



(86) Date de dépôt PCT/PCT Filing Date: 1993/03/26

(87) Date publication PCT/PCT Publication Date: 1993/10/14

(45) Date de délivrance/Issue Date: 2004/06/22

(85) Entrée phase nationale/National Entry: 1994/09/26

(86) N° demande PCT/PCT Application No.: US 1993/002844

(87) N° publication PCT/PCT Publication No.: 1993/020581

(30) Priorités/Priorities: 1992/03/30 (860,454) US;
1992/08/10 (927,822) US

(51) Cl.Int.⁵/Int.Cl.⁵ G02B 6/12, H01S 3/18

(72) Inventeurs/Inventors:

HOLONYAK, NICK, JR., US;

KISH, FRED A., US;

CARACCI, STEPHEN J., US;

ELZEIN, NADA, US

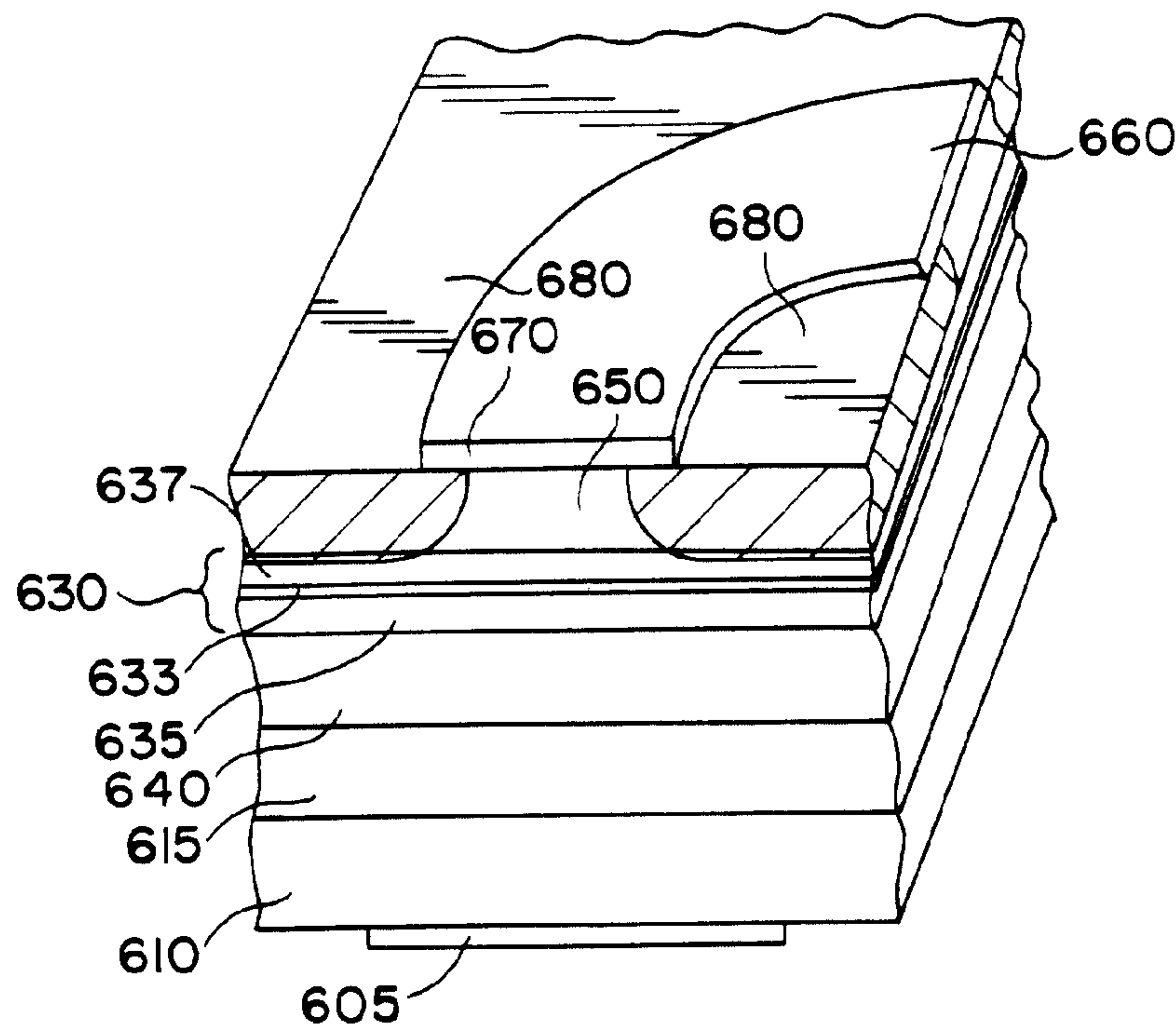
(73) Propriétaire/Owner:

BOARD OF TRUSTEES OF THE UNIVERSITY OF
ILLINOIS (THE), US

(74) Agent: GOUDREAU GAGE DUBUC

(54) Titre : DISPOSITIFS OPTIQUES A SEMICONDUCTEUR ET LEURS METHODES DE FABRICATION

(54) Title: SEMICONDUCTOR OPTICAL DEVICES AND TECHNIQUES



(57) Abrégé/Abstract:

The disclosure is directed to improved techniques and devices employing an aluminum-bearing III-V semi-conductor material and a native oxide of aluminum that is formed in the semiconductor material. In a form of the disclosure, two linear arrays of end-coupled minicavities, defined by a native oxide of an aluminum-bearing III-V semiconductor material, are arranged side by side to obtain a two dimensional array, with resultant lateral coupling between the linear arrays. The two dimensional array exhibits mode switching and multiple switching in the light power (L) versus current (I) characteristic (L-I) with increasing current. In another form of the disclosure, a stripe laser (1210) is transversely coupled (or side-coupled) with a linear array of end-coupled minicavities (1221-1275). Bistability and switching are demonstrated in the light versus current (L-I) characteristic of a native-oxide-defined structure of this type.



INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification ⁵ :

H01L 21/20, H01S 3/19

A1

(11) International Publication Number:

WO 93/20581

(43) International Publication Date:

14 October 1993 (14.10.93)

(21) International Application Number: PCT/US93/02844

(22) International Filing Date: 26 March 1993 (26.03.93)

(30) Priority data:

860,454

30 March 1992 (30.03.92)

US

927,822

10 August 1992 (10.08.92)

US

(71) Applicant: THE BOARD OF TRUSTEES OF THE UNIVERSITY OF ILLINOIS [US/US]; 506 South Wright Street, Urbana, IL 61801 (US).

(72) Inventors: HOLONYAK, Nick, Jr. ; 2212 Fletcher, Urbana, IL 61801 (US). KISH, Fred, A. ; 715 East El Camino Real, Sunnyvale, CA 94087 (US). CARACCI, Stephen, J. ; 604 East Clark, Champaign, IL 61820 (US). ELZEIN, Nada ; 511 East White, #5, Champaign, IL 61820 (US).

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(74) Agent: NOVACK, Martin; 1465 Post Road East, Westport, CT 06880 (US).

(81) Designated States: AU, CA, JP, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

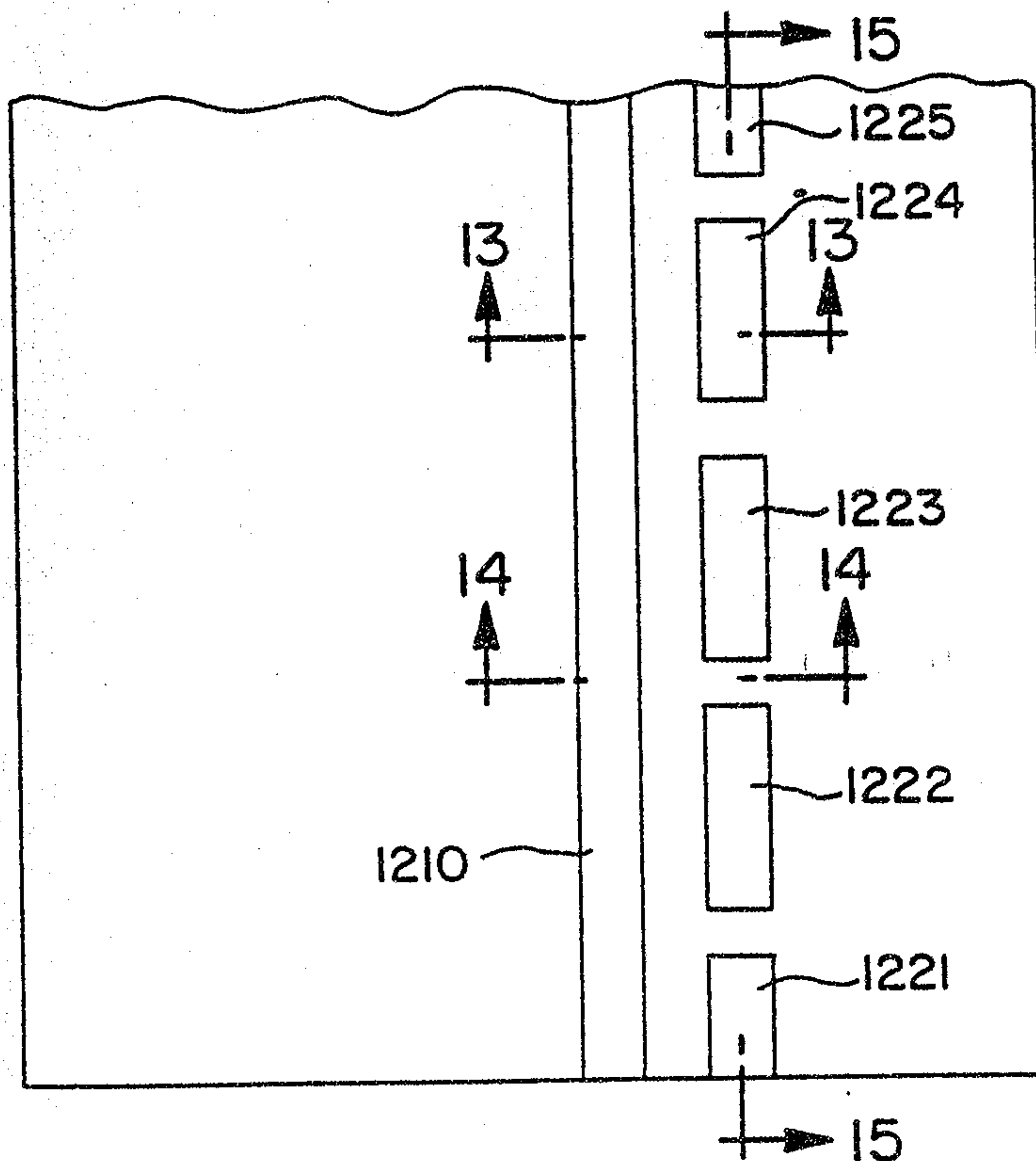
Published

With international search report.

(54) Title: SEMICONDUCTOR OPTICAL DEVICES AND TECHNIQUES

(57) Abstract

The disclosure is directed to improved techniques and devices employing an aluminum-bearing III-V semiconductor material and a native oxide of aluminum that is formed in the semiconductor material. In a form of the disclosure, two linear arrays of end-coupled minicavities, defined by a native oxide of an aluminum-bearing III-V semiconductor material, are arranged side by side to obtain a two dimensional array, with resultant lateral coupling between the linear arrays. The two dimensional array exhibits mode switching and multiple switching in the light power (L) versus current (I) characteristic (L-I) with increasing current. In another form of the disclosure, a stripe laser (1210) is transversely coupled (or side-coupled) with a linear array of end-coupled minicavities (1221-1225). Bistability and switching are demonstrated in the light versus current (L-I) characteristic of a native-oxide-defined structure of this type.



SEMICONDUCTOR OPTICAL DEVICES AND TECHNIQUES

FIELD OF THE INVENTION

This invention relates to semiconductor devices and, more particularly, to techniques which employ a grown native oxide of aluminum to obtain improvements in III-V semiconductor lasers and waveguides, and also relates to semiconductor lasers which exhibit improved properties, including improved single mode operation, optical switching and bistability.

The present invention was made, in part, with U.S. Government support, and the U.S. Government has certain rights in this invention.

BACKGROUND OF THE INVENTION

Semiconductor lasers in the shape of a ring, or a partial ring, have been known in the art for a number of years. Reference can be made, for example, to J. Carran et al., IEEE J. Quantum Electron. QE-6 367 (1970); A.S.H. Liao et al., Appl. Phys. Lett. 36, 801 (1980); and P. Sansonetti et al., Electron Lett. 23, 485 (1988). These types of devices have various applications and proposed applications. For example, it has been proposed that a semiconductor ring laser, in which light circulates in both clockwise and counter-clockwise directions, could be used as a very small and inexpensive gyroscope. Briefly, certain motion of the gyroscope would have a different effect on the clockwise and counter-clockwise light components, and the effect can be measured to determine the motion or orientation of the device. Ring lasers, or "circular resonators" have also been proposed for applications such as filtering and multiplexing in so-called optoelectronic or integrated optical circuits. Fractions of a ring, such as a half-ring or a quarter-ring, with cleaved

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facets, have been used for various applications in optical communications.

In a ring laser the curved light path makes optical confinement more difficult. Because of the greater incident angles the light subtends with respect to the confining walls (particularly for a small radius of curvature), the difference in indices of refraction must be relatively large to ensure internal reflection of sufficient light in the ring laser "waveguide". It is among the objects of the present invention to overcome difficulties in the prior art of producing a laser in the shape of a ring or having a curved light path, for example part of a ring or a non-circular arc.

Another application where control of index of refraction is important is in coupled-stripe laser diode arrays. These arrays offer the possibility of obtaining high output powers with decreased beam divergence and single-longitudinal mode operation. Index-guided arrays, compared to their gain-guided counterparts, have advantages of increased mode stability and coherence, and decreased beam astigmatism. Several methods have been employed to fabricate index-guided arrays, including: channel etching, epitaxial regrowth or overgrowth, and impurity induced layer disordering ("IILD") [see, for example, D. G. Deppe et al., Appl. Phys. Lett. 50, 632 (1987); L. J. Guido, Appl. Phys. Lett. 50, 757 (1987); and J. S. Major, Jr. et al., Appl. Phys. Lett. 55, 271 (1989)]. Many of these techniques require relatively sophisticated processing and/or provide limited control of the index-step between emitters. More precise adjustment of the index-step would permit control of the optical field between emitters and, thus, control of the coupling between stripes. This coupling dramatically affects the far-field radiation patterns, determining the supermode(s) in which the array will oscillate.

Opto-electronic circuits (in which devices in a semiconductor chip have interacting optical and electronic elements) are utilized in conjunction with fiber optics communications systems and are expected to ultimately have

widespread application for other systems. In such circuits, circular or other curved optical signal paths are needed, particularly for the design and fabrication of relatively complex circuits. It is among the further objects of the present invention to provide an efficient semiconductor optical waveguide for use in opto-electronic semiconductor circuits.

The high gain required for oscillation in semiconductor lasers results in a large optical bandwidth in which laser operation is possible. This large bandwidth generally results in multiple-longitudinal-mode operation. For many applications, single-longitudinal-mode operation is required. Consequently, sophisticated structures such as the distributed feedback (DFB) laser [see D. R. Scifres, R. D. Burnham, and W. Streifer, *Appl. Phys. Lett.* 25, 203 (1974)] and the cleaved-coupled-cavity (C^3) laser [see W. T. Tsang, *Lightwave Communications Technology, Part B, Semiconductor Injection Lasers, I*, edited by W. T. Tsang, in *Semiconductors and Semimetals*, Vol. 22, edited by R. K. Willardson and A. C. Beer (Academic, Orlando, 1985), Chap. 5, pp. 257-373] have been developed to ensure single-mode operation. The DFB laser employs a fine-scale periodic corrugation of relatively small index steps to interact with the electromagnetic wave. The C^3 laser relies on several large-scale nonperiodic monolithic cavities for feedback and mode selection.

Optical switching and bistability are important for applications such as optical memories, optical signal processing, and optical logic elements. A variety of semiconductor laser devices have exhibited switching and bistability, including: lasers with saturable absorbers [see M. I. Nathan, J. C. Marinace, R. F. Rutz, A. E. Michel, and G. J. Lasher, *J. Appl. Phys.* 36, 473 (1965); C. Harder, K. Y. Lau, and A. Yariv, *IEEE J. Quantum Electron.* QE-18, 1351 (1982); N. Yamada and J. S. Harris, Jr., *Appl. Phys. Lett.* 60, 2463 (1992)], ordinary tandem coupled-cavity lasers [see N. K. Dutta, G. P. Agrawal, and M. W. Focht, *Appl. Phys. Lett.* 44, 30 (1984)] and vertical-cavity surface-emitting lasers [see D.

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G. Deppe, C. Lei, T. J. Rogers, and B. G. Streetman, Appl. Phys. Lett. 58, 2616 (1991)]. It is also among the objects of the present invention to provide a semiconductor laser that exhibits relatively large amplitude switching and bistability in its light versus current characteristics.

SUMMARY OF THE INVENTION

An aspect of the present invention is directed to improved techniques and devices employing, inter alia, an aluminum-bearing III-V semiconductor material and a native oxide of aluminum that is formed in the semiconductor material.

There has been previously disclosed a technique of forming a high quality, stable, and compact native oxide layer from an aluminum-bearing Group III-V semiconductor material. [See Dallesasse et al., Appl. Phys. Lett. 57 (26), 2844-6, 24 December 1990; Dallesasse et al., Appl. Phys. Lett. 58 (4), 394-396, 28 January 1991; Dallesasse et al., Appl. Phys. Lett. 58 (8), 834-836, 25 February 1991; and Sugg et al., Appl. Phys. Lett. 58 (11), 1199-1201, 18 March 1991.] The technique comprises exposing an aluminum-bearing Group III-V semiconductor material to a water-containing environment and a temperature of at least about 375°C to convert at least a portion of the aluminum-bearing Group III-V semiconductor material to a native oxide. The thickness of said native oxide formed thereby is substantially the same as or less than the thickness of that portion of said aluminum-bearing III-V semiconductor material converted into the native oxide. The native oxide layer thus grown is denser and more stable than oxide layers formed from previous methods, meaning, for example, that they do not degrade under conditions of normal use and atmospheric exposure. Further, the native oxide was demonstrated to exhibit improved operating and performance characteristics, for example with regard to metallization adherence and dielectric properties. The native oxides were described as being useful in lasers, transistors, capacitors, waveguides and in other electrical and opto-electrical devices. Anhydrous oxides of aluminum were noted to exhibit a relatively low index of refraction (less than about 2.0) and index of refraction can be used to distinguish the anhydrous oxide forms from the higher index hydrated oxide forms that are generally unsuitable for semiconductor applications due to

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properties such as expansion and instability.

A form of the invention is directed to a method of making a semiconductor laser having a light path that is at least partially curved, and comprises the following steps: forming a layered semiconductor structure comprising an active region between first and second semiconductor confining layers, the first and second semiconductor confining layers being of opposite conductivity types, and said first semiconductor confining layer being an aluminum-bearing III-V semiconductor material; applying a mask pattern over said first semiconductor confining layer, the pattern including a stripe that is at least partially curved; exposing unmasked portions of the first semiconductor confining layer to a water-containing environment and a temperature of at least 375 degrees C for a time sufficient to form a thick native oxide of aluminum in said first semiconductor confining layer; and coupling respective electrodes with said first and second semiconductor confining layers. Generally, the active region includes at least a waveguide layer and a quantum well layer, and the respective electrodes are coupled to the semiconductor confining layers through further respective semiconductor layers. The aluminum-bearing material may comprise, for example, $\text{Al}_x\text{Ga}_{1-x}\text{As}$, where x is at least 0.3. Generally, a higher aluminum fraction, for example $x = 0.7$ or greater, will be used to facilitate the thick oxide growth rate, which also depends on temperature. A temperature of at least about 450 degrees C is generally preferred. For a ring laser, the time of exposure may be selected to have said native oxide extend through at least most of the thickness of said first confining layer, and possibly through the entire thickness of said first confining layer. Another form of the invention comprises a semiconductor passive optical waveguide, having a light path which is at least partially curved, that employs a thick native oxide of aluminum.

In a further form of the invention, two linear arrays of end-coupled cavities (called minicavities) of a QWH semiconductor laser are defined by a native oxide of an

aluminum-bearing III-V semiconductor material and are arranged side by side to obtain a two dimensional array, with resultant lateral coupling between the linear arrays. The two dimensional array exhibits mode switching and multiple switching in the light power (L) versus current (I) characteristic (L-I) with increasing current.

In another form of the invention, a stripe laser is transversely coupled (or side-coupled) with a linear array of end-coupled minicavities. Bistability and switching are demonstrated in the light versus current (L-I) characteristic of a native-oxide-defined structure of this type. The device, with internally coupled elements and the current partitioned among the elements, exhibits a large hysteresis in the L-I curve, with switching from the stimulated to the spontaneous regime occurring over substantial power (light) and current ranges. The linear array of "minilasers" and its resonance modulates and switches the stripe laser operation.

In accordance with a further definition of the invention, a semiconductor laser device includes first and second adjacent laser units formed on the same semiconductor substrate, each of the units including a laser cavity. The laser cavity of the first unit has a substantially different longitudinal mode selection characteristic than the laser cavity of said second unit. [As used herein, substantially different longitudinal mode section characteristics means that the first unit has a cavity mode spacing that is at least 10 percent greater than the cavity mode spacing of the second unit, and/or a primary emission wavelength that is at least 50 Å greater than the primary emission wavelength of the second unit.] Means are provided for applying energizing signals to the first and second units to obtain laser emission from the units and lateral coupling between the cavities of the units.

In an embodiment of the invention there is disclosed a semiconductor laser device that includes a semiconductor active region disposed between first and second semiconductor confining layers. An electrode array has electrode elements coupled with the first confining layer. [As used herein, the

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term "electrode elements" is intended to include electrical contact regions (e.g. highly doped semiconductor regions) that contact an underlying semiconductor structure.] At least one opposing electrode is coupled with the second confining layer. The electrode elements of the array are spaced apart and form a two-dimensional array that includes a plurality of electrode elements along a line and at least one further electrode element laterally spaced from the electrode element of said line. Means are provided for applying electrical signals between the electrode elements and the at least one further electrode element and the opposing electrode to effect light emission in the active regions defined under the plurality electrode elements and at least one active region defined under the at least one further electrode element, and to effect lateral coupling of the emissions.

Further features and advantages of the invention will become more readily apparent from the following detailed description when taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a scanning electron microscope image of a stained cross-section of a device in accordance with an embodiment of the invention.

Fig. 2 is a graph of cw light output (both ring ends) versus current for a device in accordance with an embodiment of the invention, and shows, in an inset, a surface photograph of the device.

Fig. 3 is a graph of pulsed light output (both ring ends) versus current for a device in accordance with an embodiment of the invention and shows, in the inset, single mode operation.

Fig. 4 shows near field image plots for the Fig. 3 device.

Fig. 5 is a graph of pulsed light output versus current for another device in accordance with the invention, the inset showing the device geometry.

Fig. 6 is a simplified cross-sectional representation of a semiconductor laser diode device in accordance with an embodiment of the invention.

Fig. 7 is a simplified cross-sectional diagram of another semiconductor laser device in accordance with a embodiment of the invention.

Fig. 8 is a simplified cross-sectional representation of a semiconductor optical waveguide in accordance with an embodiment of the invention.

Fig. 9 illustrates the surface configuration of a ring laser device.

Fig. 10 illustrates the surface configuration of a quarter-ring laser or waveguide.

Figs 11 and 12 illustrate the surface configuration of ring lasers or waveguides with different branch coupling arrangements.

Figs 13 and 14 illustrate the surface configuration of multi-stripe lasers or waveguides with ring coupling.

Fig. 15 illustrates the surface configuration of a series

of coupled half-ring lasers or waveguides.

Fig. 16 illustrates the surface configuration of a multi-stripe laser or waveguide with half-ring coupling.

Fig. 17 illustrates the surface configuration of a curved laser or waveguide in which the light path becomes laterally offset.

Fig. 18 illustrates the surface configuration of a laser or waveguide which couples light in a single branch with four curved branches.

Fig. 19 shows continuous (cw) 300 K light output (single facet) versus current characteristic (L-I) of a native-oxide-defined two-dimensional (2-D) coupled-cavity $\text{Al}_x\text{Ga}_{1-x}\text{As}$ -GaAs QWH laser array (uncoated facets, $\sim 300 \mu\text{m}$ total cavity length). The threshold is 45 mA, and the power peaks at $\sim 12.5 \text{ mW}$ (115 mA). The inset shows a surface photomicrograph of the unmetallized 2-D twin linear array. The rectangular minicavities are $4 \mu\text{m}$ wide, $19 \mu\text{m}$ long, and separated end-to-end by $\sim 3 \mu\text{m}$. The two coupled linear arrays are separated by $\sim 1 \mu\text{m}$.

Fig. 20 shows longitudinal mode spectra (cw, 300 K) of the diode of Fig. 19 at (a) 115, (b) 150, and (c) 164 mA (points shown on the L-I of Fig. 5). The single mode behavior at (a) $8280 \text{ \AA}$ (115 mA) shifts to $8313 \text{ \AA}$ at (b) 150 mA. At (c) 164 mA single mode operation has switched off and the resonances of the $19 \mu\text{m}$ long minicavities are evident and marked with arrows. The mode spacing is $\sim 50 \text{ \AA}$, which agrees with the $19 \mu\text{m}$ minicavity length.

Fig. 21 shows the light output versus current characteristic (L-I, cw, 300 K) of a diode with the same geometry as that shown in Fig. 19. The diode turns on and off twice as the current is increased. The dashed line shows that the emission intensity in the valley region is in the range of spontaneous emission. The inset shows single mode behavior ($8340 \text{ \AA}$) persists to at least 415 mA ($\sim 8I_{\text{th}}$), and is marked with a solid dot on the L-I curve.

