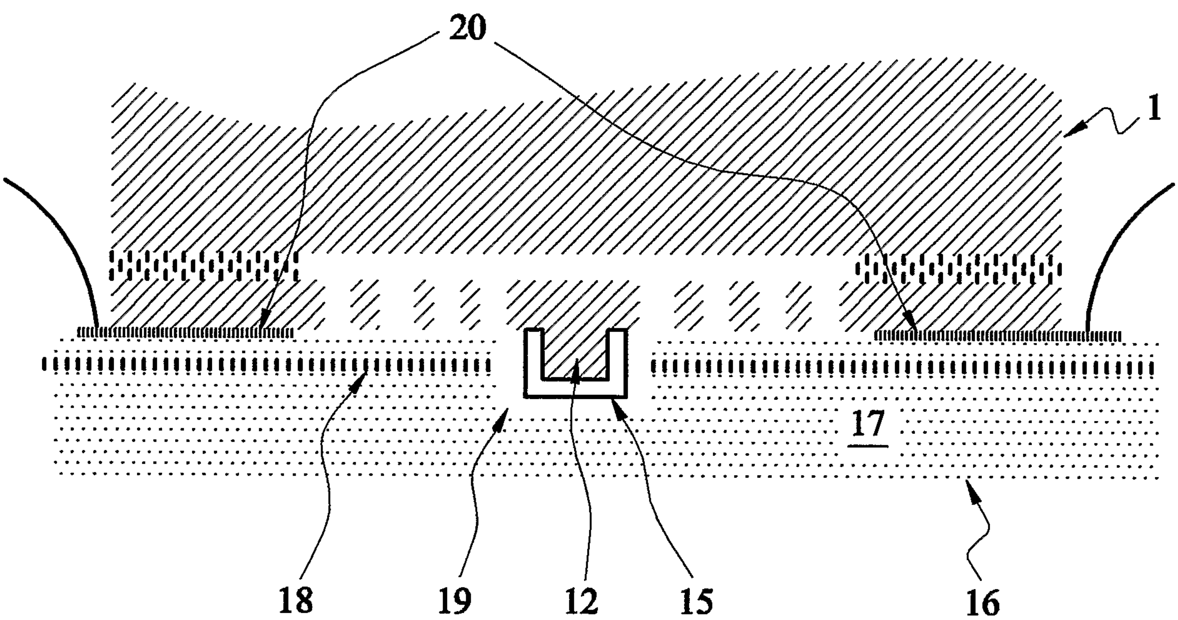

FIG. 12

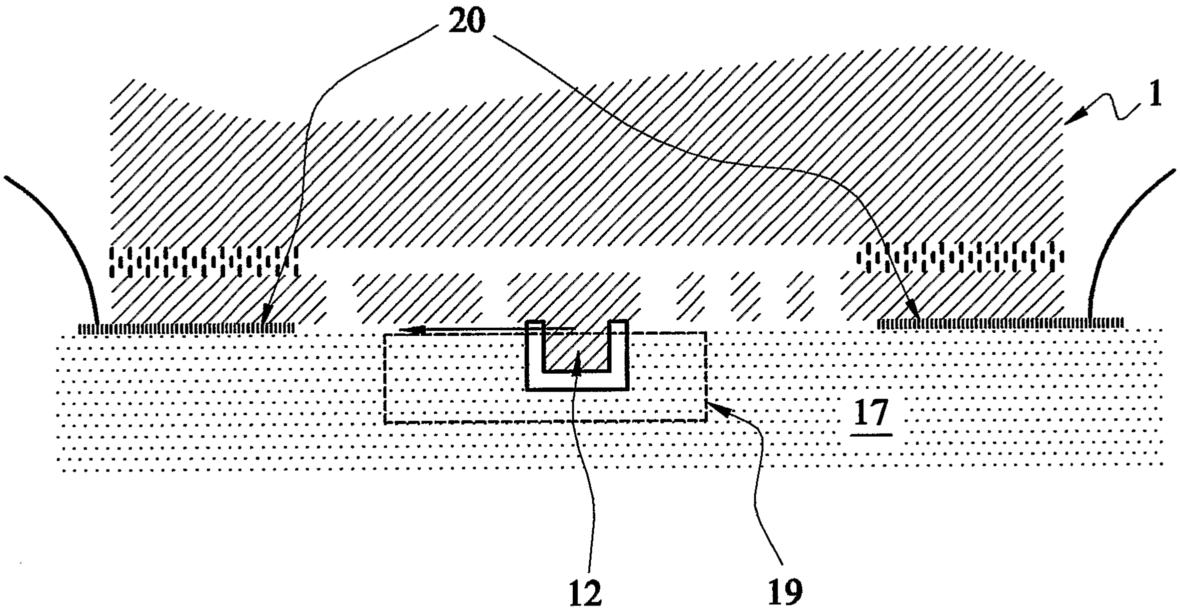

FIG. 13

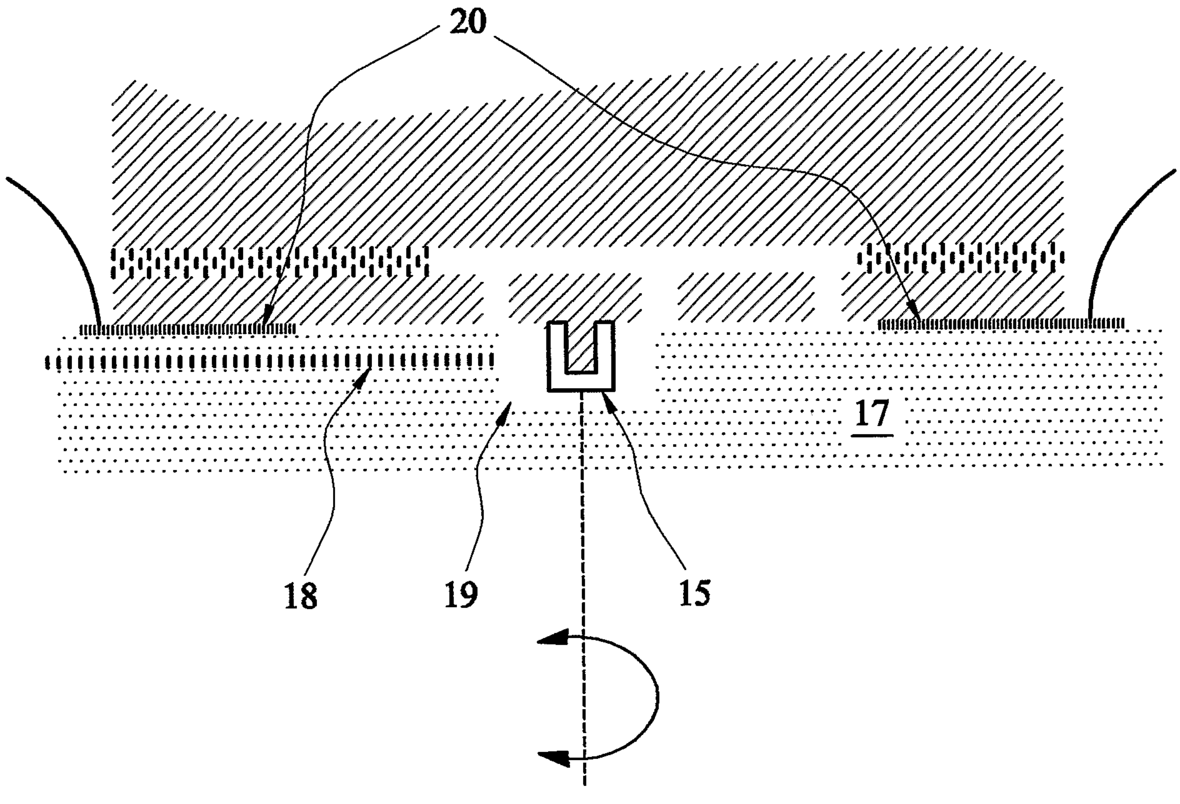

FIG. 14

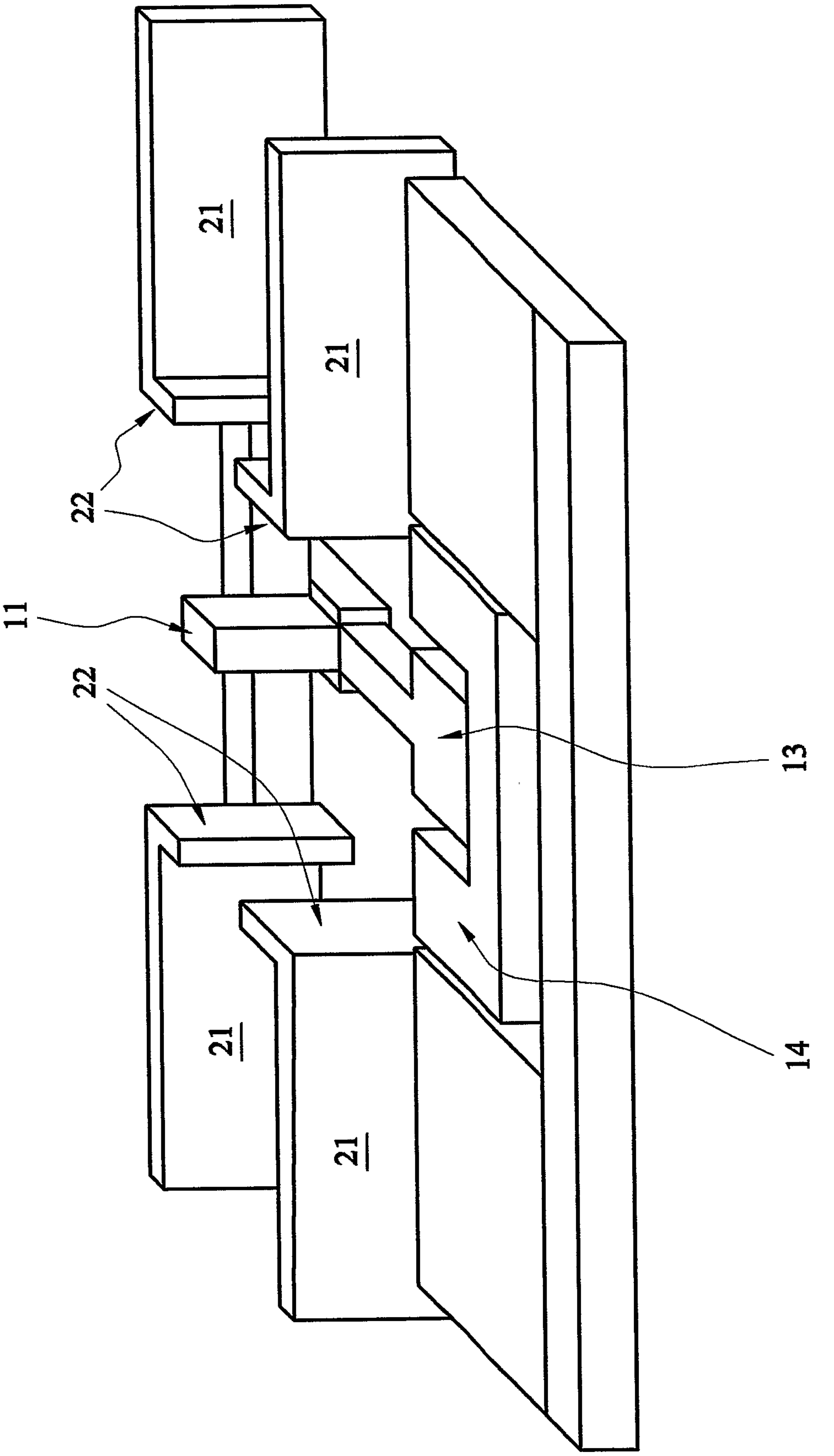

FIG. 15

INTERNATIONAL SEARCH REPORT

PCT/GB 03/02260

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G02B6/35

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 7 G02B

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 practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	FR 2 817 050 A (COMMISSARIAT ENERGIE ATOMIQUE) 24 May 2002 (2002-05-24) figure 2 page 12, line 9 -page 13, line 20 figures 10-12 page 17, line 11 -page 18, line 2 ---	1-17
A	US 2002/016080 A1 (KHAN ANISUL ET AL) 7 February 2002 (2002-02-07) abstract ---	1
A	US 6 046 840 A (HUIBERS ANDREW) 4 April 2000 (2000-04-04) column 7, line 51 -column 8, line 63 figures 2B-2D --- -/--	1

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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Date of the actual completion of the international search	Date of mailing of the international search report
20 October 2003	27/10/2003

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Luck, W

INTERNATIONAL SEARCH REPORT

PCT/GB 03/02260

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	EP 1 164 404 A (CORNING INC) 19 December 2001 (2001-12-19) cited in the application abstract -----	1

INTERNATIONAL SEARCH REPORT

I[redacted]mation on patent family members

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