Fig. 22 shows the near field (NF) emission patterns and longitudinal mode spectra of the diode of Fig. 21 near the

diamond-shaped point at ~ 70 mA on the L-I characteristic. At (a) 40 mA (spontaneous regime) the near field (NF) shows two intensity peaks of the twin linear array, with the width of $9.2 \mu\text{m}$ in accord with the geometry shown in Fig. 19. At (b) 71 mA the NF is twin lobed, with the device operating single mode ($8260 \text{ \AA}$) but with also strong satellite longitudinal modes. At (c) 72 mA, the NF emission from the right stripe disappears abruptly, with also an abrupt disappearance of the satellite longitudinal modes.

Fig. 23 shows the continuous 300 K light output (single facet, uncoated) versus current characteristic (L-I) of a native-oxide-defined $\text{Al}_x\text{Ga}_{1-x}\text{As}$ -GaAs single laser stripe side-coupled to a linear array of end-coupled minilasers. The laser threshold is 32 mA, with abrupt switching from the stimulated (ON) to spontaneous (OFF) regime occurring at 168 mA. The device exhibits bistability, switching back sharply from the spontaneous (OFF) to stimulated (ON) regime at 123 mA. The diode geometry (prior to metallization) is shown in the inset and consists of a single $\sim 6 \mu\text{m}$ -wide laser stripe side-coupled ($\sim 5 \mu\text{m}$ away) to a linear array of end-coupled minilasers ($6 \mu\text{m}$ -wide, $19 \mu\text{m}$ long and $22 \mu\text{m}$ centers).

Fig. 24 shows the continuous 300 K light output (single facet, uncoated) versus current characteristic (L-I) of a device of the form of Fig. 23 (inset). The laser exhibits a threshold of 27 mA, with switching and bistability occurring in the range 96-100 mA. Throughout the entire operating range, the device output consists essentially of a $\sim 5.5 \mu\text{m}$ Gaussian near-field (NF) pattern from the single continuous stripe of Fig. 23. The NF pattern is shown just before switching at (a) 99 mA (inset). After switching at (b) 100 mA, essentially no output is observed; on a higher sensitivity scale (b'), however, the same NF pattern is revealed.

Fig. 25 shows longitudinal mode spectra (cw, 300 K) of the diode of Fig. 24 corresponding to single mode stimulated emission (ON) at (a) and switched OFF to spontaneous emission at (b). Single mode laser operation is observed from threshold (~ 27 mA) to (a) ~ 99 mA, with output at large

amplitude from only the continuous stripe of the diode (left stripe in Fig. 23 inset). In the spontaneous emission OFF regime (b) the lower energy group of modes corresponds to the laser stripe and the higher energy group of modes to the linear array (see inset of Fig. 23).

Fig. 26 is diagram of a portion of the top surface of the device described in conjunction with Figures 23-25.

Fig. 27 is a cross-sectional diagram (not to scale), as taken through a section of the Fig. 26 device defined by arrows 13-13.

Fig. 28 is a cross-sectional diagram (not to scale), as taken through a section of the Fig. 26 device defined by arrows 14-14.

Fig. 29 is a cross-sectional diagram (not to scale), as taken through a section of the Fig. 26 device defined by arrows 15-15.

Fig. 30 illustrates a two-dimensional array that can be operated using two, three, or four terminals.

Fig. 31 illustrates a two-dimensional array with terminal control in both dimensions.

Figures 32-35 show plan views of ring lasers including minicavities in curved configurations in accordance with embodiments of the invention.

Figures 36-39 show plan views of adjacent ring and straight line lasers, with transverse coupling between laser cavities, and including configurations where the ring, the straight line, or both, are divided into minicavities.

Fig. 40 is a cross-sectional diagram (not to scale) of a vertical cavity laser device with transverse coupling between adjacent laser cavities having different mode selection characteristics.

Fig. 41 illustrates a two-dimensional array of vertical cavity laser units of the type illustrated in Fig. 40.

DETAILED DESCRIPTION

In an example hereof, a quantum well heterostructure is grown by metal-organic chemical vapor deposition ["MOCVD" - see for example, R.D. Dupuis et al., Proceedings of The International Symposium on GaAs and Related Compounds, pp. 1-9, Institute of Physics, London, 1979, and M.J. Ludowise, J. Appl. Phys., 58, R31, 1985] on an n-type GaAs substrate. After a GaAs buffer layer, an $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ lower confining layer is grown to a thickness of about $1\text{ }\mu\text{m}$. [The confining layers are also sometimes called cladding layers.] The active region of the quantum well heterostructure is then grown, and includes symmetrical $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}$ waveguide layers, undoped and of thickness about $750\text{ }\text{\AA}$ each, on either side of a GaAs quantum well of thickness about $100\text{ }\text{\AA}$. An upper confining (or cladding) layer of p-type $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ is grown to a thickness of about $0.6\text{ }\mu\text{m}$, and a heavily doped p-type GaAs contact layer is grown thereon, the contact layer having a thickness of about $800\text{ }\text{\AA}$. In this example, fabrication of a laser begins with the patterning of about $1000\text{ }\text{\AA}$ of Si_3N_4 into rings [$25\text{-}\mu\text{m}$ wide annulus, $250\text{ }\mu\text{m}$ inside diameter (ID), $300\text{ }\mu\text{m}$ outside diameter (OD)]. The Si_3N_4 rings serve as a mask for the chemical etching ($\text{H}_2\text{SO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}$, 1:8:80) of the contact layer, thus leaving the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ upper confining layer exposed inside and outside of the masked rings. The sample is then placed in an open tube furnace, supplied with H_2O vapor and N_2 , at 450°C for 35 minutes. This process results in the conversion of the upper confining layer (where exposed) to a native oxide having an index of refraction of about 1.6. In this case, at the ring edges the oxide extends downward through the entire upper confining layer as shown in Fig. 1 by the scanning electron microscope (SEM) image of a stained cross section. The oxide is deeper at the ring edge than beyond (to the right in Fig. 1). This effect may be a result of changes in H_2O adsorption, O/H diffusion, or stress induced by the presence of the masking stripe. The oxide profile is fairly isotropic, however, extending laterally essentially to the same extent as

it does in depth. Transmission electron microscope (TEM) images of similarly oxidized crystals indicate that some oxidation (about 200 Å) of the underlying $\text{Al}_{0.23}\text{Ga}_{0.77}\text{As}$ waveguide region occurs. Thus, the low-index native oxide extends into the waveguide layer, creating large lateral index steps for sidewise optical confinement and waveguiding. Calculations based on propagation in a 4-layer slab waveguide [see G.E. Smith, IEEE J. Quantum Electron., QE-4, 288 (1968)] for this deep oxide edge indicate an effective lateral index step greater than 0.05. For this example, structures with the native oxide located about 1000 Å vertically away from the waveguide result in an insufficient index step for ring oscillation. However, as discussed further below, effective lasers can be made with lateral native oxide that extends only partially through the confining layer.

After the indicated oxidation, the Si_3N_4 masking rings are selectively removed in a CF_4 plasma, resulting in a self-aligned geometry. The sample is then Zn-diffused (540°C, 20 min) to improve the contacts and metallized with Ti-Au for the p-type contact and Ge-Ni-Au for the n-type contact. In an example hereof the rings are then cleaved in half (or on a chord through the annulus) and the remaining three sides of the crystal are saw cut (SC) to prevent resonance across the edges. The surface of a typical half-ring laser diode hereof after metallization, cleaving, and sawing is shown in the inset of Fig. 2.

The 300 K cw light versus current (L-I) curve of a typical half-ring laser diode hereof is shown in Fig. 2. The threshold current is ~ 105 mA (~ 890 A/cm²). The curve is linear above threshold with a total external differential quantum efficiency (η of ~ 49%) and a total output power (both ends of the half ring) exceeding 40 mW. The pulsed threshold (2 μs pulse width, 0.5% duty cycle) of this diode is 78 mA.

The pulsed (2 μs, 0.5% duty cycle) L-I characteristic of a moderate quality half-ring laser diode, fabricated as above, is shown in Fig. 3. The diode threshold current is ~ 103 mA. Longitudinal mode spectra show well defined modes, with

single-mode operation occurring at 150 mA (Fig. 3, inset). The mode spacing ($\Delta\lambda$) is ~ 1.7 Å, corresponding to a cavity length of ~ 560 μm . This is longer than the half-circumference (~ 470 μm) and may be due to some misalignment of the cleave (creating a longer cavity) or a longer effective path length caused by the curved resonator.

Operation around the curved resonator is confirmed by imaging the output of each end of the half-ring laser separately into a monochromator. The longitudinal mode spectrum is confirmed to be identical from each end, indicating that laser emission indeed occurs from the circular cavity (data not shown). Further evidence of oscillation around the circular cavity was provided by sawing a half-ring device, which is originally observed to lase, in two along the vertical arrows "SC" and "25 μm " in the inset of Fig. 2. This was found to destroy the resonator and the laser operation. If the device were originally lasing linearly from the front cleave to the opposite saw cut (SC), the device should continue to exhibit laser operation, which is not the case. Thus, there is strong confirmation that laser operation occurs around the ring. However, half-ring laser diodes that were cleaved in two (not saw cut) to form quarter-ring diodes continue to lase, with stimulated emission being observed from both perpendicular cleaved facets.

The near field (NF) intensity profiles of the laser diode of this example are collected with a f/0.95 25 mm focal length lens. A low magnification view (Si MOS camera) with the diode operating at 130 Ma (pulsed) shows distinct emission from the two ends of the half-ring laser (Fig. 4(a)). The 267 μm center-to-center separation agrees well with the device geometry. The corresponding intensity profiles (CCD array image) are shown in Fig. 4(b). Both peaks exhibit asymmetry, with the intensity dropping off faster towards the outside diameter (OD) of the annulus. This asymmetry is more evident in the higher magnification view of the right-hand end (Fig. 4(c)). Such asymmetric intensity profiles agree well with those calculated for a circular waveguide (see E. Marcatilli,

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Bell Syst. Tech. J. 48, 2103, 1969).

Polarization-resolved L-I characteristics indicate that the half-ring diodes lase in the TM mode. This behavior is opposite to that observed in conventional GaAs QWH laser diodes and in native-oxide defined linear resonator QWH laser diodes, which lase in the TE mode. The radiation losses in the native-oxide circular resonator for the TE modes are greater than for the TM modes, indicating application for mode filtering.

Fig. 5 shows the L-I characteristic of a native oxide ring laser diode fabricated in similar manner but on a lower (vertical) confinement $\text{Al}_x\text{Ga}_{1-x}\text{As}$ -GaAs QWH laser crystal ($x \sim 0.6$ confining layers). A cleave through the ring annulus permits laser light to leak out (inset of Fig. 5), with oscillation still maintained around the ring.

Fig. 6 is a simplified diagram of a laser device 600 made using the foregoing technique. The device, on GaAs substrate and buffer layers 610 and 615, includes an active region 630 between $\text{Al}_x\text{Ga}_{1-x}\text{As}$ confining layers 640 and 650, of opposite conductivity types. The active region includes the quantum well 633 between undoped $\text{Al}_x\text{Ga}_{1-x}\text{As}$ waveguide layers 635 and 637. The diagram also shows the curved top contact stripe 660, the underlying GaAs cap layer 670, and bottom electrode 605. As noted in the foregoing description the native oxide of this example, 680, extends through the entire upper confining layer 650 and slightly into the upper waveguide layer 637.

In the description in conjunction with Figs. 1-6, the native oxide of aluminum extends through the entire upper confining layer of the laser diode and even, to a small extent, into the waveguide region. Applicant has discovered that effective optical confinement, tailored to obtain desired operating conditions, can be achieved with a thick (generally, about 3000 Å or more) native oxide that does not necessarily extend through the entire confining layer. Generally, a native oxide that extends through at least one-third of the confining layer is preferred. Fig. 7 shows an embodiment of

the invention having a linear stripe 760 and wherein the thick oxide 780 is controlled (e.g. by controlling the time of exposure and/or temperature in producing the native oxide) to extend about half way through the upper confining layer. In this example, the aluminum fraction (x) of the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ confining layers 740 and 750 is relatively low, for example about 0.4, which results in lower vertical (i.e., in the direction transverse the layers) confinement of the laser beam. [Layers with like reference numerals to those of Fig. 6 represent similar structure.] As described further hereinbelow, less vertical confinement permits greater expansion of the beam into the confining layers and, accordingly, a larger effective lateral refractive index step encountered by the beam as a result of the native oxide in the confining layer.

Reference can be made to the following publications which relate, inter alia, to control of the optical field and gain profile by adjusting the thickness of native oxide outside the active stripe and to control of oxide thickness to determine the degree of optical confinement:

F.A. Kish, S.J. Caracci, N. Holonyak, Jr., J.M. Dallesasse, K.C. Hsieh, M.J. Ries, S.C. Smith, & R.D. Burnham, "Planar Native-Oxide Index-Guided $\text{Al}_x\text{Ga}_{1-x}\text{As}$ -GaAs Quantum Well Heterostructure Lasers", Appl. Phys. Lett. 59, 1755, September 30, 1991;

F.A. Kish, S.J. Caracci, N. Holonyak, Jr., and S.A. Maranowski, J.M. Dallesasse, R.D. Burnham, and S.C. Smith, "Visible Spectrum Native-Oxide Coupled-Stripe $\text{In}_{0.5}(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{P}$ - $\text{In}_{0.5}\text{Ga}_{0.5}\text{P}$ Quantum Well Heterostructure Laser Arrays", Appl. Phys. Lett. 59 2883, November 25, 1991;

F.A. Kish, S.J. Caracci, N. Holonyak, Jr., P. Gavrilovic, K. Meehan, & J.E. Williams, "Coupled-Stripe In-Phase Operation Of Planar Native-Oxide Index-Guided $\text{Al}_y\text{Ga}_{1-y}\text{As}$ -GaAs- $\text{In}_x\text{Ga}_{1-x}\text{As}$ Quantum-Well Heterostructure Laser Arrays", Appl. Phys. Lett. 60, 71, January 6, 1992;

F.A. Kish, S.J. Caracci, S.A. Maranowski, N. Holonyak, Jr., K.C. Hsieh, C.P. Kuo, R.M. Fletcher, T.D. Osentowski, &

M.G. Craford, "Planar Native-Oxide Buried-Mesa $\text{Al}_x\text{Ga}_{1-x}\text{As}-\text{In}_{0.5}(\text{Al}_y\text{Ga}_{1-y})_{0.5}\text{P}-\text{In}_{0.5}(\text{Al}_z\text{Ga}_{1-z})_{0.5}\text{P}$ Visible-Spectrum Laser Diodes", J. Appl. Phys. 71, 2521, March 15, 1992.

Fig. 8 illustrates a passive curved waveguide in accordance with a form of the invention. The waveguide, which can be coupled (directly, or evanescently) with a suitable light source [not shown], includes, for example, GaAs substrate and buffer layers 810 and 815, and an $\text{Al}_x\text{Ga}_{1-x}\text{As}$ ($x = 0.8$, for example) waveguide layer 820. The GaAs cap layer 870, native oxide confining regions 880 (which extend about half way through the aluminum-bearing material in this case), and the contact stripe 860, can be formed using the previously described techniques.

Figs. 9-18 illustrate configurations of lasers or waveguides (cross-sections of which may be, for example, of the types shown in Figs. 6, 7 and/or 8) that can be advantageously implemented utilizing the principles of the invention. In these Figures, the white regions represent either the laser stripe configuration, which has thereunder, inter alia, a waveguide region with the index of refraction confinement in accordance with the present invention or, in the case of a waveguide, the index-confined waveguide region in accordance with the principles hereof. Fig. 9 illustrates a ring configuration, with light energy travelling in both directions. Fig. 10 illustrates a quarter ring, with light energy again travelling in both directions. This configuration, in an active or a passive device, can be utilized to obtain a ninety degree change of direction of the light path. Figs. 11 and 12 illustrate ring laser or waveguide configurations with tangentially coupled branches. In Figs. 13 and 14, multi-stripe lasers are shown as being coupled by ring lasers, such as for phase locking. The stripe spacing can be substantial. Fig. 16 shows a similar arrangement, but with half-ring lasers, and Fig. 15 shows a series of coupled half-rings. The locking or tuning provided by these configurations can result in enhanced longitudinal and/or transverse mode operation. Fig. 17 shows curved

sections in an "S-bend" arrangement for providing an active or passive lateral offset of the optical beam path. Fig. 18 illustrates the surface configuration of a laser or waveguide which couples light in a single branch with four curved branches.

In a further form of the invention, a quantum well heterostructure is grown by metal-organic chemical vapor deposition ["MOCVD"] on an n-type GaAs substrate. After n-type buffer layers of GaAs ($\sim 0.5\mu\text{m}$) and an $\text{Al}_{0.23}\text{Ga}_{0.77}\text{As}$ ($\sim 1\mu\text{m}$) layer, an $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$ lower confining layer is grown to a thickness of $\sim 1.5\mu\text{m}$. The active region of the quantum well heterostructure is then grown, and includes a $\sim 2100\text{ \AA}$ waveguide region of undoped $\text{Al}_{0.23}\text{Ga}_{0.77}\text{As}$ with $\sim 100\text{ \AA}$ undoped GaAs quantum well (QW) grown inside the waveguide region $\sim 700\text{ \AA}$ from the lower confining layer. An upper confining layer of p-type $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ is grown to a thickness of about $3500\text{ \AA}$, and a heavily doped p-type GaAs contact layer is grown thereon, the contact layer having a thickness of about $800\text{ \AA}$.

The position of QW is displaced from the center of the waveguide for more effective overlap of the high-gain region with the optical mode, which is displaced towards the substrate due to the asymmetric confining layers. This asymmetry is purposely introduced to minimize the effects of the surface of the laser crystal (located $\sim 3500\text{ \AA}$ from the waveguide) by shifting the optical field toward the substrate. The shallow upper confining layer is desirable in order to minimize current spreading, allow finer pattern definition, and improved heat dissipation with the crystal mounted p side "down" and thus the active region closer to the heat sink. The thin upper confining layer structure combined with the p-type metallization may also serve to reflect light emitted toward the surface back into the crystal for improved device properties. [A laser diode, fabricated using the described type of QW heterostructure, and comprising a linear array of small rectangular internal coupled cavities delineated by oxidation of the high-gap $\text{Al}_x\text{Ga}_{1-x}\text{As}$ upper confining layer, is described in N. El-Zein, F.A. Kish, N. Holonyak, Jr., A.R.]

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Sugg, M.J. Ries, S.C. Smith, J.M. Dallesasse, and R.D. Burnham, "Native-Oxide Coupled-Cavity $\text{Al}_x\text{Ga}_{1-x}\text{As}$ -GaAs Quantum Well Heterostructure Laser Diodes", Appl. Phys. Lett. 59, 2838, November 25, 1991.]

A laser diode array in accordance with an embodiment hereof is fabricated by patterning $\sim 1000 \text{ \AA}$ of Si_3N_4 into repeated (masked) rectangular cavities ($\sim 19 \text{ }\mu\text{m}$ long, $\sim 4 \text{ }\mu\text{m}$ width, $\sim 3 \text{ }\mu\text{m}$ end-to-end spacing), which are arranged lengthwise in two parallel stripes with $\sim 1 \text{ }\mu\text{m}$ separation. The exposed GaAs cap is then removed by chemical etching ($\text{H}_2\text{SO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}$, 1:8:80) and the crystal is placed in an open-tube furnace (supplied with a N_2 carrier gas bubbled through H_2O at $\sim 95^\circ\text{C}$) at 425°C for 20 min. As above, this process results in the transformation of $\sim 1300 \text{ \AA}$ of the $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ upper confining layer to native oxide outside of the repeated cavities. The Si_3N_4 is then removed in a CF_4 plasma. The inset of Fig. 19 shows a photomicrograph of the surface of the crystal after these processing steps. In order to increase the doping in the rectangular GaAs contact areas, the crystal is sealed in an evacuated quartz ampoule and is shallow Zn-diffused (ZnAs_2 source, 540°C for 20 min). The crystal is then lapped and polished (on the substrate side) to a thickness of $\sim 100 \text{ }\mu\text{m}$, and is metallized with Ti-Au across the oxide and the p-type GaAs "contacts" and with Ge-Ni-Au on the n-type substrate side. The sample is then cleaved into $250\text{--}500 \text{ }\mu\text{m}$ wide Fabry-Perot resonators, diced, and individual dies are mounted p-side down on In-coated Cu heat sinks for continuous (cw) operation.

The unusual switching behavior of the resultant 2-D stripe lasers is evident from the L-I characteristic shown in Fig. 19, which, after reaching a peak in power of $\sim 12.5 \text{ mW}$ at (a) 115 mA , decreases over 50% in power from (a) 115 to (b) 150 mA , and simultaneously shifts its single mode operation (Fig. 20) to longer wavelength. At (c) 164 mA (Fig. 20) the single mode operation of (a) and (b) has switched off, and in the broad spectrum of (c) 164 mA the resonances of the $19 \text{ }\mu\text{m}$ long minicavities are evident and marked with arrows. In the broad

spectral region of weak stimulated emission, the minicavities tend to store photons, making the mode amplitudes (marked with arrows) smaller (c of Fig. 20). Note that the mode structure near the peak of the spectrum in (c) is sufficiently complicated that it is not evident that at (b) 150 mA the single mode laser operation has shifted fully, from (a) 115 mA, to a minicavity resonance (e.g., $\Delta h\omega \sim 6$ meV vs. $\Delta E \sim 9$ meV from resonance to resonance). It is evident from (a) to (b) to (c) in Figs. 19 and 20, however, that single mode operation is turning-off and multi-mode operation, and weaker stimulated emission, is turning-on as the current is increased.

The unusual switching behavior of these 2-D array QWH stripe laser diodes is much more evident in Fig. 21. The L-I characteristic shows that, with increasing current, the laser turns on and off twice. As shown by the inset, which corresponds to the peak of the L-I characteristic (> 12 mW, 415 mA, marked), single mode operation still occurs. In the valley region between 220 and 300 mA, broad-spectrum multi-mode operation similar to that of Fig. 20(c) occurs (data not shown). As the dashed line of Fig. 21 shows, the emission intensity in this region is at or somewhat above spontaneous emission. Most of the 2-D array lasers examined behaved as shown in Fig. 21.

The data of Fig. 22 show in some detail the behavior of the diode of Fig. 21 near the diamond-shaped point located at ~ 70 mA on the L-I characteristic. For comparison, at (a) 40 mA in the spontaneous regime the near field (NF) exhibits two intensity peaks expected of a twin linear array, with the spacing of $9.2 \mu\text{m}$ agreeing with the 2-D array width shown in the inset of Fig. 19. At (b) 71 mA the near field still exhibits twin intensity peaks, and the spectrum a single main mode corresponding to the left NF peak and significant satellite longitudinal modes corresponding to the right NF peak. A small current change of 1 mA ($71 \rightarrow 72$ mA) produces abrupt switching: The satellite longitudinal modes (Fig. 22c) vanish abruptly, and simultaneously the right NF emission peak. It is clear that the strong coupling of one side of the

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diode interferes, constructively or destructively, with the other side of the diode. Also it is evident that the manner in which the current has been partitioned among many identical coupled rectangular minicavities insures that the resonant operation between the cavities is favored.

The data of Figures 19-22 demonstrates a laser diode having two parallel linear arrays of small coupled rectangular cavities delineated by oxidation of the high-gap $\text{Al}_x\text{Ga}_{1-x}\text{As}$ -GaAs QWH. The two dimensional laser array exhibits mode switching and switching in the L-I characteristic with increasing current. Depending on the bias position (current) on the L-I curve, the laser operates in a single longitudinal modes in or near the spontaneous regime. For example, the resonances of the minicavities are evident in the spontaneous spectra in spite of small heating effects and carrier-induced changes in dielectric properties. As above, optimization of the geometry, size, and number of the minicavities, and their coupling, may result in improved behavior of these devices.

In another form of the invention, described beginning with Fig. 23, the QW heterostructure crystal is substantially the same as the one described above in conjunction with the previous device. In the present embodiment, the laser diode array is fabricated by first depositing $\sim 1000 \text{ \AA}$ of Si_3N_4 on the crystal surface, which is then patterned into end-to-end repeated (masked) rectangular cavities (minicavities, $6 \mu\text{m}$ wide and $19 \mu\text{m}$ long on $22 \mu\text{m}$ centers) arranged lengthwise. Next, $6 \mu\text{m}$ photoresist (PR) stripes are patterned $\sim 5 \mu\text{m}$ away from the linear array of minicavities. The patterned PR and Si_3N_4 then serve as a mask for the chemical etching ($\text{H}_2\text{SO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}$, 1:8:80) of the GaAs cap layer, leaving the high-gap $\text{Al}_x\text{Ga}_{1-x}\text{As}$ exposed outside of the patterned regions. The PR is then removed and the sample is placed immediately in an open-tube furnace (425°C) supplied with H_2O vapor in an N_2 carrier gas for 20 min. Again, this process results in the conversion of the exposed high-gap $\text{Al}_x\text{Ga}_{1-x}\text{As}$ to a low-index ($n \sim 1.6$) insulating native oxide located $\sim 1000 \text{ \AA}$ above the QWH waveguide region. The patterned Si_3N_4 and unetched GaAs

regions are unaffected by this treatment. The patterned Si_3N_4 is then removed in a CF_4 plasma. The inset of Fig. 23 shows the surface of the device after these processing steps. Next the sample is Zn-diffused (540°C , 20 min) to increase the doping in the contact regions (labeled "GaAs" in Fig. 23). The crystal is then lapped and polished to a thickness of $\sim 125\text{ }\mu\text{m}$ and, again, metallized over the entire top surface with Ti-Au for p-type contacts and with Ge-Ni-Au for n-type contacts. Finally the crystal is cleaved, diced, and individual dies mounted on In-coated copper heat sinks for continuous (cw) operation.

The large amplitude switching properties of the single-stripe laser coupled to the active linear array are shown by the 300 K continuous (cw) L-I curve of Fig. 23. The laser threshold current is 32 mA, and laser operation persists up to a current of 168 mA. At this point the diode switches abruptly from stimulated emission, ON (19.6 mW/facet, uncoated), to the spontaneous regime, OFF (0.4 mW/facet, uncoated). This behavior corresponds to a large ON:OFF power ratio of 49. These are inherently nonlinear devices, and exhibit bistable operation with a large hysteresis. As the current is decreased (returned) to 123 mA, the diode switches back from the spontaneous regime, OFF, to the simulated regime, ON. For further current increase beyond 168 mA, after the device has switched OFF with increasing current, only a slight increase in the spontaneous output is observed until failure at 187 mA. We mention that, although hysteresis occurs in the L-I characteristics, no hysteresis is observed in the current versus voltage (I-V) characteristics of these devices.

The L-I characteristic (cw 300 K) of another diode exhibiting similar switching behavior is shown in Fig. 24. The laser threshold current is 27 mA, with the device exhibiting essentially a single $\sim 5.5\text{ }\mu\text{m}$ -wide Gaussian near-field pattern (data not shown). This intensity pattern corresponds to laser operation of the $\sim 6\text{ }\mu\text{m}$ wide uniform stripe (inset of Fig. 23), which is expected to reach

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threshold before the segmented linear array. From gain-loss considerations, the linear array with its repeated unpumped absorbing sections should have a higher laser threshold.

Throughout the entire operating range, a single-stripe near-field pattern persists, i.e., only very weak output is observed from the linear array portion of the device. The near-field pattern (300 K, cw operation) at (a) 99 mA just before the switching from ON to OFF, i.e., before switching from single-mode stimulated emission to spontaneous emission, is shown in the inset of Fig. 24. Similar to operation just above threshold, only a $\sim 5.5 \mu\text{m}$ Gaussian near-field is observed at significant amplitude. After the diode switches OFF at (b) 100 mA, no pattern is observed on the same sensitivity scale of the CCD detector. However, at higher sensitivity (11.3x), emission from the same aperture ($\sim 5.7 \mu\text{m}$) is observed (b'). This near-field pattern also is observed as the laser is switched back from OFF to ON. These data indicate unambiguously that only the uniform laser stripe provides much of the optical output of the system. The side-coupled linear array serves mainly to effect the interferences and switching, ON-OFF, and does not contribute primarily to the optical output.

Further understanding of the operation of these diodes is obtained by examining the output spectra. Somewhat above the threshold at 30 mA, the diode of Fig. 24 operates in a single longitudinal mode ($\lambda \sim 8353 \text{ \AA}$, data not shown). This behavior continues to the peak of the L-I curve of Fig. 24 (63 mA), where the single mode operation "hops" to longer wavelength ($\lambda \sim 8367 \text{ \AA}$, data not shown). Throughout the entire stimulated emission operating regime (30 $\rightarrow$ 99 mA), the output occurs in a well developed single longitudinal mode. For example, at 63 mA the laser exhibits a side-mode suppression of 29 dB. The mode hopping, and corresponding structure in the L-I curve (Fig. 24), is attributed to the interaction (interference) of the single laser stripe with side-coupled active linear array and its resonances and stop bands.

Longitudinal mode spectra in the higher-current switching

regime of the device of Fig. 24 are shown in Fig. 25. Immediately before switching from ON (stimulated emission) to OFF (spontaneous regime), (a) in Fig. 24, the laser operates in a single longitudinal mode at $\lambda \sim 8415 \text{ \AA}$, which is shown as (a) in Fig. 25. When the diode switches OFF to the spontaneous regime, (b) of Fig. 24, the longitudinal mode spectra appear as shown in (b) of Fig. 25. At this point, the output consists of the spontaneous emission of the single stripe laser (group of lower energy modes) and the linear array (group of higher energy modes). The coupling of the linear array to the stripe laser leads to interference. The resonances of the minicavities of the linear array are apparent (clearer in the laboratory data) at higher energy in the spectrum of Fig. 25(b) and are marked with arrows. The spacing of these resonances ($\Delta\lambda \sim 50 \text{ \AA}$) corresponds to the $\sim 19 \text{ }\mu\text{m}$ minicavity length shown in the inset of Fig. 23. It is noted that the output in the OFF spontaneous regime (Fig. 25(b)) differs significantly from that observed in the spontaneous regime below laser threshold ($\leq 27 \text{ mA}$), where only the longitudinal mode output of the single laser stripe (group of lower energy modes) is observed (data not shown).

The described switching and storage are fundamentally different from previously reported switching laser devices. The ON-OFF switching behavior occurs in this embodiment in a single unbroken or uninterrupted laser stripe. The switching behavior is owing to the influence (via sidewise coupling) of an active linear array. The switching and bistability is effected by the periodic structure of the linear array (see H.G. Winful, J.H. Marburger, and E. Garmire, Appl. Phys. Lett. 35, 379 (1979); J. He and M. Cada, IEEE J. Quantum Electron. QE-27, 1182 (1991)) and the obvious inhomogeneous carrier distribution, and inhomogeneous operation, resulting from the native-oxide patterning of the array.

Thus, this embodiment sets forth a new form of optical switching element in which a conventional single-stripe laser is side-coupled to a linear array of coupled minilasers. The resulting many-element twin-stripe laser is easily realized

via native-oxide device processing. The planar devices exhibit large hysteresis in the L-I curve, with large amplitude switching from the peak of the stimulated emission regime (ON) to the spontaneous regime (OFF). Changes in the coupling, e.g., the spacing between the laser stripe and linear array and between the array elements, and in the geometry of the structure should improve the switching behavior of these lasers. Independent control of the current (carrier population) in the single laser stripe in the linear array, e.g., via a third terminal electrode, should allow control of the switching behavior, and other variations are possible.

Fig. 26 shows a part of the surface of the device described in conjunction with Figures 23-25, and is used as a reference to show the cross-sections used for the illustrations of Figures 27-29. In Figure 26 the stripe is labelled 1210 and the minicavities, or portions thereof, are labelled 1221-1225. The cross-section 13-13 is taken through the stripe 1210 and an adjacent minicavity 1224. The illustrated layers, which were previously described, include the bottom contact metallization 1250 (it being understood throughout that references to "bottom" or "top" are for ease of description, as the device may be mounted and used in any desired orientation), followed, in ascending order, by the n-type GaAs substrate layer 1255, the n-type GaAs buffer layer 1258, the n-type $\text{Al}_{0.23}\text{Ga}_{0.77}\text{As}$ buffer layer 1260, the n-type $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$ lower confining layer 1262, and active active region 1270 that includes a GaAs quantum well layer 1271 between waveguide layers 1273 and 1275 of undoped $\text{Al}_{0.23}\text{Ga}_{0.77}\text{As}$. Above the active region is the upper confining layer 1278 of p-type $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$. The layer thicknesses may be, for example, as previously indicated above for the experimental device. The p-type GaAs contact 1281 and the p-type GaAs contact 1283 respectively define the contact positions of the stripe 1210 and the minicavity 1225 of Fig. 26. The native oxide is shown at 1291, 1292, and 1293, and, in this example, has a thickness of about 1300 Å. The oxide also extends somewhat under the GaAs contact regions. The top (p-side) metallization is labeled 1240.

The diagram of Fig. 28 illustrates the cross-section defined by arrows 14-14 of Fig. 26. In this view, only the contact region 1281 of the stripe 1210 is visible. The oxide (1294) extends continuously to the right of the stripe.

Fig. 29 shows the cross-section defined by arrows 15-15 of Fig. 26. This view is longitudinally through the minicavities, with two minicavities being shown between three oxide regions 1296, 1297, 1298. The longitudinal dimension of the contact 1283 is seen in this view.

In the illustrated embodiments, operation may be "two terminal", such as by applying the electrical potential between the bottom electrode and the top common metallization. The device can alternatively be made for operation as a three terminal or multiple terminal device. For example, Fig. 30 illustrates a device having a stripe 1610 with mini cavities 1620 on both sides, each line having a common metallization (represented by the joining lines between minicavities) and its own terminal, so that the device can be operated with four independent terminals, with three terminals (for example, the terminals of only two adjacent lines and the bottom terminal, or with the two outside lines in common) or two terminals, with all three lines in common. [In this diagram, and in other diagrams hereof where a plan view of the minicavity and/or stripe configuration is shown, the underlying structure is of the type previously described, the fabrication masking patterns being consistent with the structures illustrated.) Fig. 31 illustrates a two-dimensional array of adjacent lines of mini cavities, with individual terminals coupled with the mini cavities. It will be understood that a terminal can be coupled with any desired combination or group of cavities or minicavities.

The previous embodiments illustrate straight line minicavity and stripe configurations, but it will be understood that the principles of the invention also apply to minicavities and stripes arranged in curved line_____

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configurations and arrays. Figures 32-39 illustrate some representative embodiments (with bottom electrode and various possible top electrodes not shown). In Fig. 32 there is shown a ring laser which is divided into curved minicavities 1815, to obtain the types of effects described in N. El-Zein, F.A. Kish, N. Holonyak, Jr., A.R. Sugg, M.J. Ries, S.C. Smith, J.M. Dallesasse, and R.D. Burnham, "Native-Oxide Coupled-Cavity $\text{Al}_x\text{Ga}_{1-x}\text{As-GaAs}$ Quantum Well Heterostructure Laser Diodes", Appl. Phys. Lett. 59, 2838, November 25, 1991, in the context of a ring laser. [It will be understood throughout that any of the curved configurations need not be precisely circular, that any desired portions of rings or curves can be used, and that the rings or portions thereof can be cleaved at any desired position to obtain one or more outputs.] Fig. 33 illustrates two concentric ring lasers, each divided into minicavities 1915, so that lateral coupling can be achieved, as first described in conjunction with Figures 19-22 above for the case of straight line arrays. In Fig. 34, one of the concentric rings 2010 is continuous, and the other is divided into minicavities 2015, to obtain a curved version of the embodiment described in conjunction with Figures 23-29. Fig. 35 illustrates a circular configuration with sector-shaped minicavities 2115 separated by radial "spokes" of native oxide.

Fig. 36 shows a ring laser 2210 laterally coupled with a stripe laser 2220. In Fig. 37 the ring is divided into minicavities 2315, and in Fig. 38, the stripe is divided into minicavities 2415. In Fig. 39, both the ring and the stripe are divided into minicavities (2515 and 2525, respectively).

It will be understood that the previous indicated variations with regard to numbers and types of stripes, array elements, and/or terminal connections are applicable to embodiments with curved lines or minicavities.

Fig. 40 illustrates, in cross-section, a form of the invention which couples cavities with different longitudinal mode characteristics, in the form of a vertical cavity laser array. Vertical cavity lasers are well known in the art (see,

for example, H. Soda et al. Japan J. Appl. Phys. 18, 59 (1979) and K. Iga et al., Electron Lett. 23, 134 (1987), and include, as in the lefthand unit of Fig. 40, a bottom contact 2610 on a substrate (e.g. GaAs 2605), an n-type superlattice 2620, an active region 2630 that includes a quantum well layer 2632 between waveguide layers 2634 and 2636, a p-type superlattice 2640, and one or more contacts 2650. Various materials may be used. As one example, the superlattices may comprise a number of alternating layers of AlAs and GaAs [or $\text{Al}_x\text{Ga}_{1-x}\text{As}$ and $\text{Al}_y\text{Ga}_{1-y}\text{As}$, $x \neq y$, or combinations of $\text{Al}_x\text{Ga}_{1-x}\text{As}$ and conductive dielectric stacks (e.g. $\text{TiO}_2/\text{SiO}_2$, ZnSe/CaF_2)], and the active region may comprise $\text{Al}_{0.1}\text{Ga}_{0.9}\text{As}$ (or GaAs) waveguides layers with a GaAs (or $\text{In}_{0.1}\text{Ga}_{0.9}\text{As}$) quantum well layer with total thickness of typically $\sim 250 \text{ \AA}$. The contacts at the surface may comprise for example Au or Ag with a standard (e.g. Ge-Au) backside (substrate) side contact. A two-dimensional vertical cavity coupled array of such devices is described for example in D.G. Deppe, J.P. Van der Ziel, Nasesh Chand, G.J. Zydzik, and S.N.G. Chu, Appl. Phys. Lett. 56, 2089 (1990). Briefly, in operation, the multiple reflections from the superlattice interfaces provide a relatively short effective cavity length (typically $\sim 5 \mu\text{m}$) from the limited thickness device, and the cavities are coupled evanescently.

In accordance with a feature of a form of the invention, adjacent vertical cavity laser units are provided with active regions of different thicknesses, as illustrated in Fig. 40, where the active region 2630' is substantially thicker than the active region thickness of its neighboring unit. In the illustration, the quantum well layer is continuous through adjacent active regions, although this is not necessary. The same is true of the superlattice layers above the active region 2630'. Variation of the upper or lower superlattice thickness laterally varies the effective lateral mirror reflectivity. Such variations may also be employed with a uniform thickness active region to achieve local variations in the cavity structure. In addition to the standard evanescent coupling, other schemes may be employed to couple such devices

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such as varying the mirror (e.g. superlattice) angles to directly reflect some of the light from one cavity into adjacent cavities.

There are various other techniques that can be utilized to obtain adjacent vertical cavities having substantially different effective vertical cavity lengths, so that lateral coupling thereof can be advantageously exploited to obtain properties such as switching, bistability, and/or tuning. [As used herein, vertical cavities having substantially different effective cavity lengths means that the cavities have substantially different longitudinal mode characteristics, as previously defined.] For example, the active regions of adjacent units may comprise different materials. Another alternative is to provide adjacent units with superlattices of different thicknesses, or superlattices of different configurations. An example of the latter would be to provide one unit having superlattices of alternating 100 Å GaAs and AlAs layers and the other unit with superlattices having alternating 200 Å GaAs layers and 100 Å AlAs layers, which results in different effective cavity lengths.

Fig. 41 illustrates a checkerboard-type array of such units, with the cross-hatched units representing the units having the thicker active regions. The array can be operated as a two terminal device, with the top contacts coupled in common, and potential applied between the top and bottom contact, or can be driven as a three terminal or multiple terminal device with separate connections to contacts. Various other shapes and configurations in one-dimension or two-dimensions can be utilized. In one example of fabricating an array, the growth may be terminated at the active region (2630'). A two-dimensional pattern (e.g. a checkerboard) is then masked using standard photolithography techniques and the sample is subjected to chemical etching to remove a portion of the active region (2636) in the unmasked areas. This process results in a lateral variation in the active layer thickness. The photoresist is then removed and the upper p-type superlattice is grown on the patterned active region, such as

by MOCVD or MBE (molecular beam epitaxy). A circular (dot) metallization can then be applied on the upper p-type superlattice for contact and reflectivity purposes.

The invention has been described with reference to particular preferred embodiments, but variations within the spirit and scope of the invention will occur to those skilled in the art. For example, while the aluminum-bearing III-V semiconductor material aluminum gallium arsenide has been described in embodiments hereof, it will be understood that the devices and technique hereof can employ other aluminum-bearing III-V semiconductor materials, such as indium aluminum gallium phosphide, indium aluminum gallium arsenide, or aluminum gallium phosphide. [Reference can be made to F. Kish et al., J. of Appl. Phys. 71, 15 March, 1992.] Also, it will be understood that the indicated confining layers can be multiple layers, one or more of which comprises the aluminum-bearing III-V semiconductor material. It will further be understood that devices can integrate the aluminum-bearing III-V semiconductor material (from which the native oxide is formed) with other non-III-V semiconductor materials. It will also be understood that laterally coupled cavities as described herein can be utilized for tuning as well as indicated functions such as switching. The lateral coupling described herein is particularly facilitated by using the native oxide formed in an aluminum-bearing III-V semiconductor material to separate laterally coupled cavities. In some of the configurations hereof, less preferred cavity definition can alternatively be implemented by techniques such as multiple regrowths/overgrowths, etch and regrowth/overgrowth, ridge formation, ridge formation and overgrowth, impurity induced layer disordering, and proton implantation.

CLAIMS:

1. A method of making a semiconductor laser having a light path that is at least partially curved, comprising the steps of:

forming a layered semiconductor structure comprising an active region between first and second semiconductor confining layers, said first and second semiconductor confining layers being of opposite conductivity types, and said first semiconductor confining layer being an aluminumbearing III-V semiconductor material;

applying a mask pattern over said first semiconductor confining layer, said pattern including a stripe that is at least partially curved;

exposing unmasked portions of said first semiconductor confining layer to a water-containing environment and a temperature of at least 375 degrees C for a time sufficient to form a thick native oxide of aluminum in said first semiconductor confining layer, said native oxide of aluminum having a thickness of at least 3000 Angstroms; and

coupling respective electrodes with said first and second semiconductor confining layers.

2. The method as defined by claim 1, wherein said active region includes at least a waveguide layer and a quantum well layer, and wherein said respective electrodes are coupled to said semiconductor confining layers through further respective semiconductor layers.

3. The method as defined by claim 1, wherein said curved portion is in the shape of an annular arc.

4. The method as defined by claim 1, wherein said curved portion is an annular ring.

5. The method as defined by claim 3 or 4, wherein said time is sufficient to have said native oxide extend through at least most of the thickness of said first confining layer.

6. The method as defined by claim 5, wherein said native oxide extends through the entire thickness of said first confining layer.

7. The method as defined by claim 1, wherein said aluminum-bearing material comprises $\text{Al}_x\text{Ga}_{1-x}\text{As}$, where x is at least 0.3.

8. The method as defined by claim 1, wherein said water-containing environment comprises water vapor and an inert gas, and wherein said temperature is at least 450 degrees C.

9. A semiconductor ring laser device; comprising:
a semiconductor active region disposed between first and second semiconductor confining layers, said first and second semiconductor confining layers being of opposite conductivity type, and said first semiconductor confining layer being an aluminum-bearing III-V semiconductor material;
first and second electrode means respectively coupled with said first and second confining layers, said first electrode means including a conductive annular ring; and
lateral confining regions of a native oxide of aluminum formed in said first confining layer around both peripheries of said annular ring, said native oxide extending through at least most of the thickness of said first confining layer.

10. The device as defined by claim 9, wherein said native oxide extends through the entire thickness of said first confining layer.

11. The device as defined by claim 10, wherein said aluminum-bearing material comprises $\text{Al}_x\text{Ga}_{1-x}\text{As}$, where x is at least 0.3.

12. The device as defined by claim 9, wherein said active region includes at least a waveguide layer and a quantum well layer, and wherein said respective electrode means are coupled to said semiconductor confining layers through further respective semiconductor layers.

13. A semiconductor optical waveguide, comprising:
a semiconductor substrate;
a generally planar semiconductor waveguide layer disposed on said substrate, said waveguide layer being an aluminum-bearing III-V semiconductor material;
an elongated optical path, which is at least partially curved, in said waveguide layer formed by said aluminum-bearing III-V semiconductor material between optically confining boundaries of native oxide of aluminum formed within the planar surface of said aluminum-bearing semiconductor material, said native oxide having a thickness of at least 3000 Angstroms and extending through at least onethird the thickness of said aluminum-bearing III-V semiconductor material.

14. The waveguide as defined by claim 13, wherein said native oxide extends through most of the thickness of-said aluminum-bearing III-V semiconductor material.

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15. The waveguide as defined by claim 13 or 14, wherein said aluminum-bearing material comprises $\text{Al}_x\text{Ga}_{1-x}\text{As}$, where x is at least 0.3.

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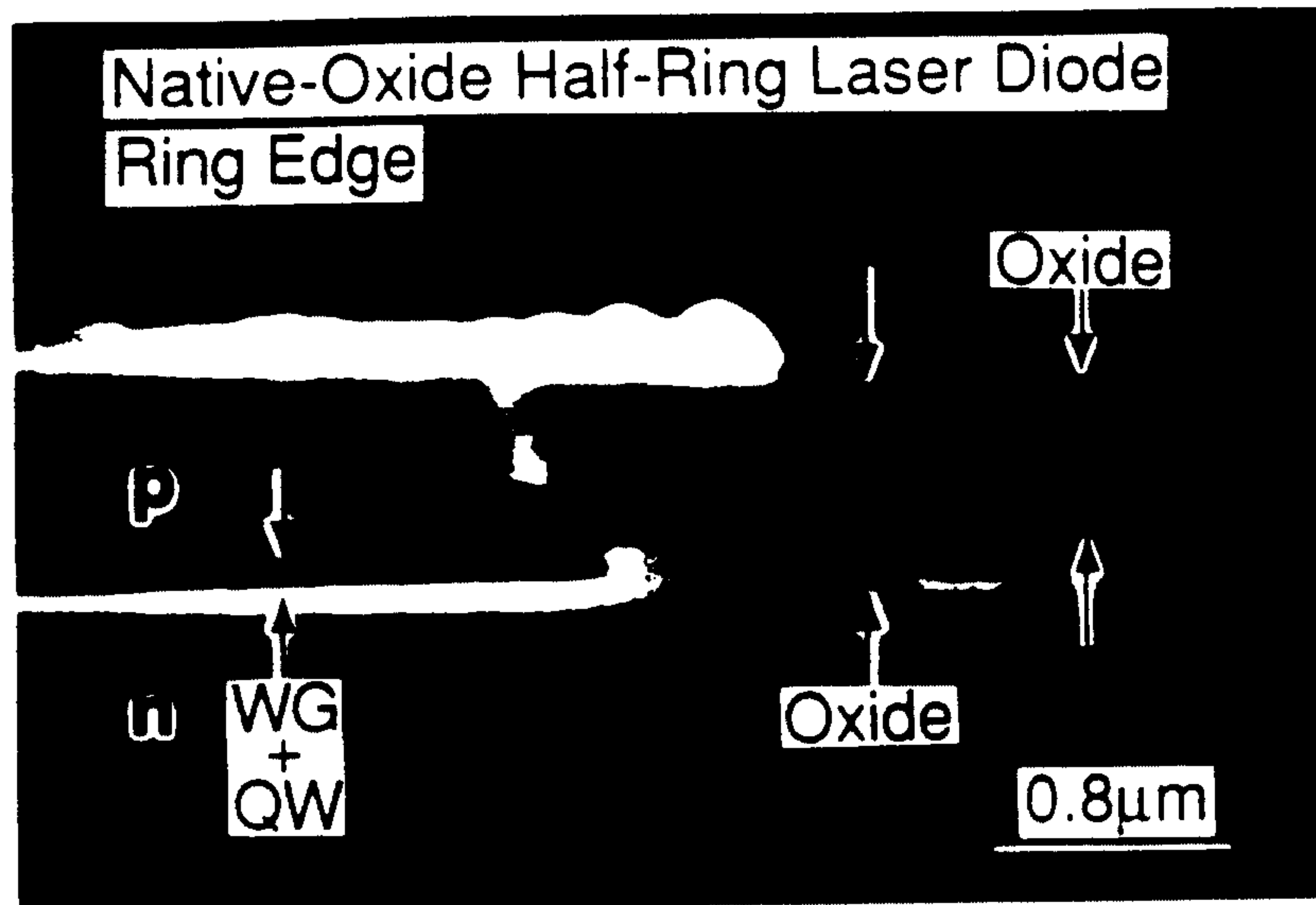


FIG. 1

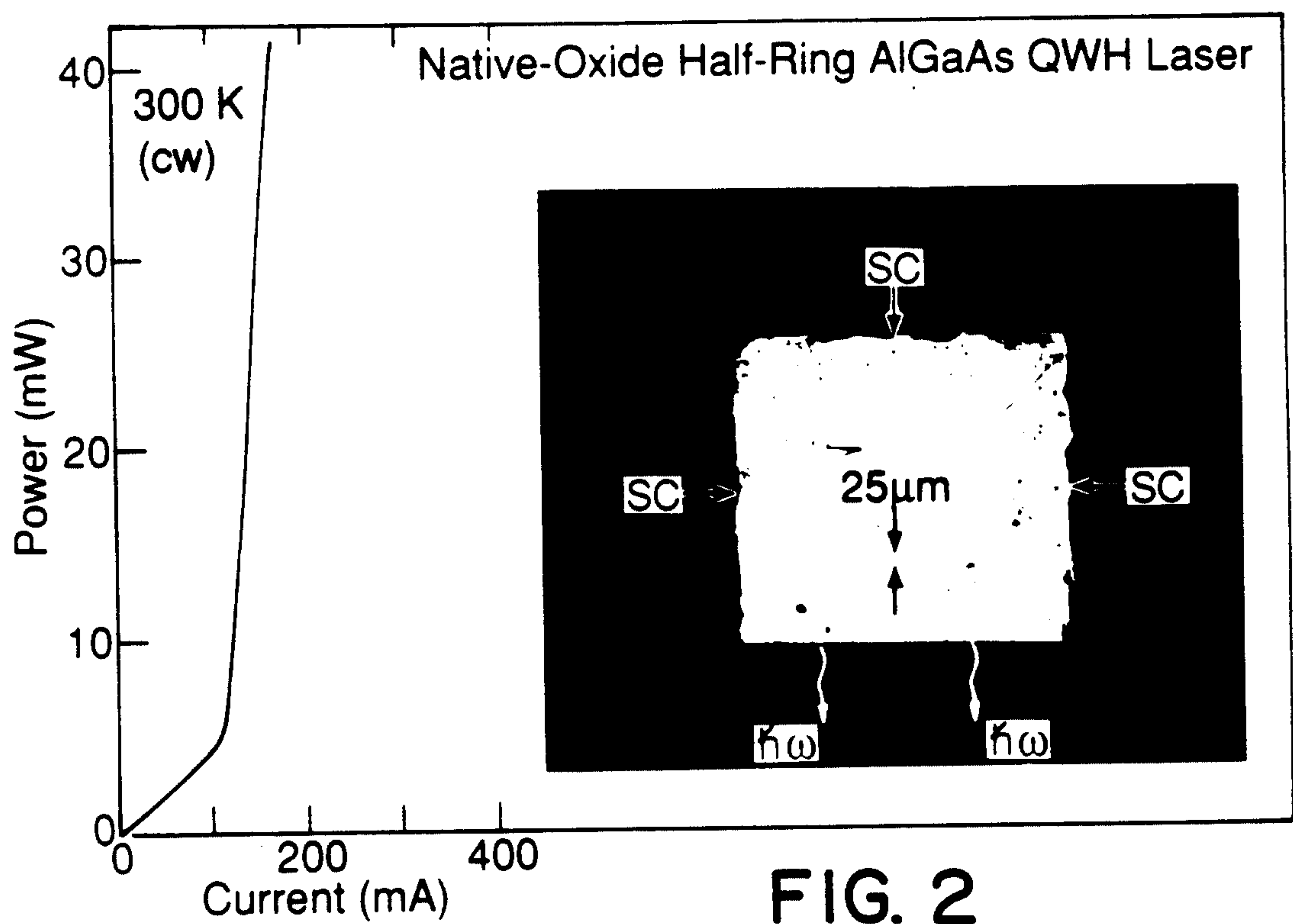


FIG. 2

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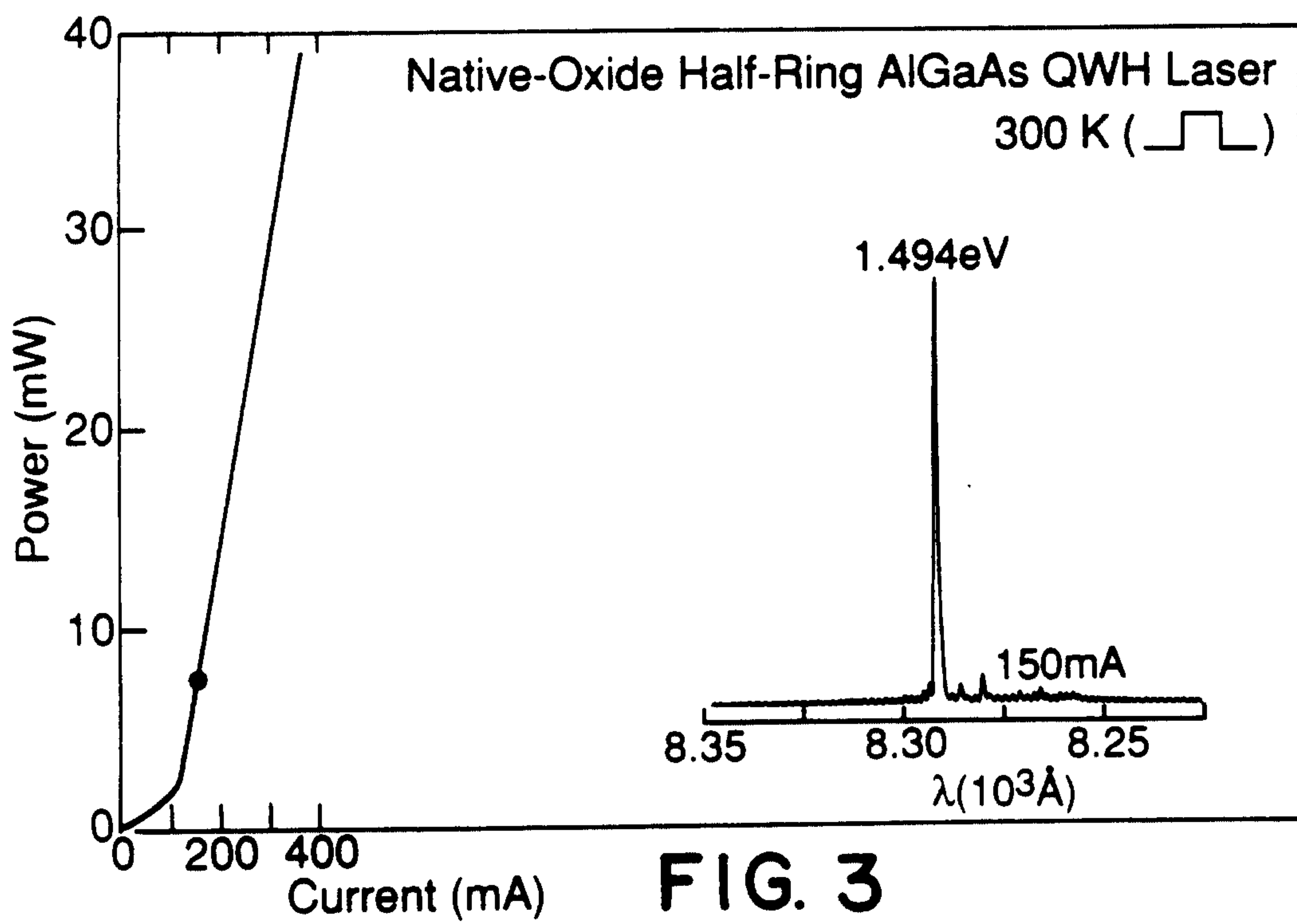


FIG. 3

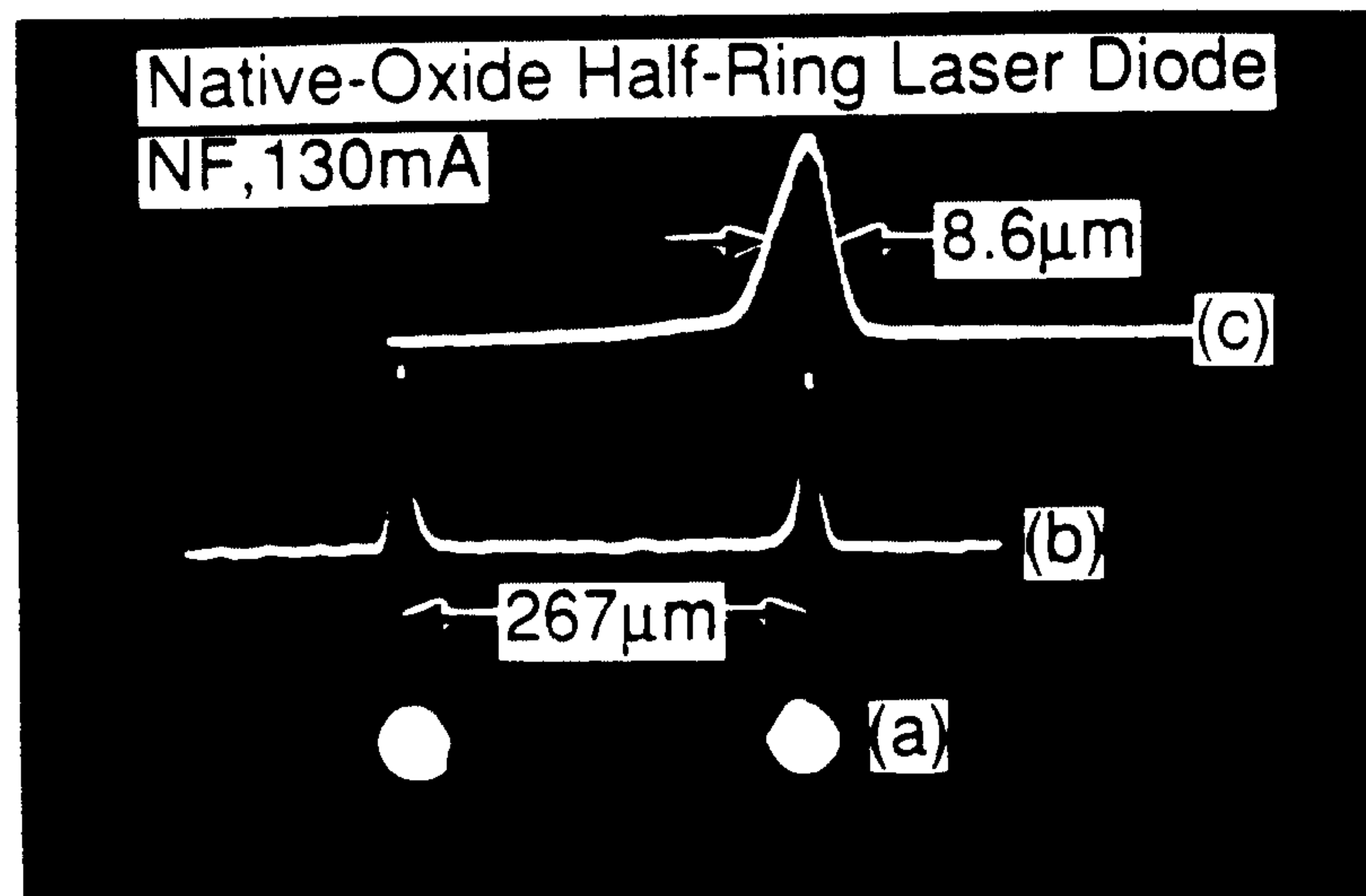


FIG. 4

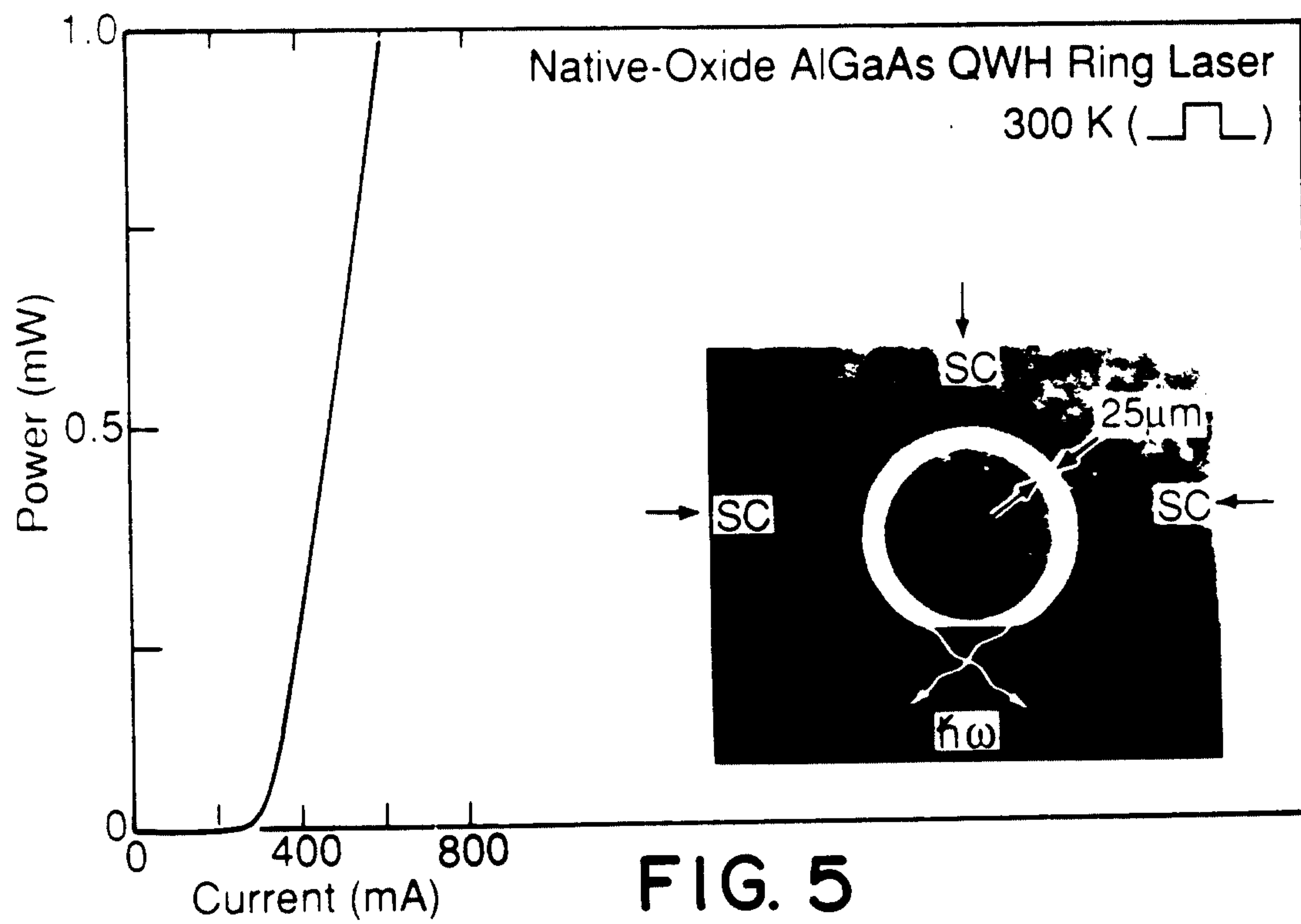


FIG. 5

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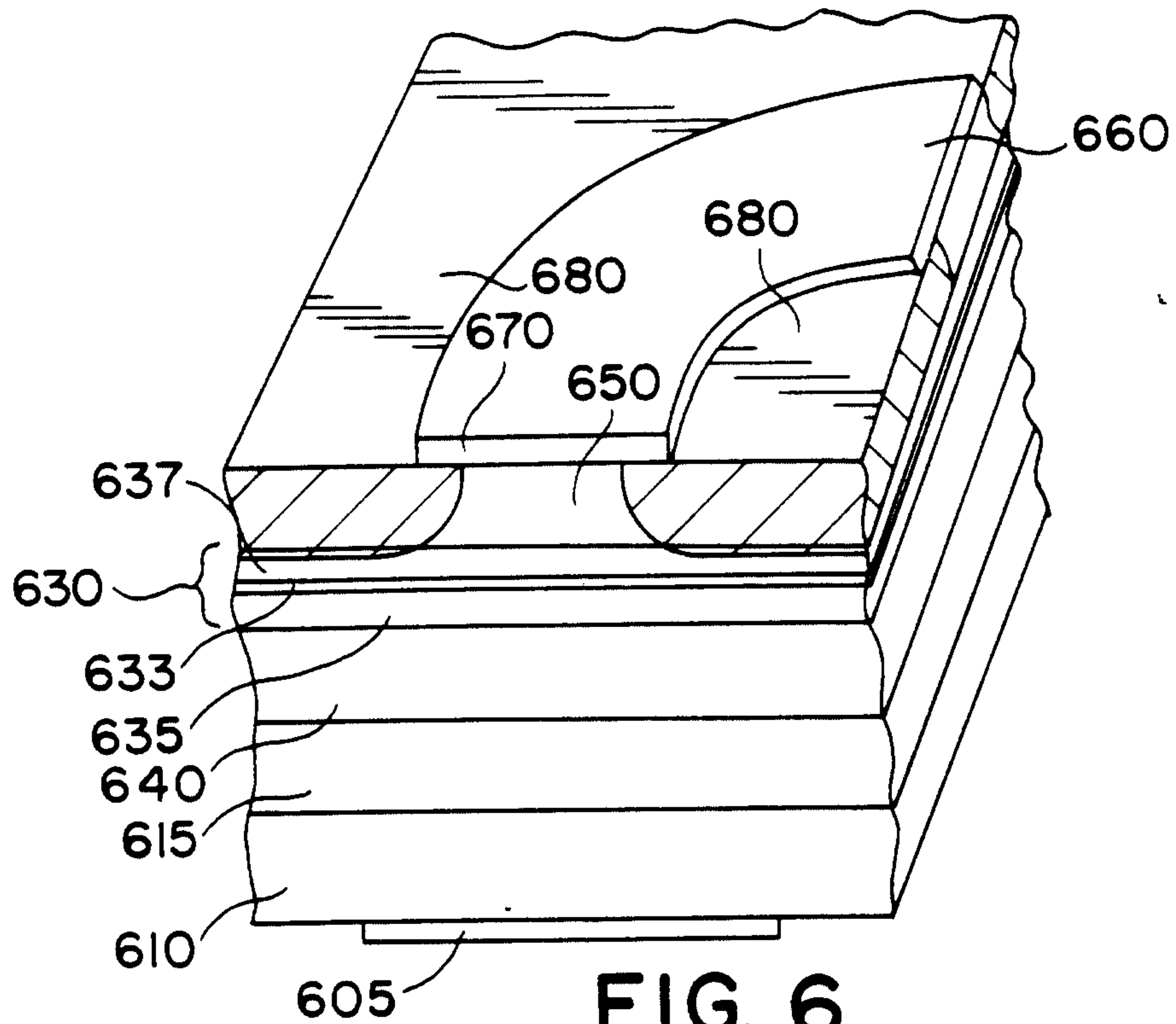


FIG. 6

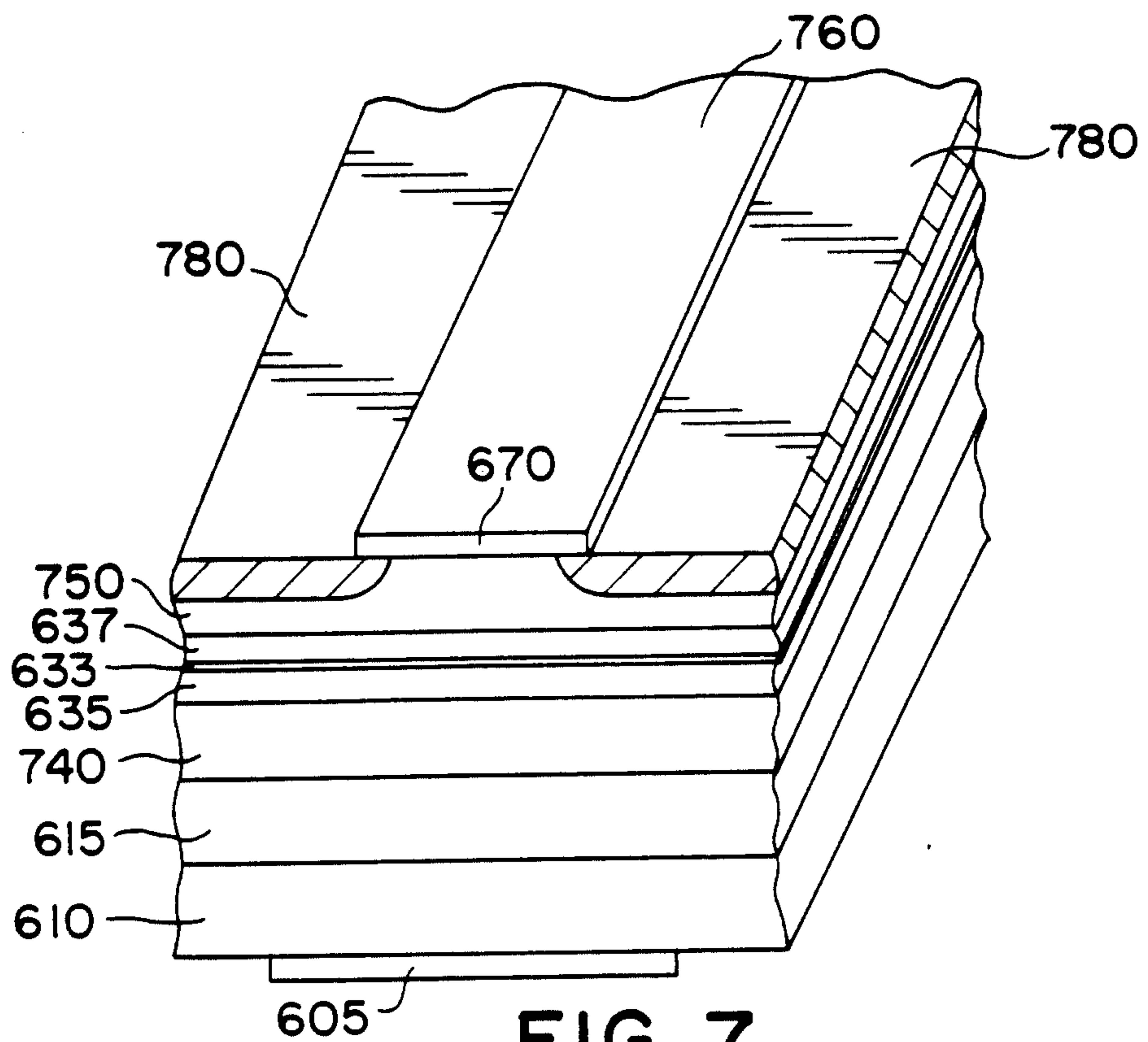


FIG. 7

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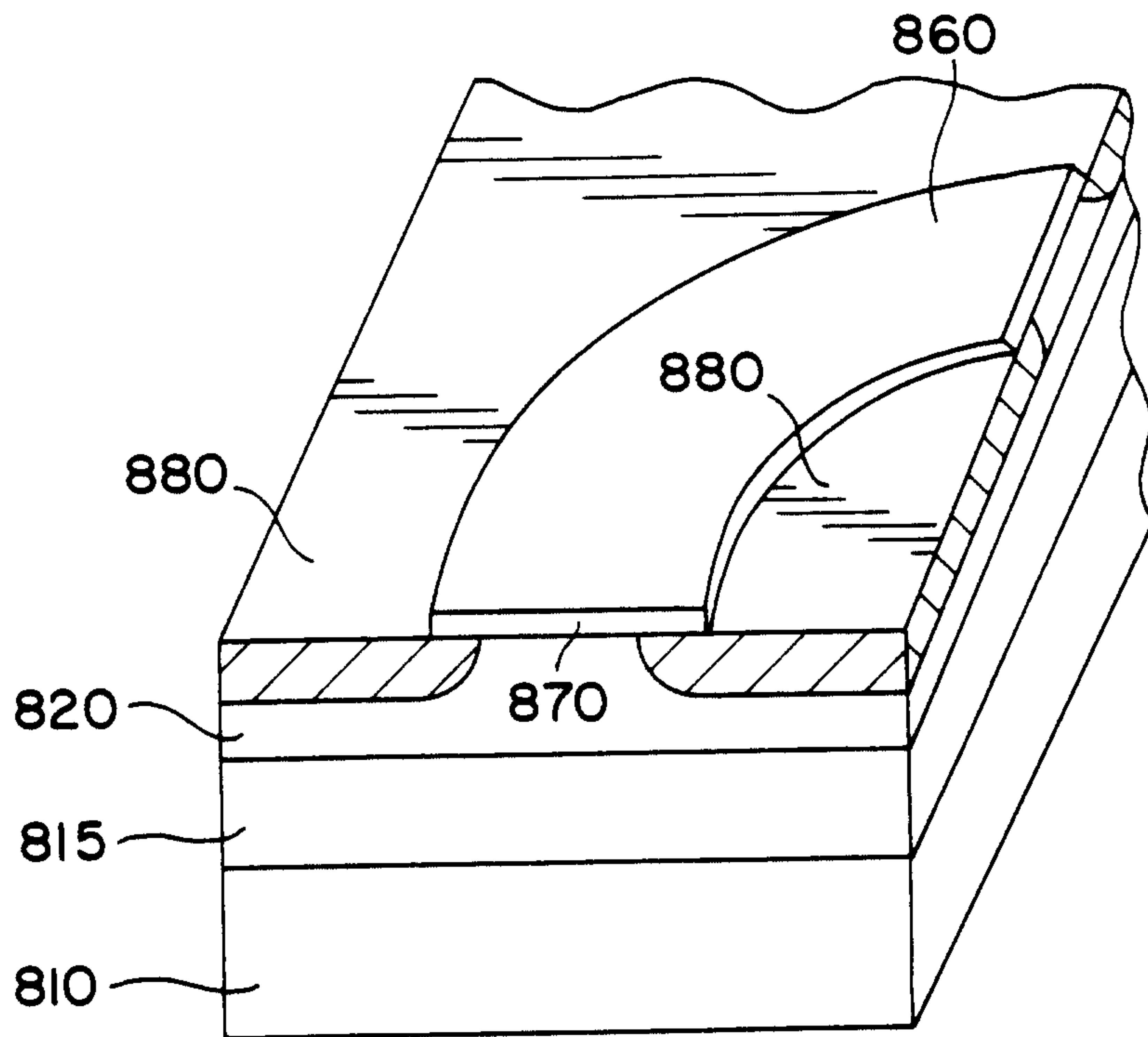


FIG. 8

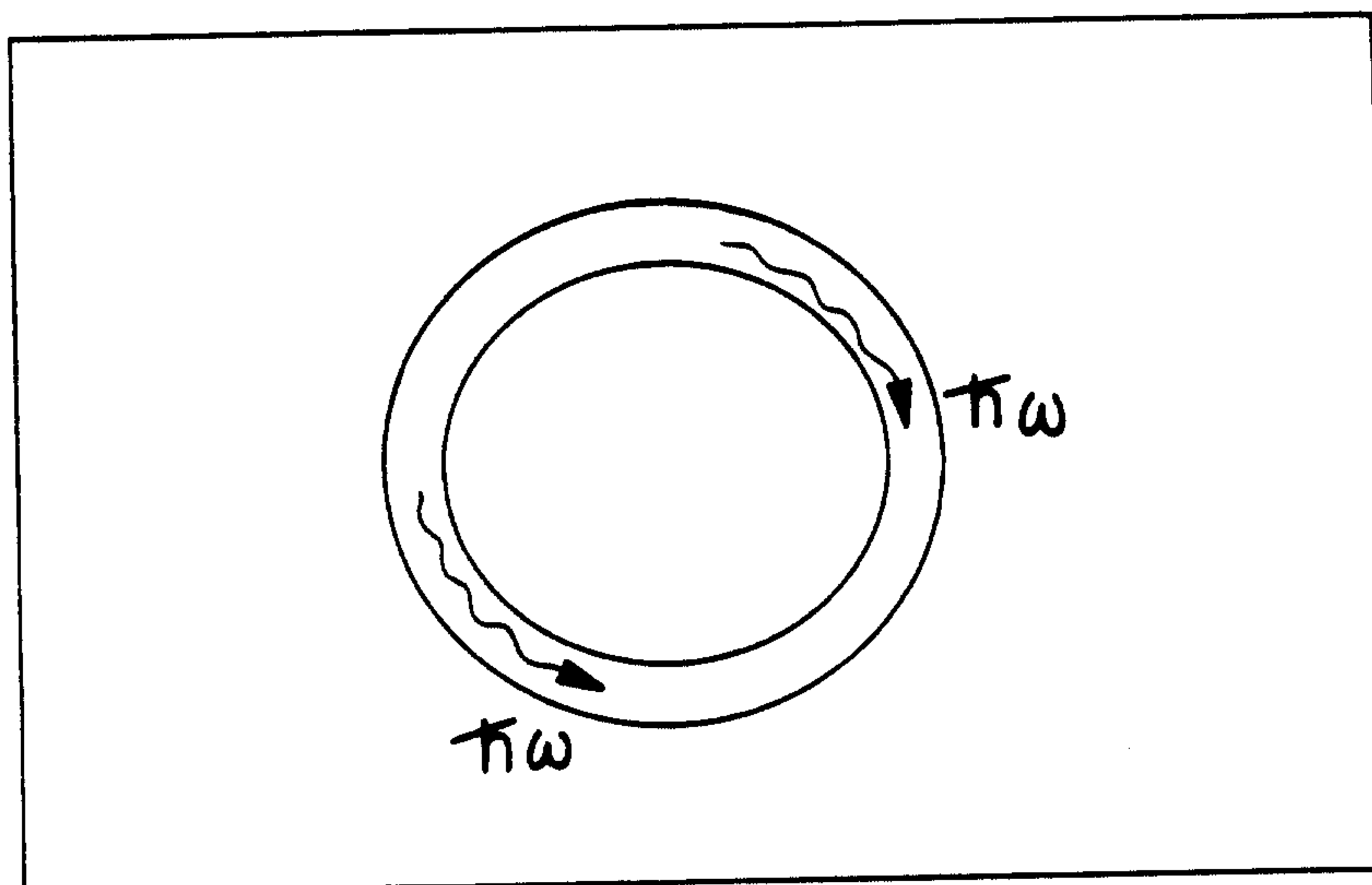
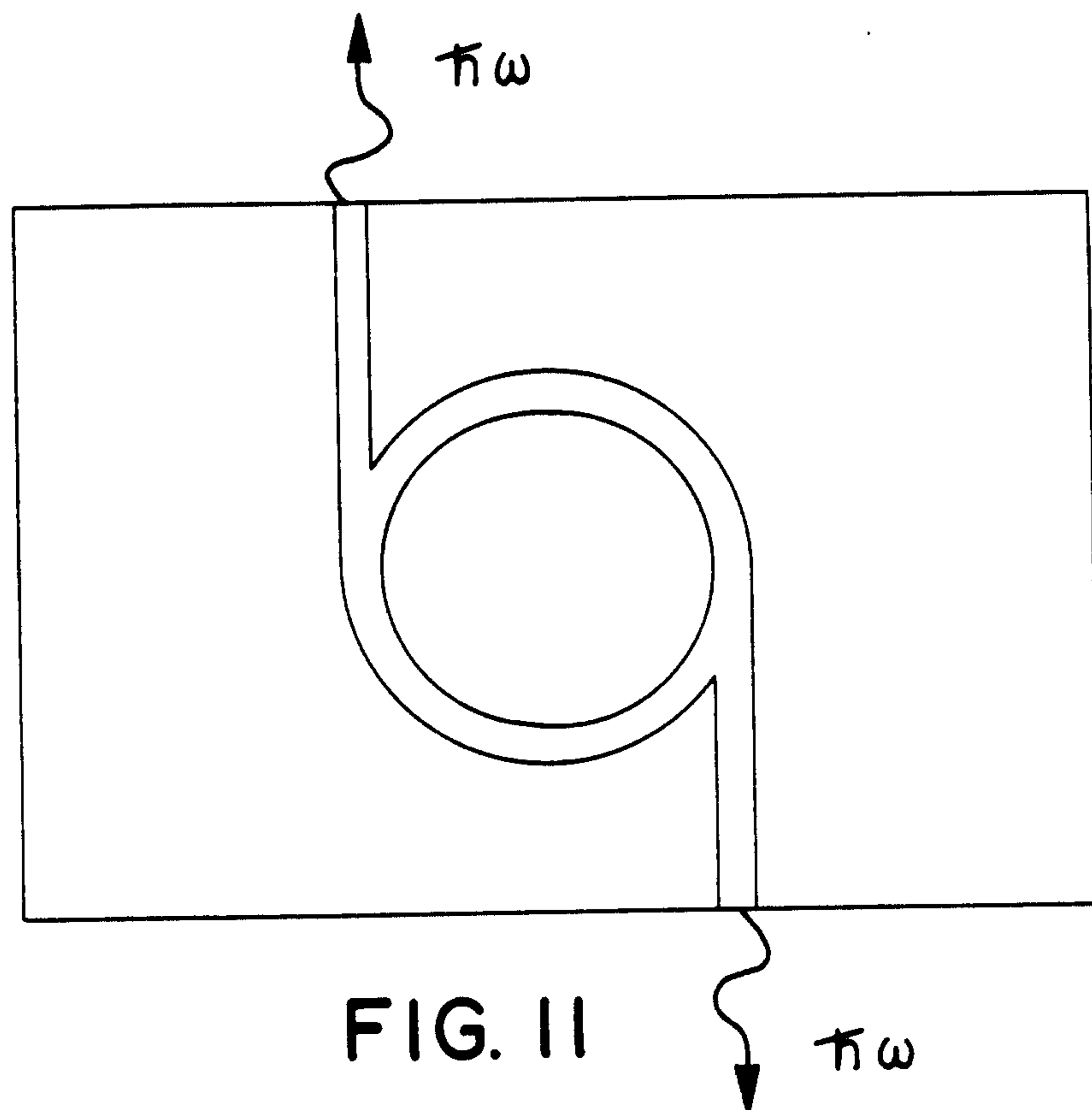
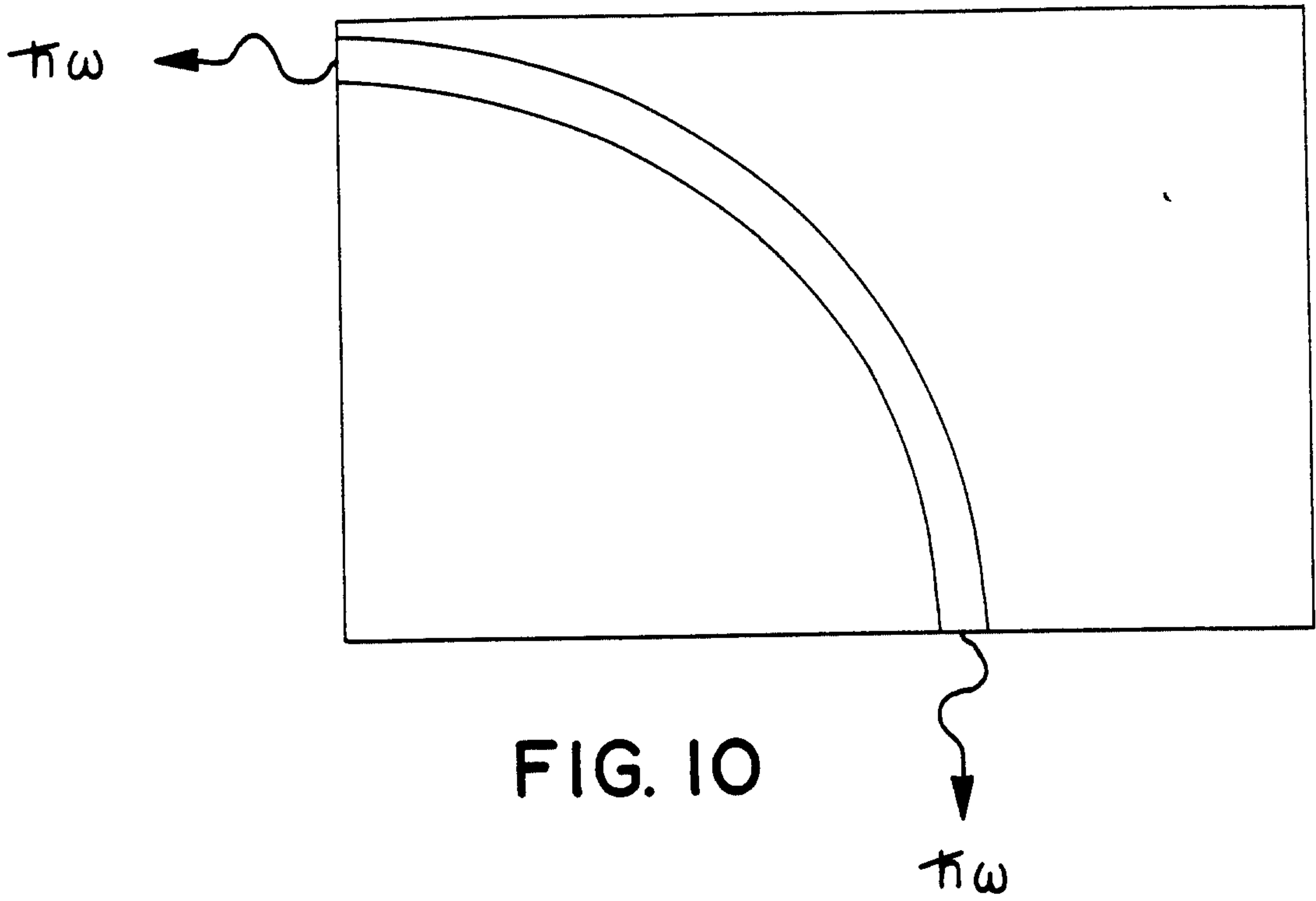


FIG. 9

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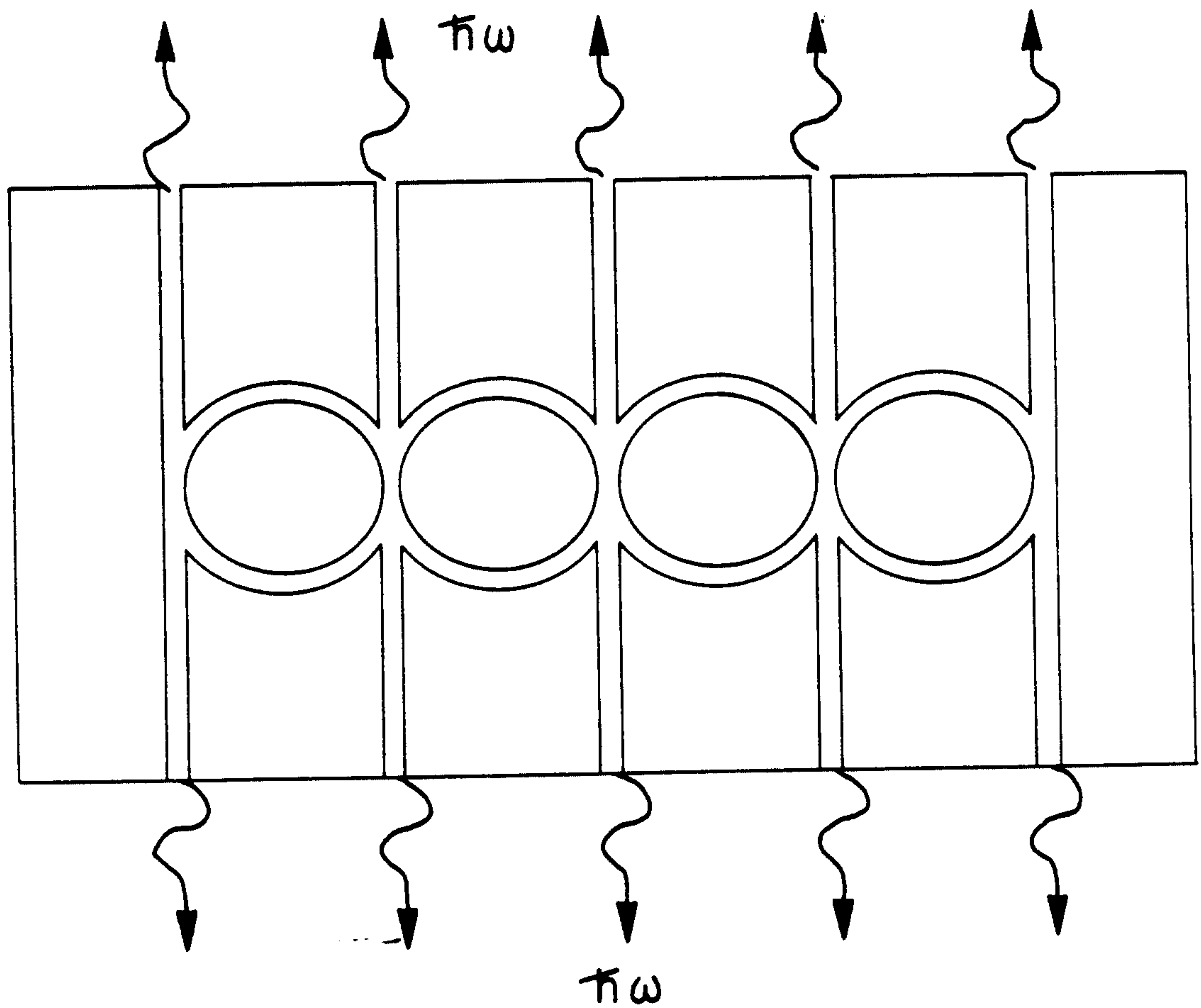
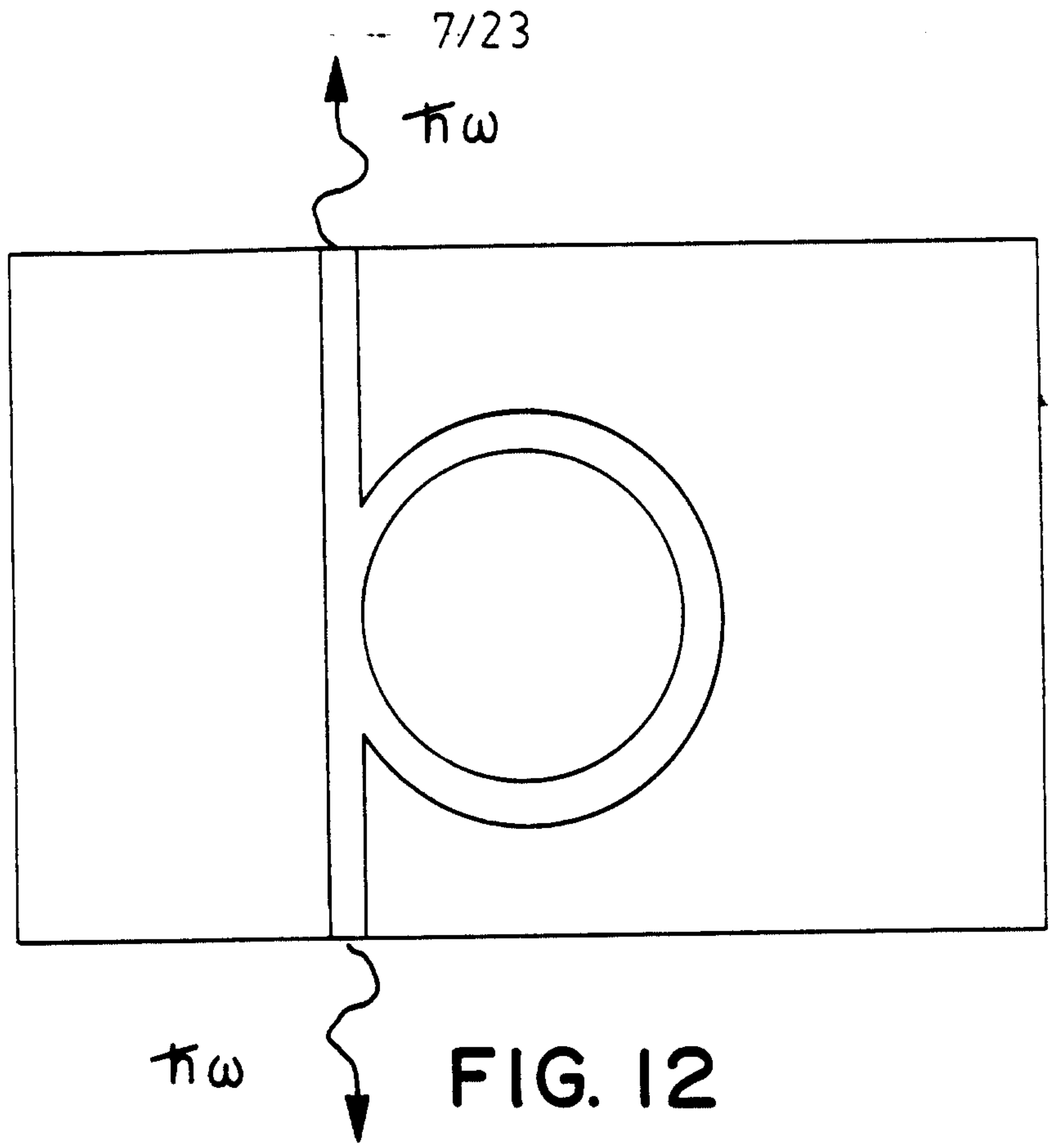
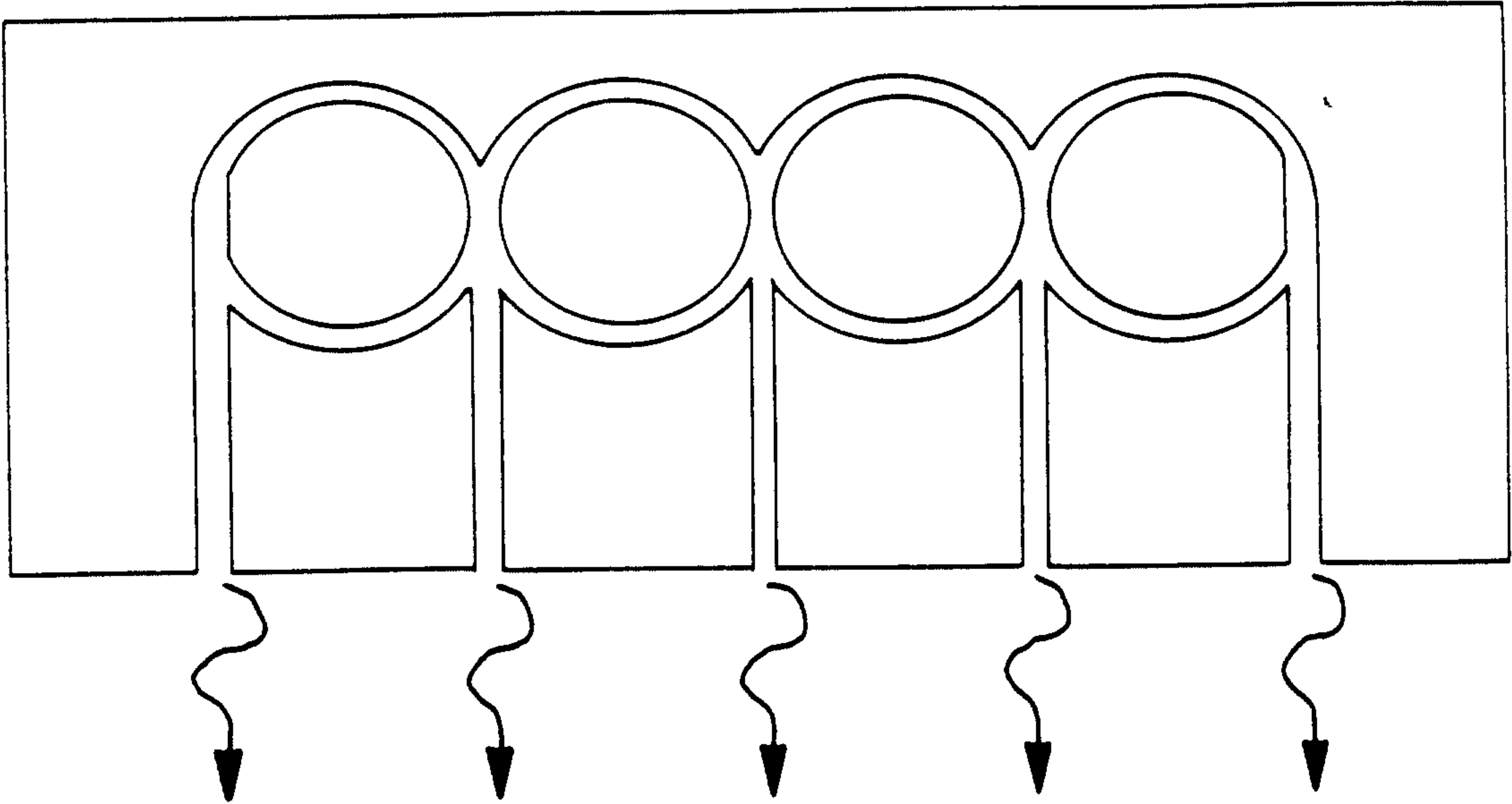
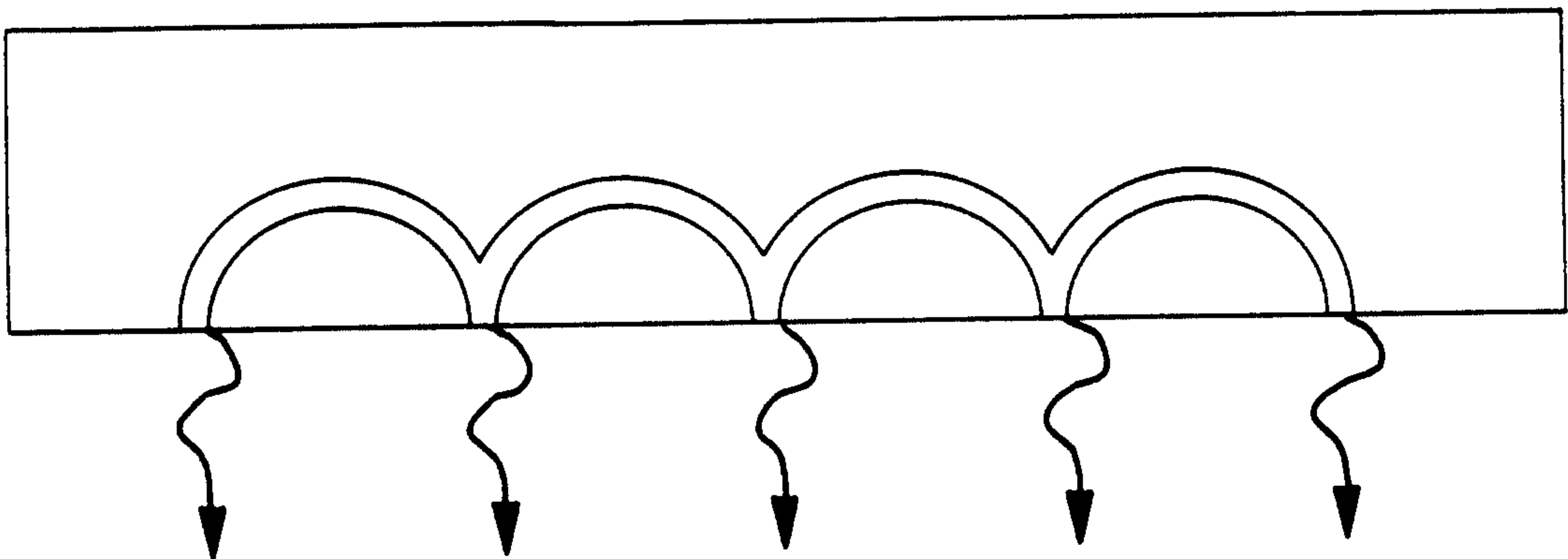


FIG. 13

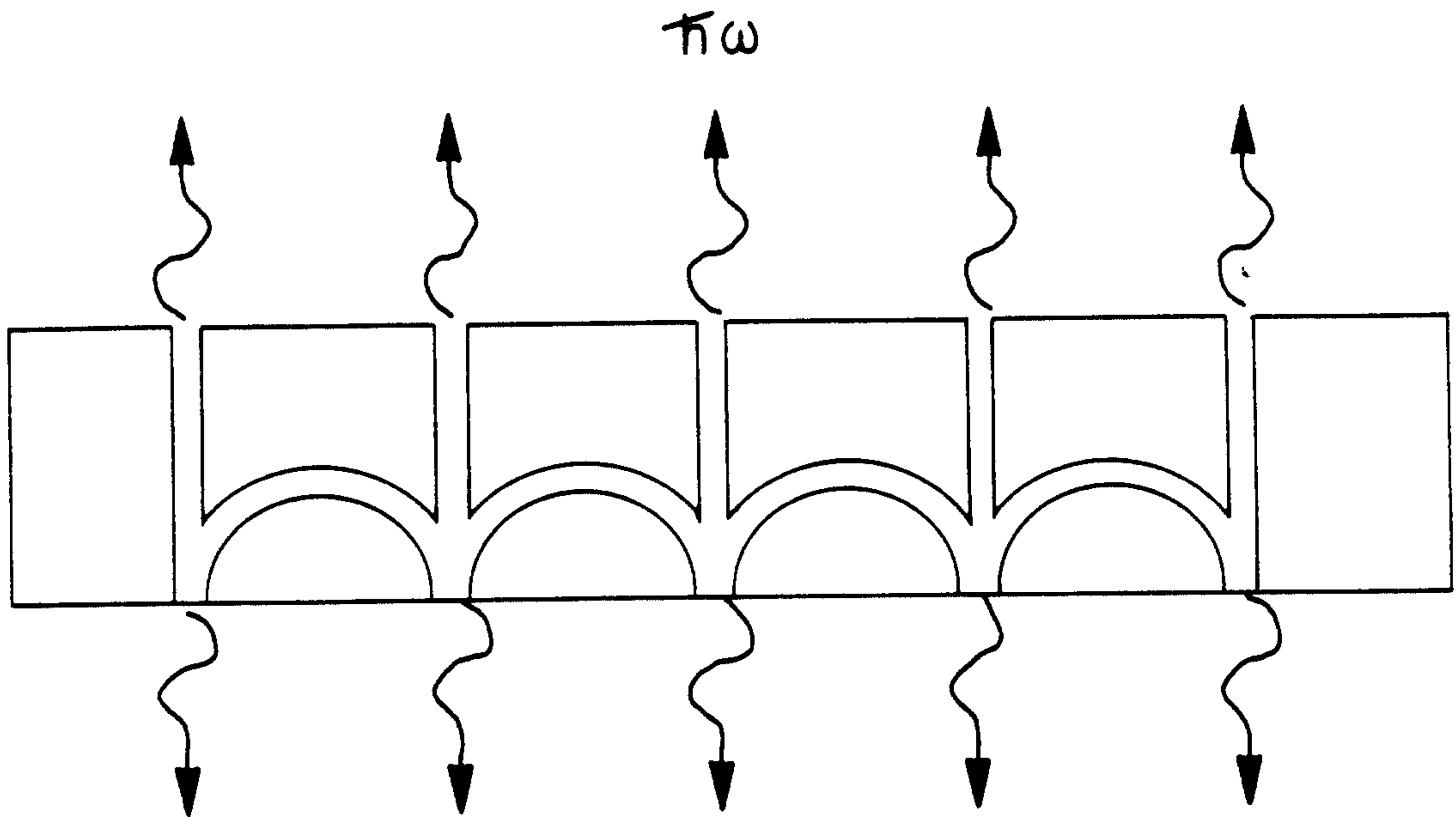


$\pi\omega$
FIG. 14

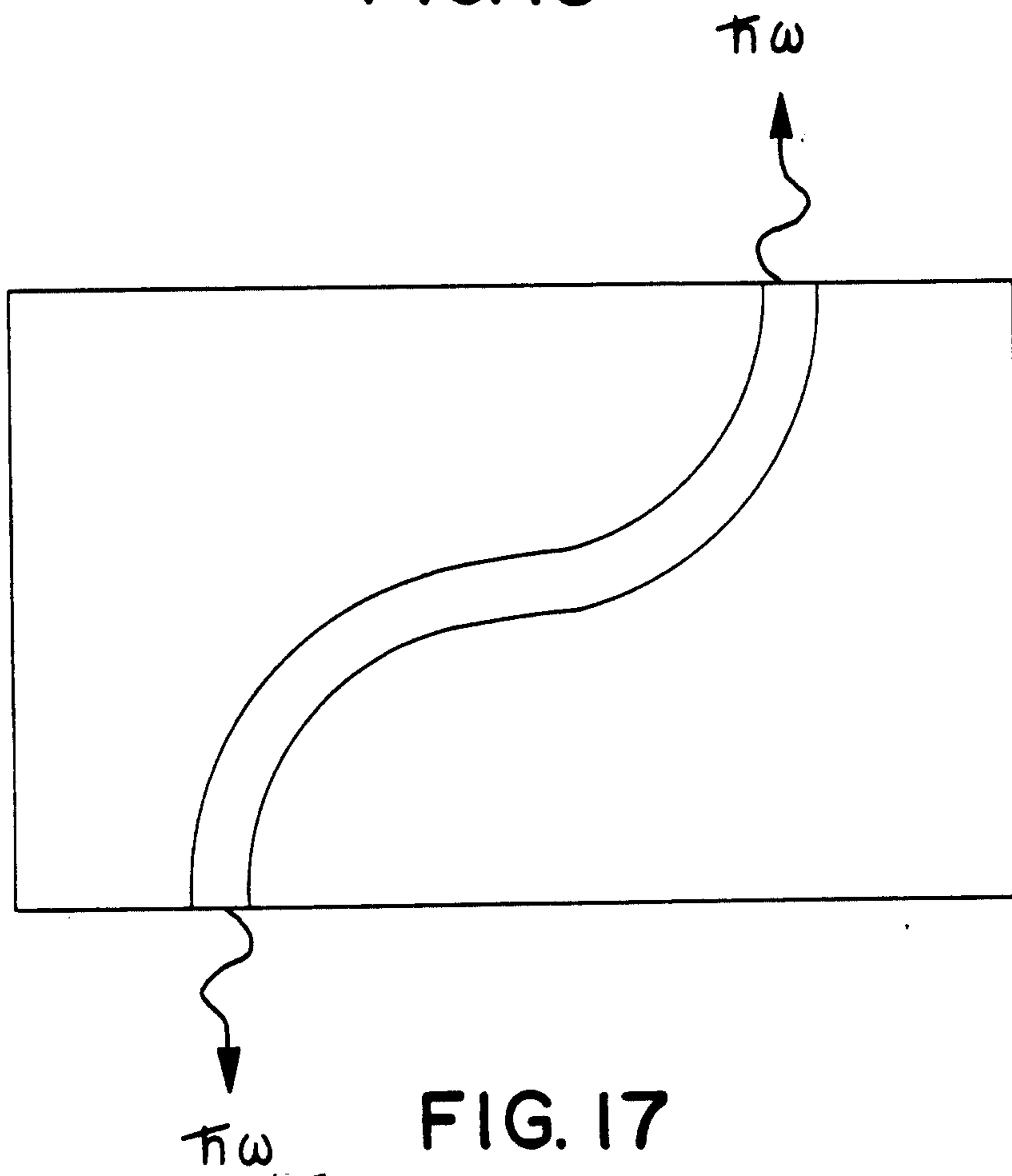


$\pi\omega$
FIG. 15

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$\pi\omega$
FIG. 16



$\pi\omega$
FIG. 17

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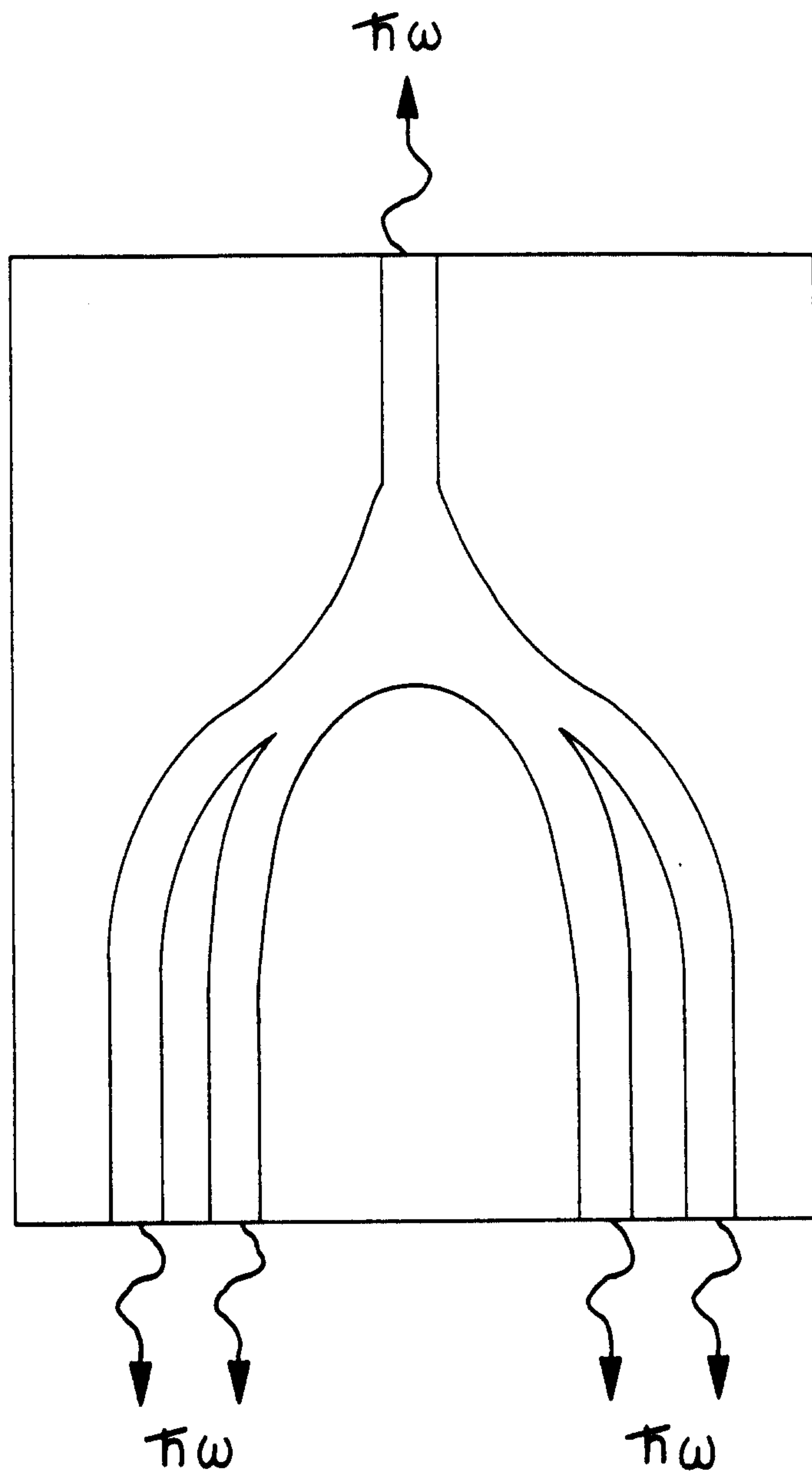


FIG. 18

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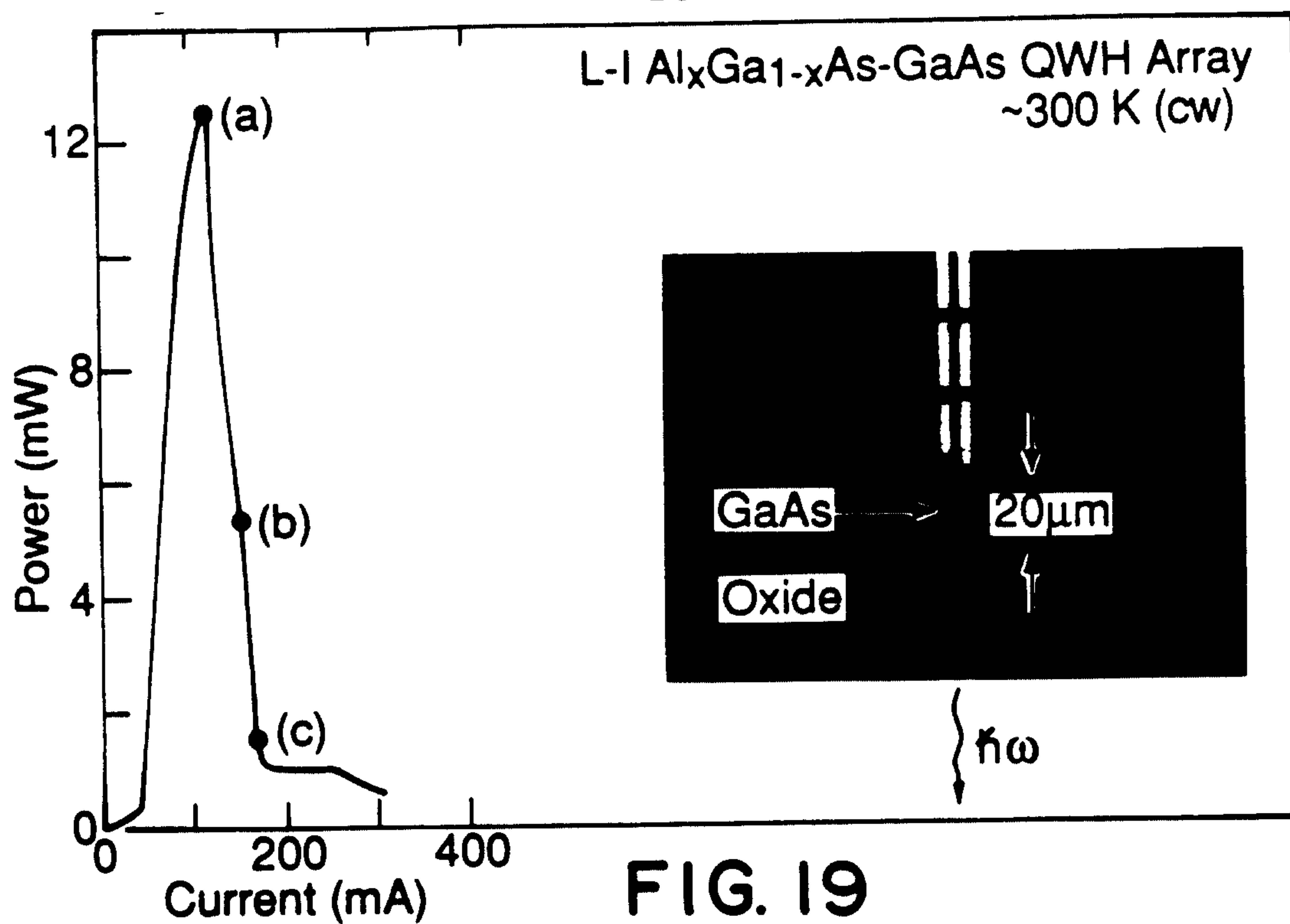


FIG. 19

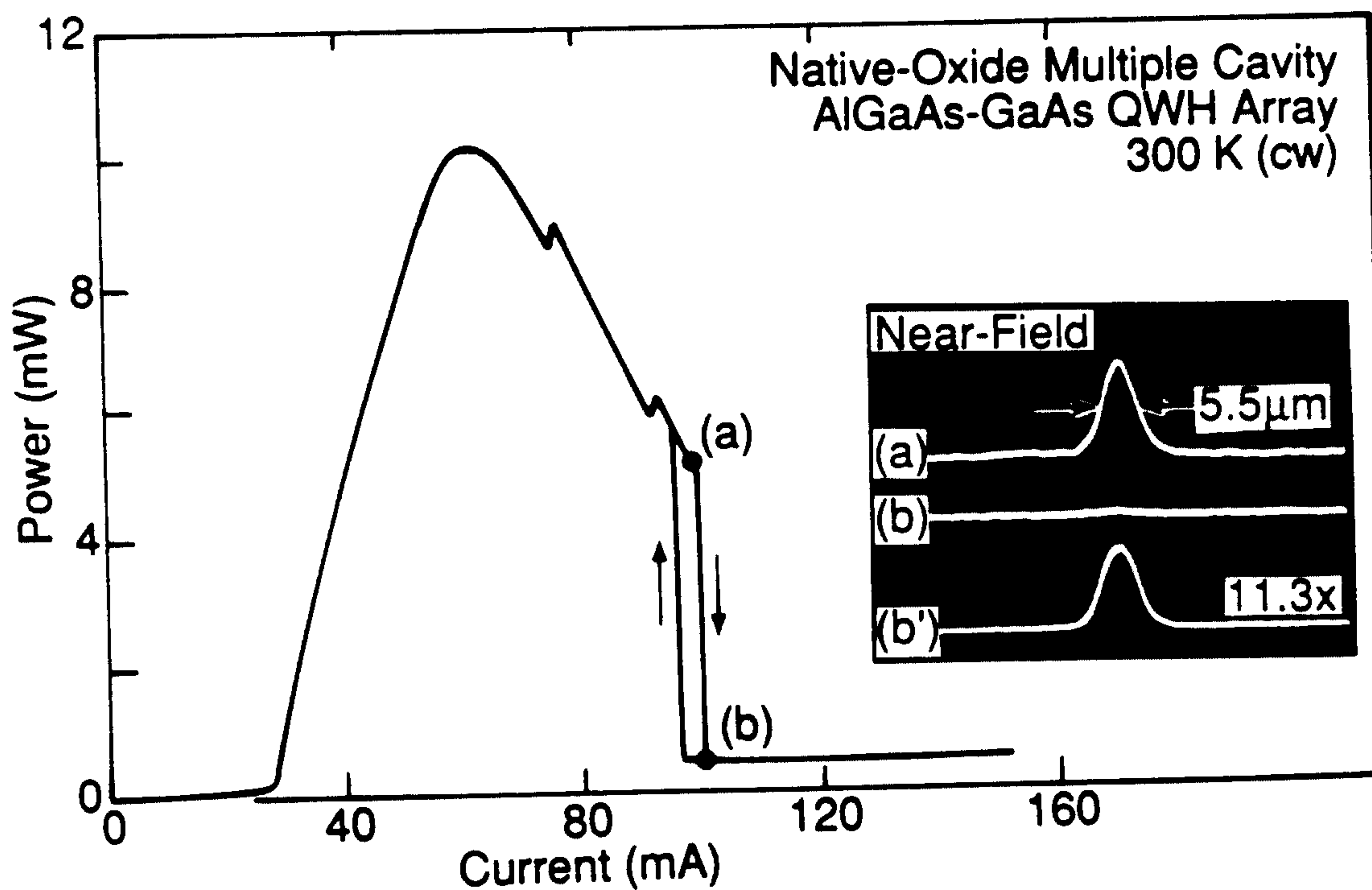


FIG. 24

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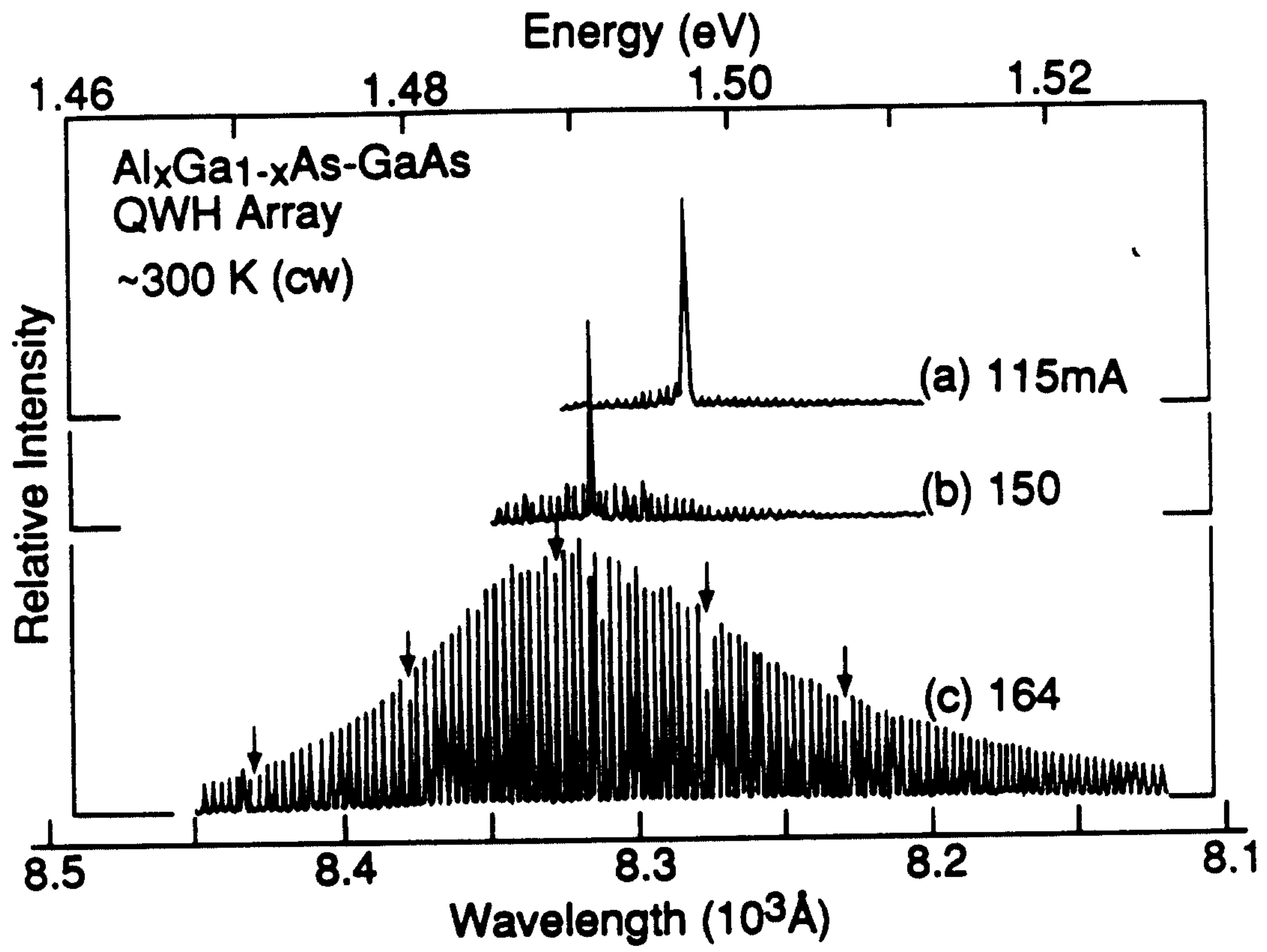


FIG. 20

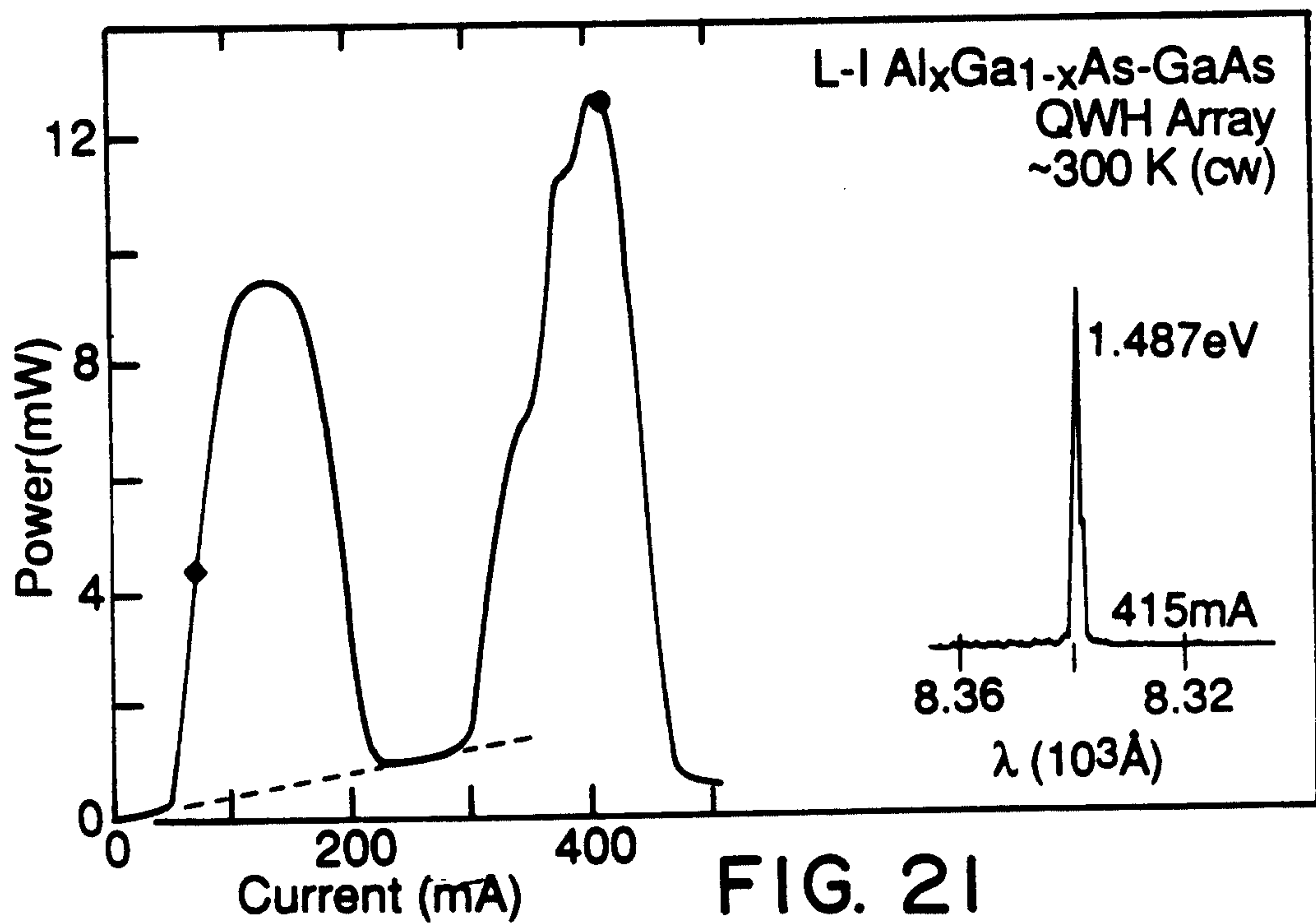


FIG. 21

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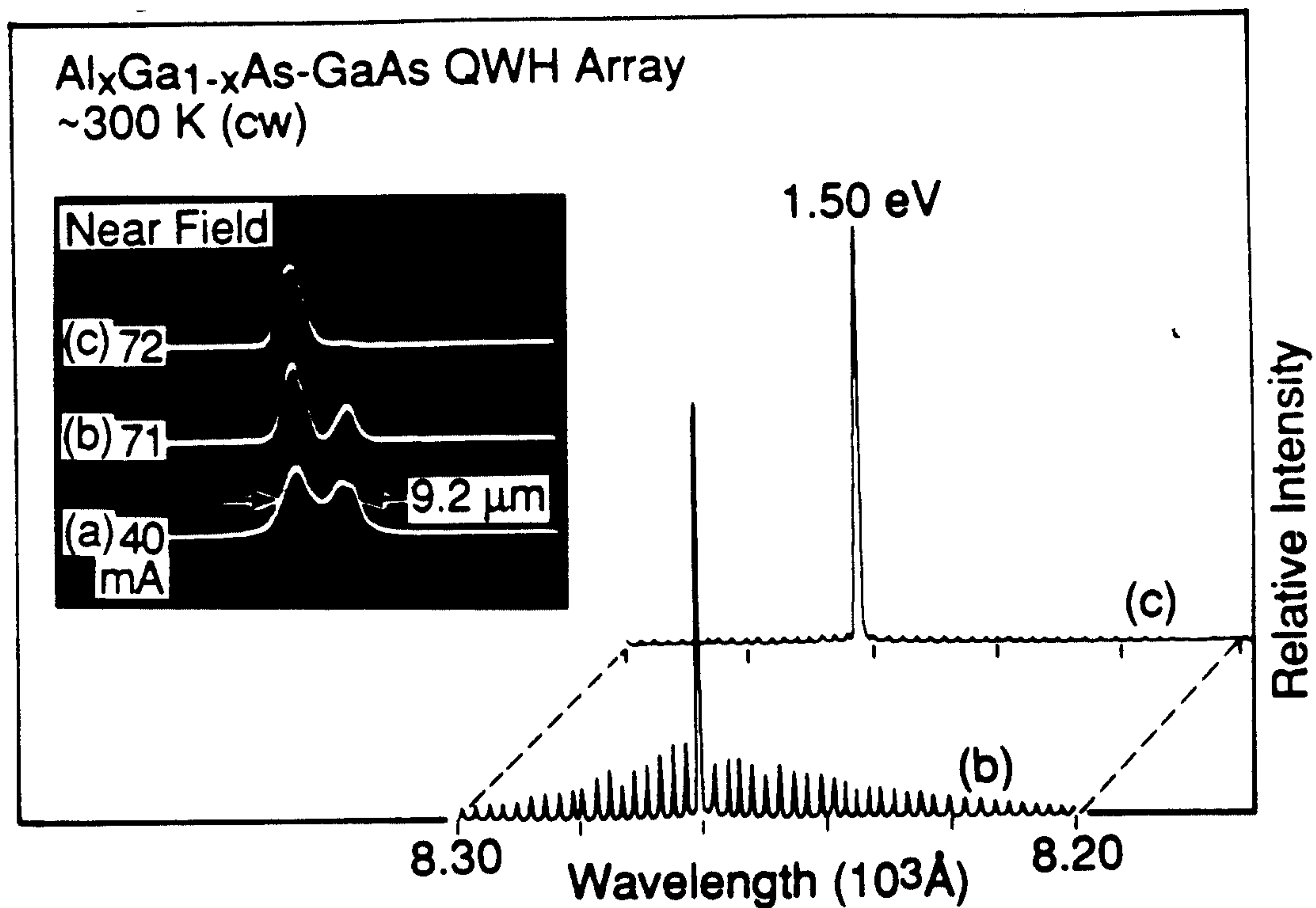


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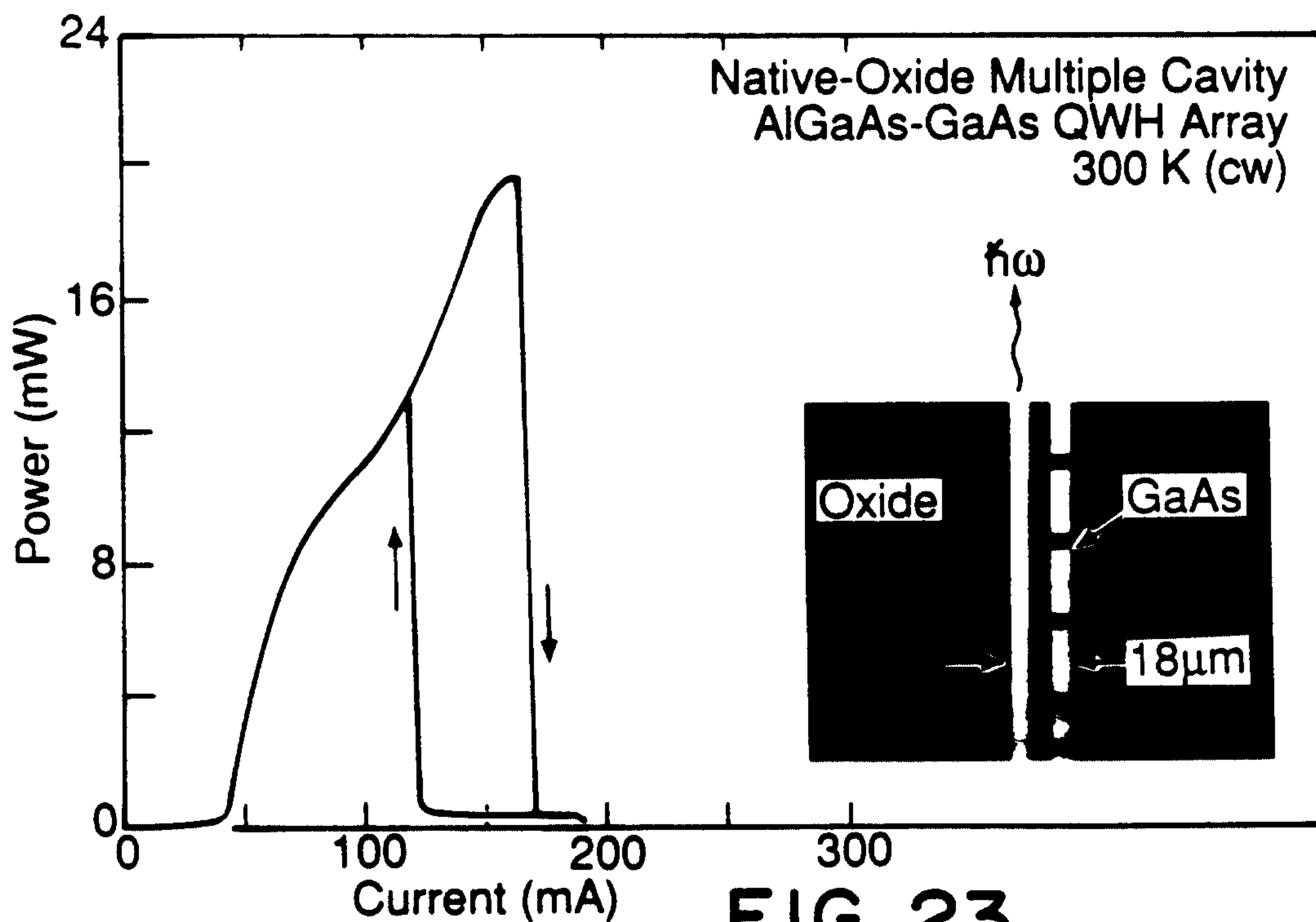


FIG. 23

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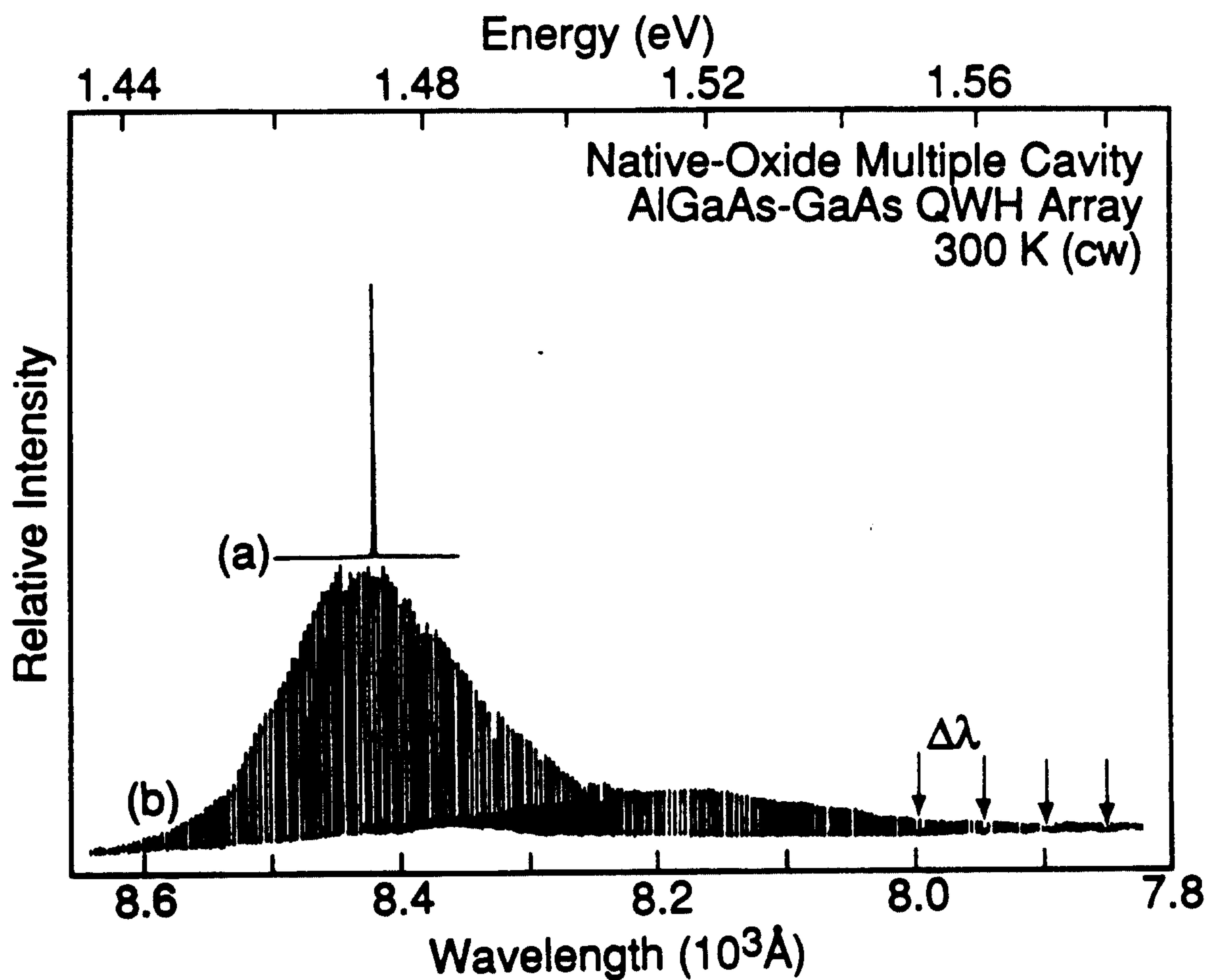


FIG. 25

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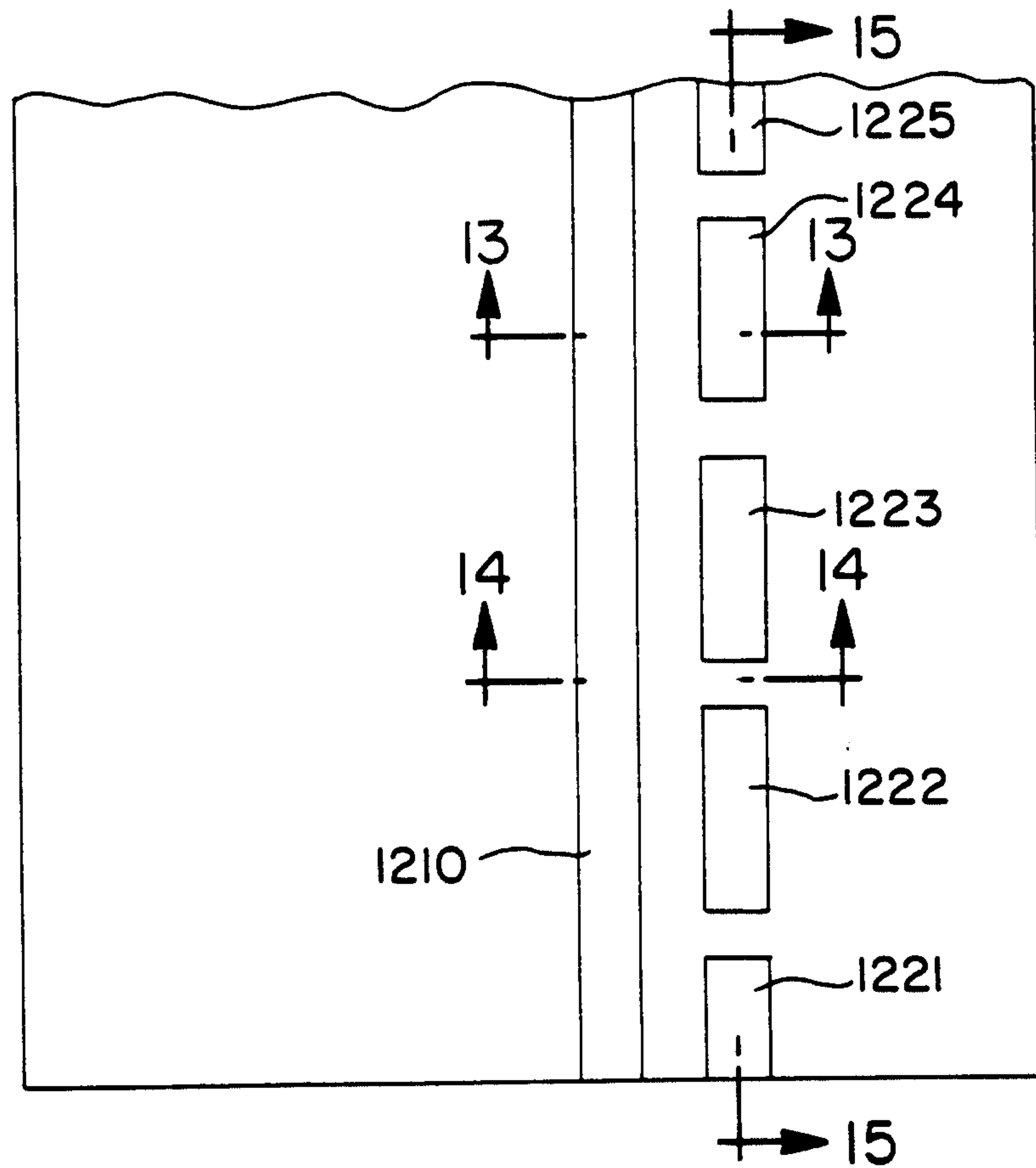


FIG. 26

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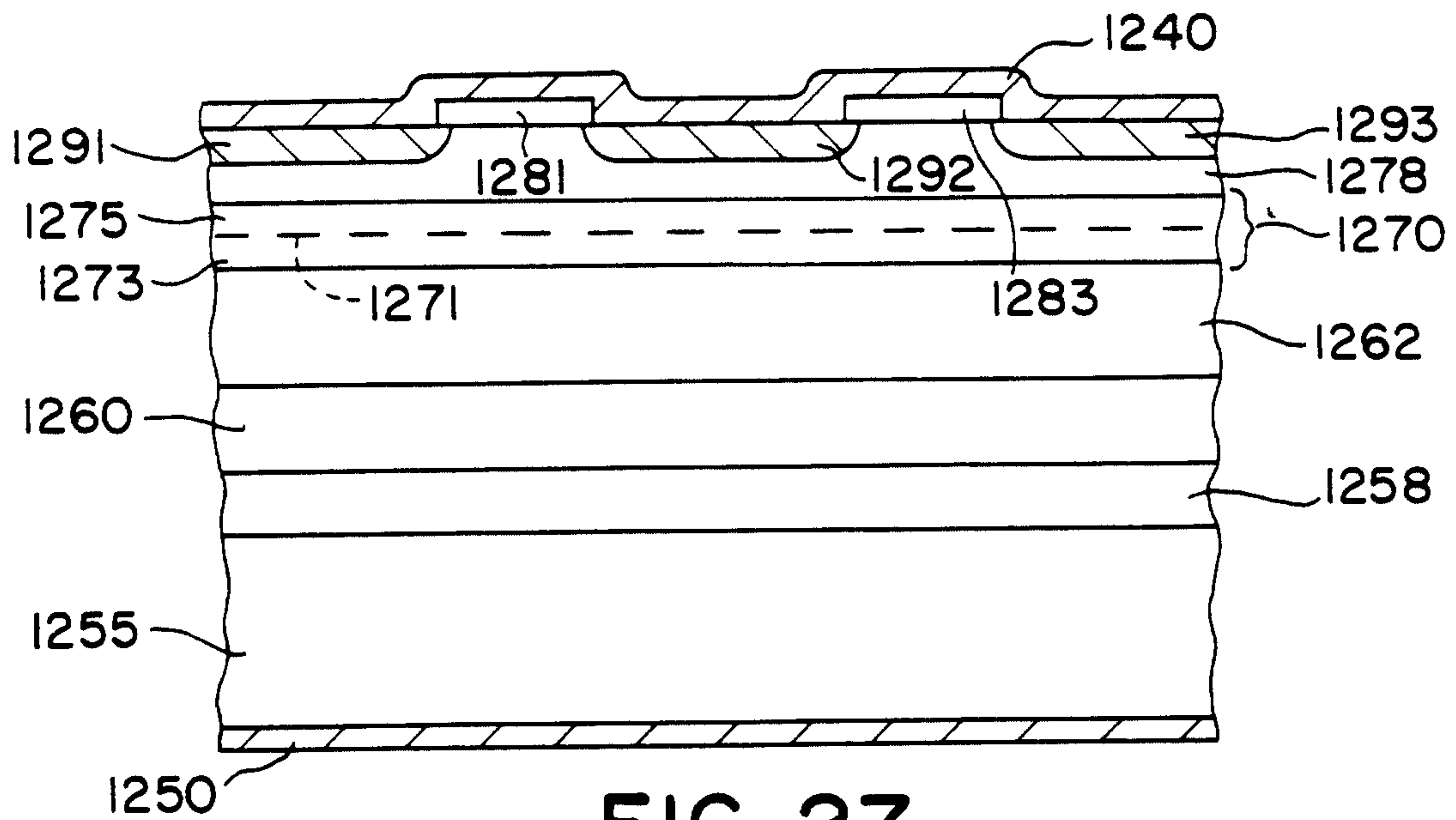


FIG. 27

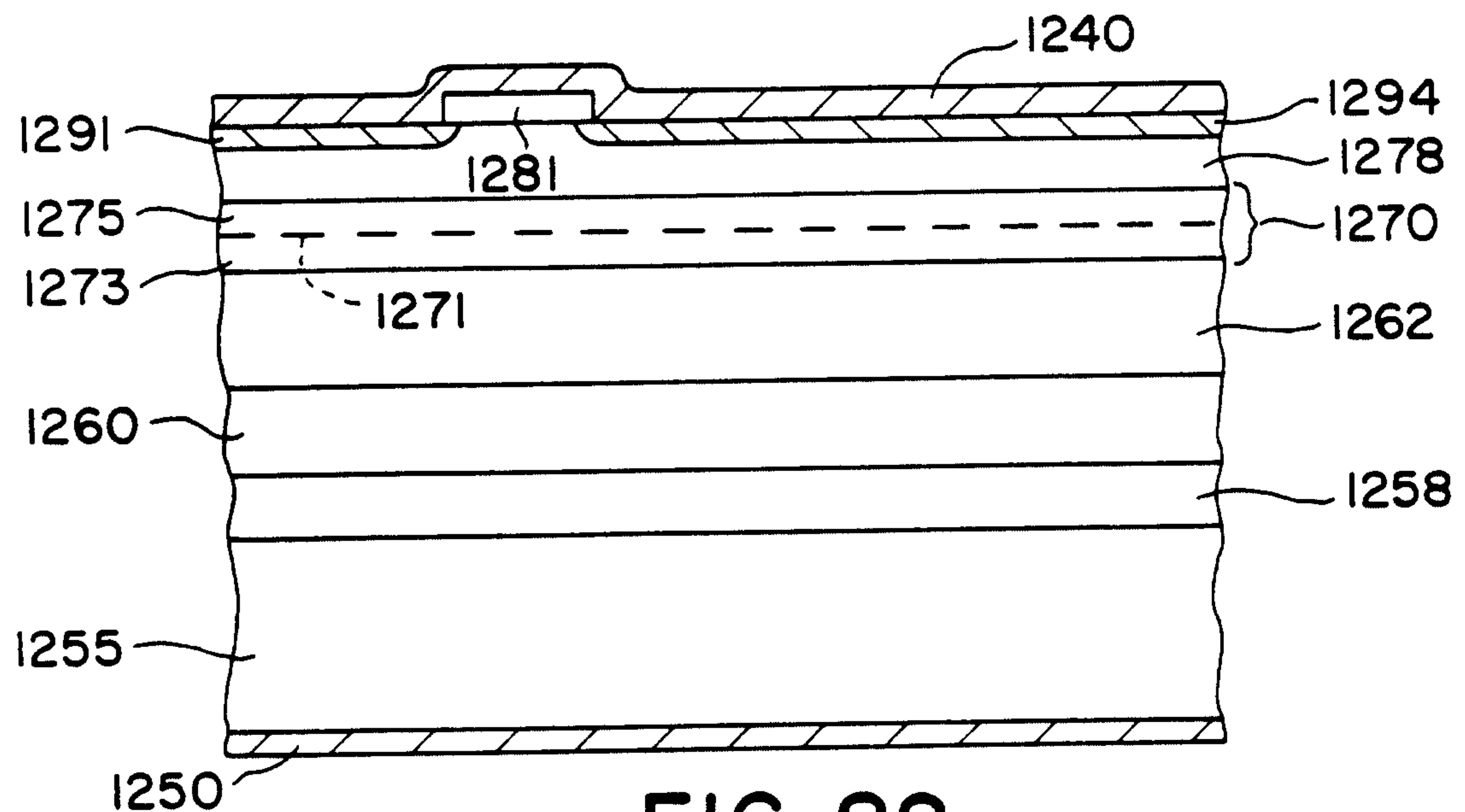


FIG. 28

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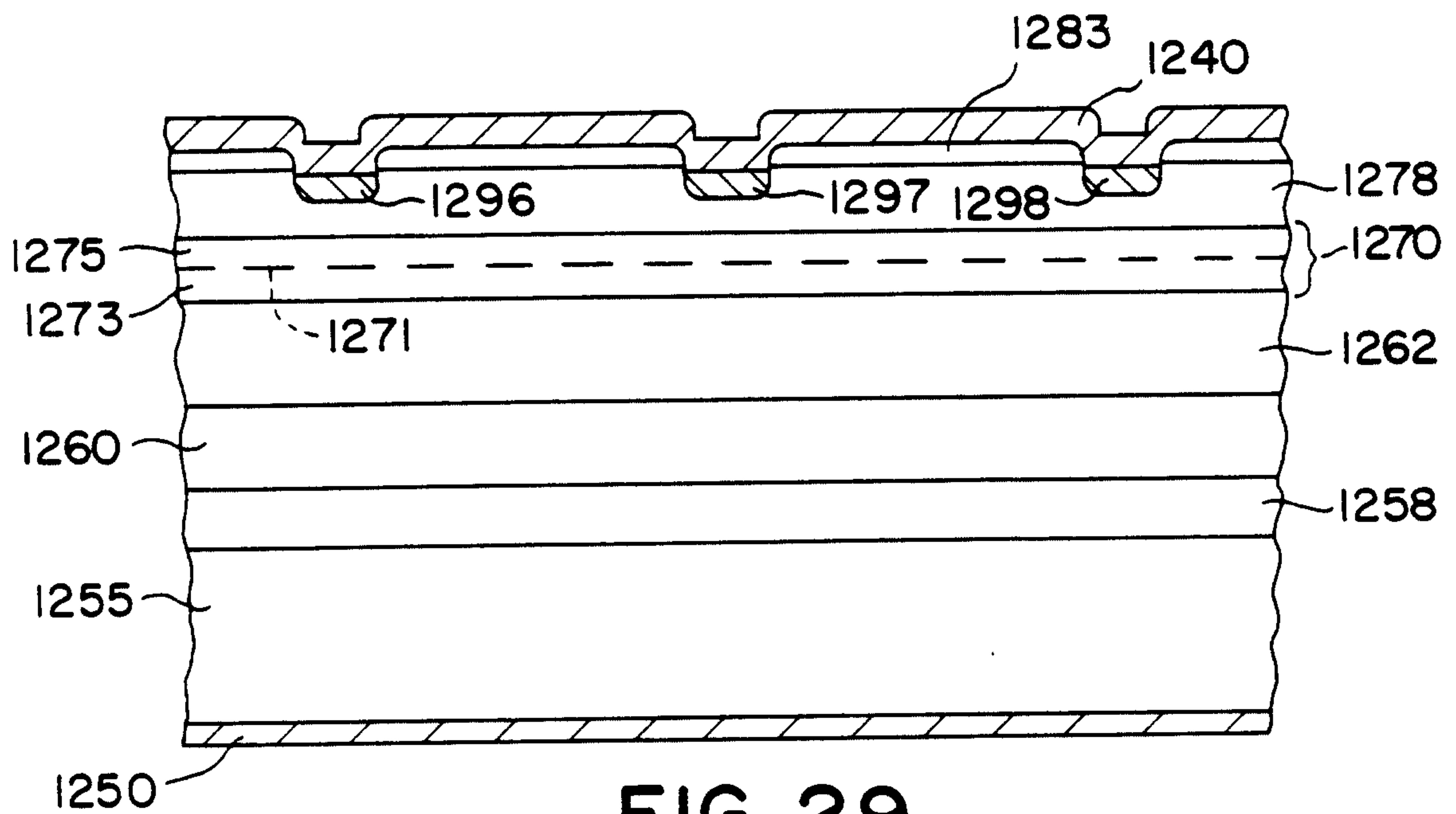


FIG. 29

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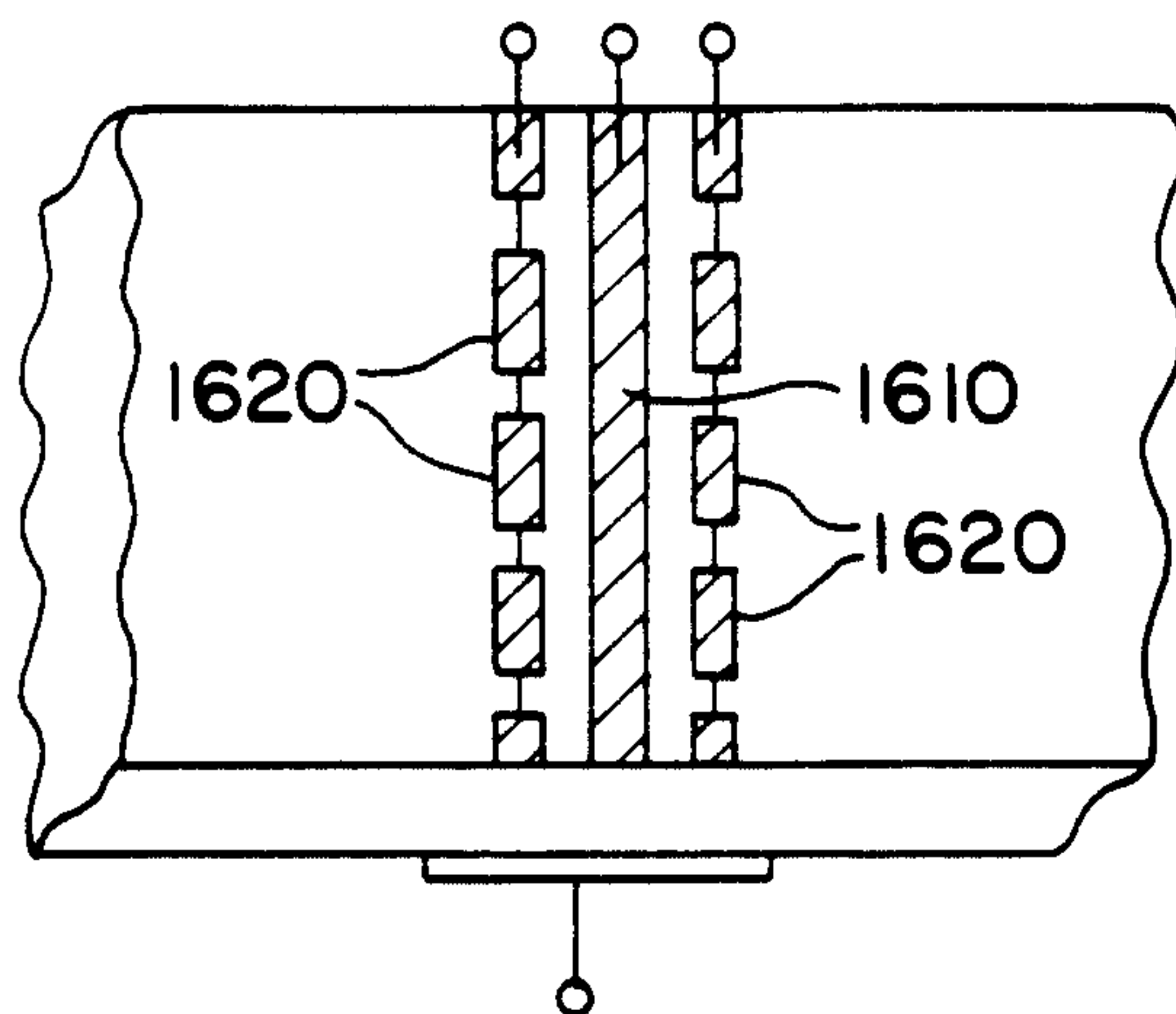


FIG. 30

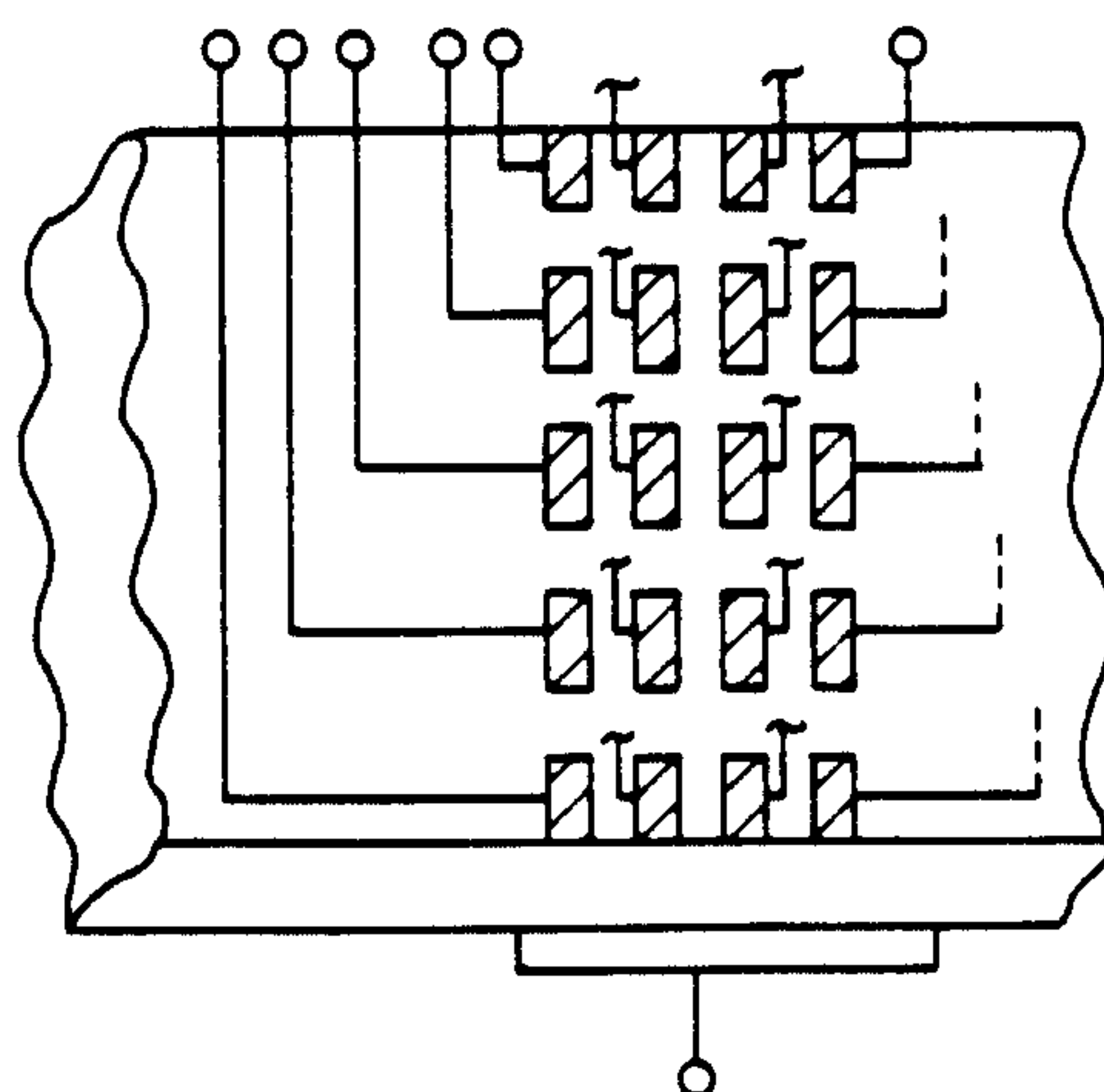


FIG. 31

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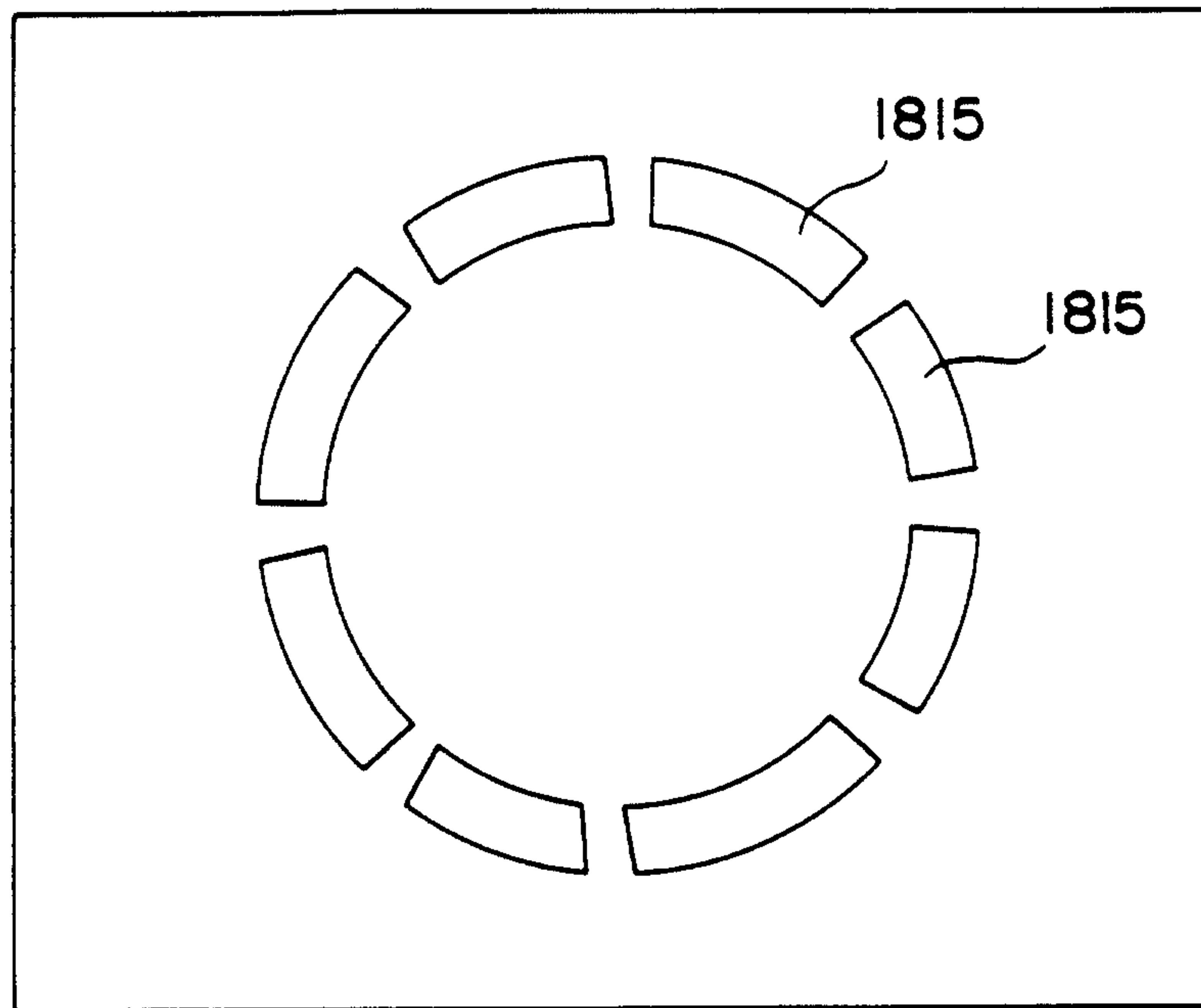


FIG. 32

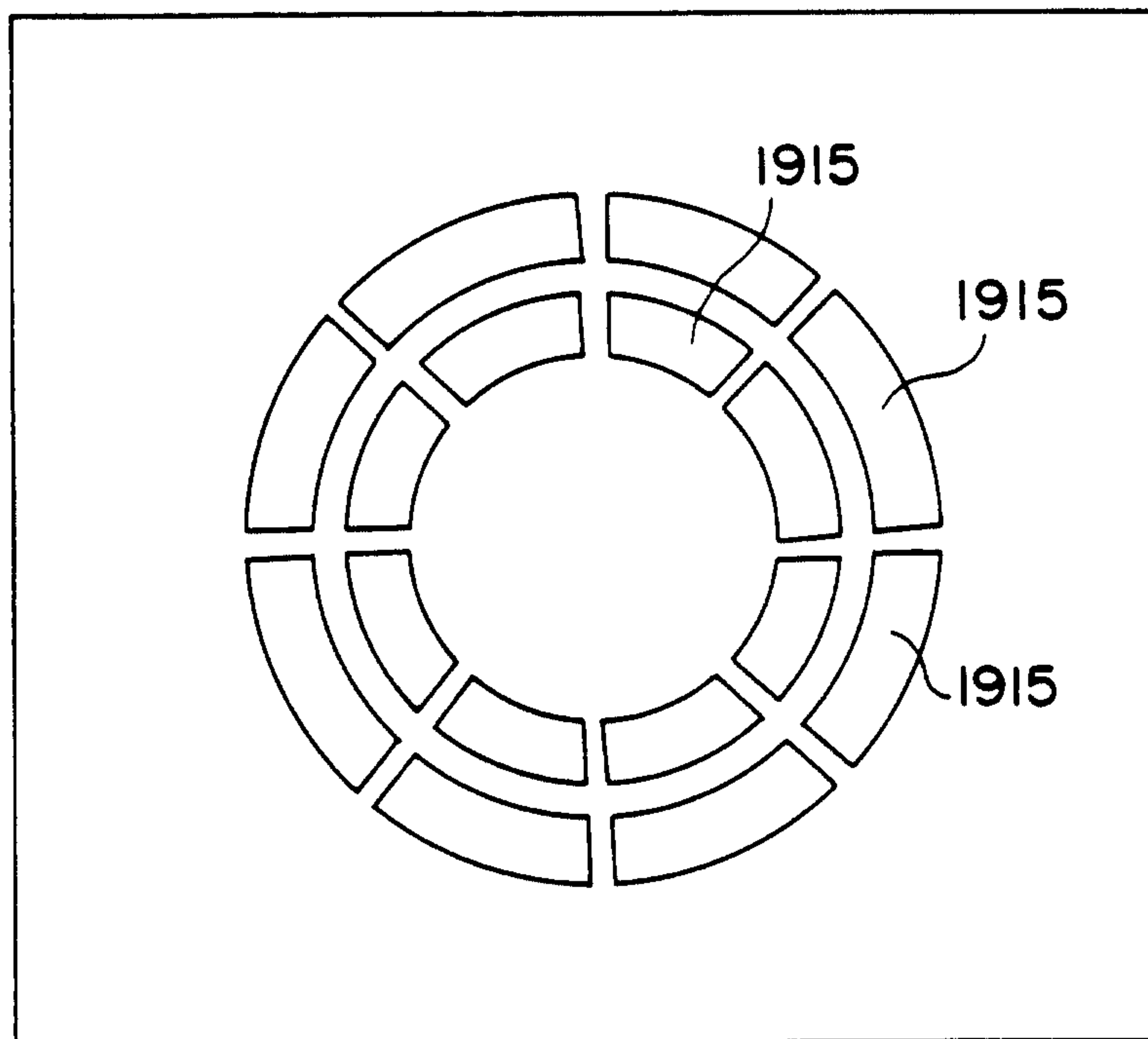


FIG. 33

SUBSTITUTE SHEET

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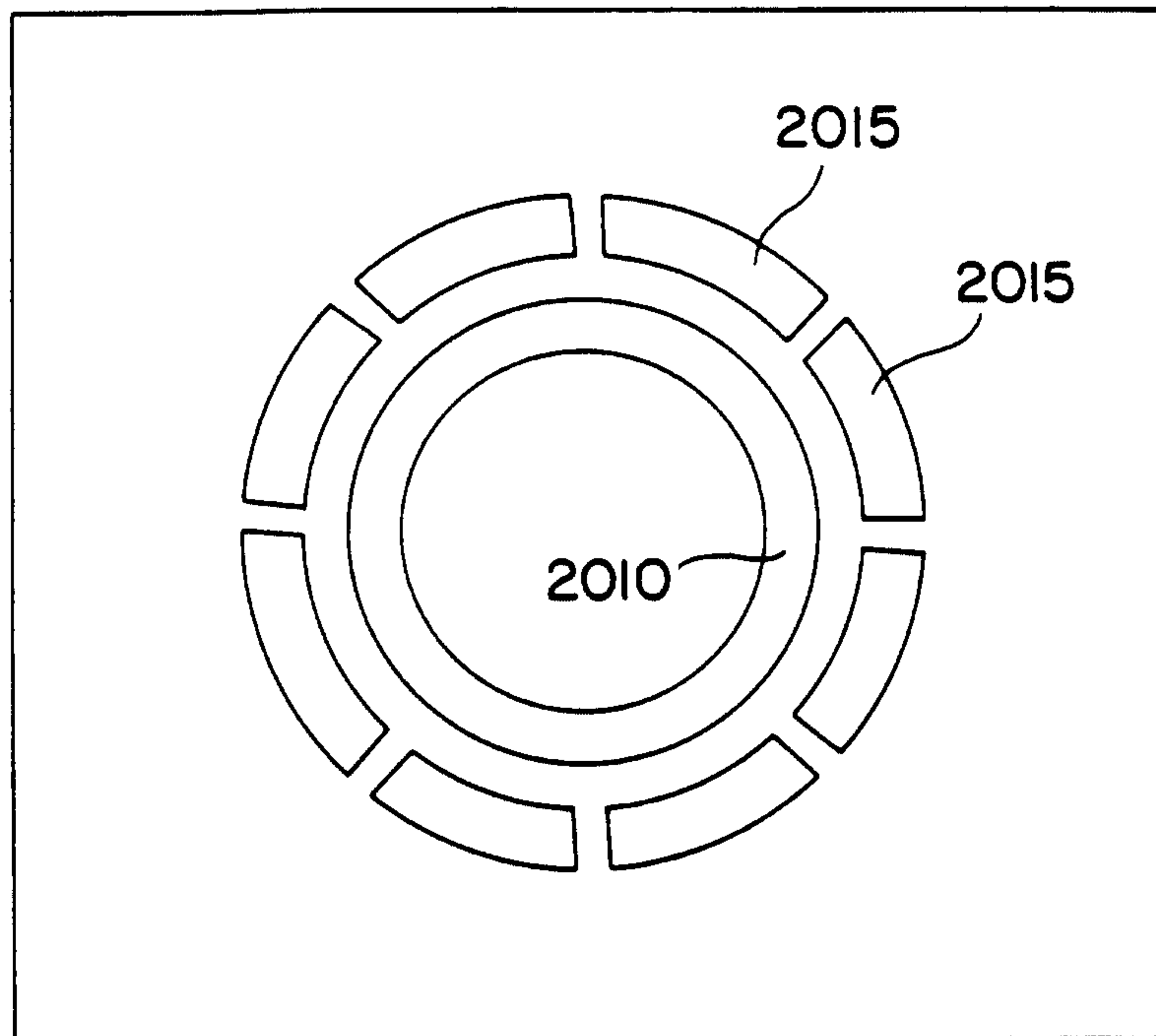


FIG. 34

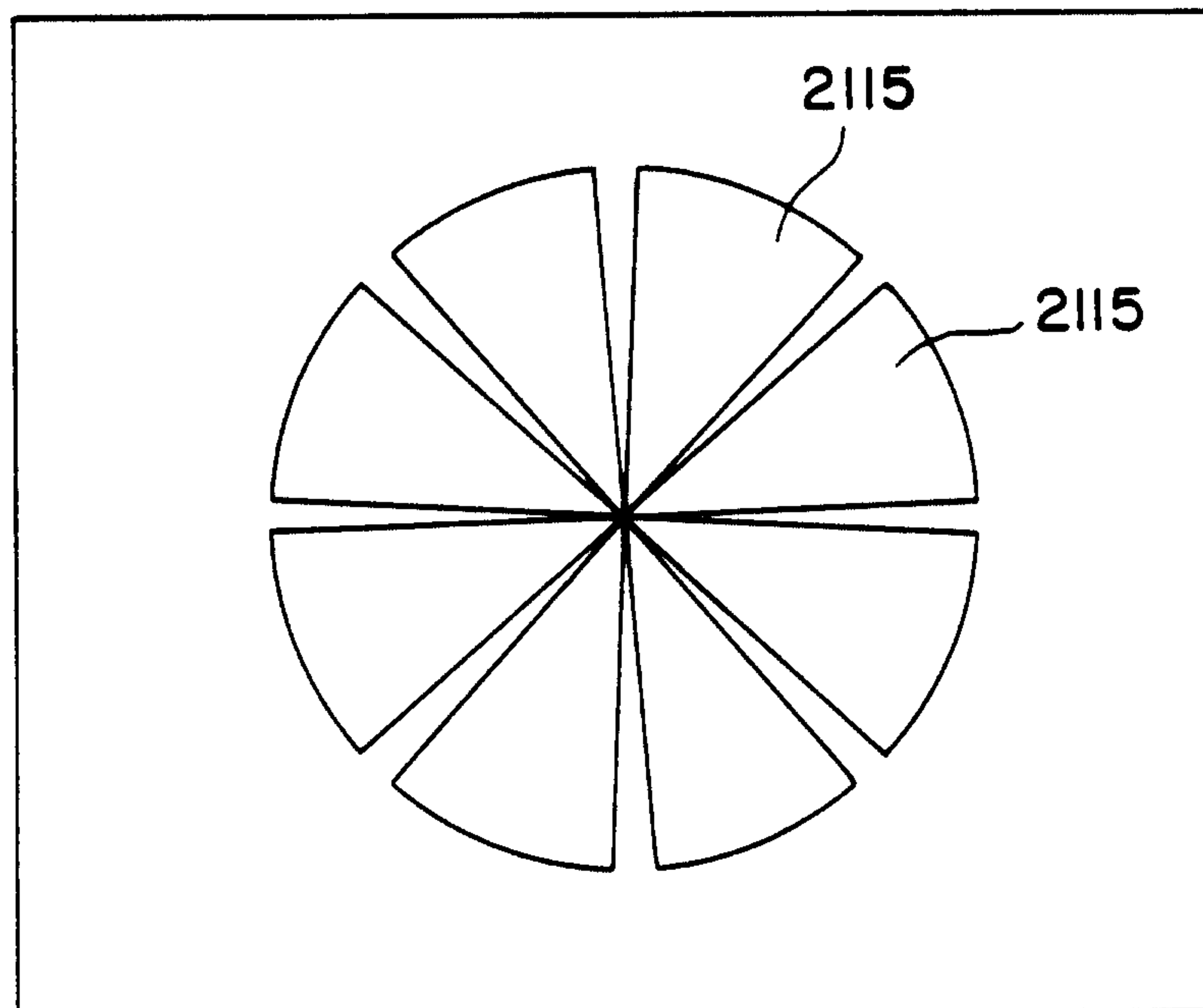


FIG. 35

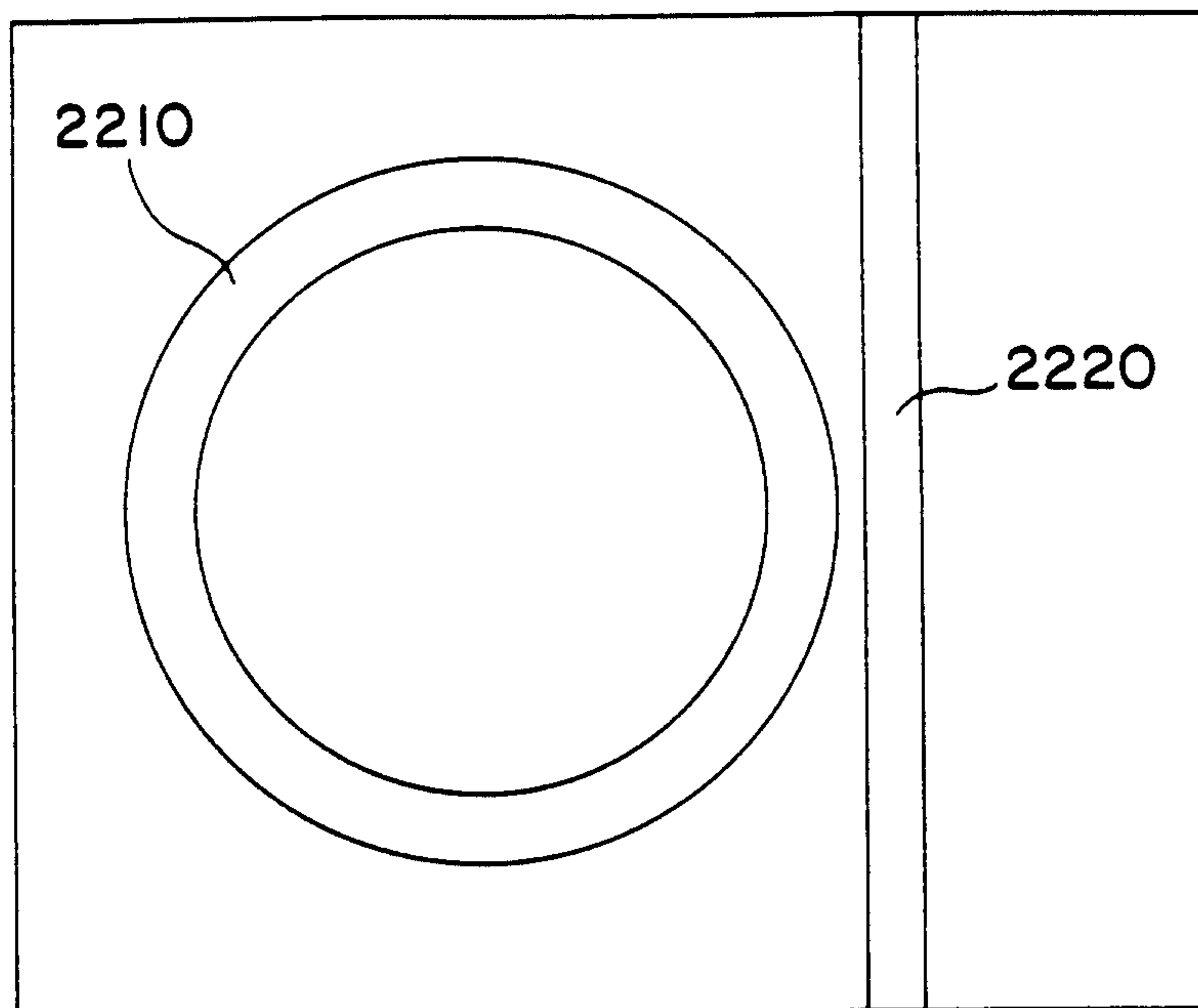


FIG. 36

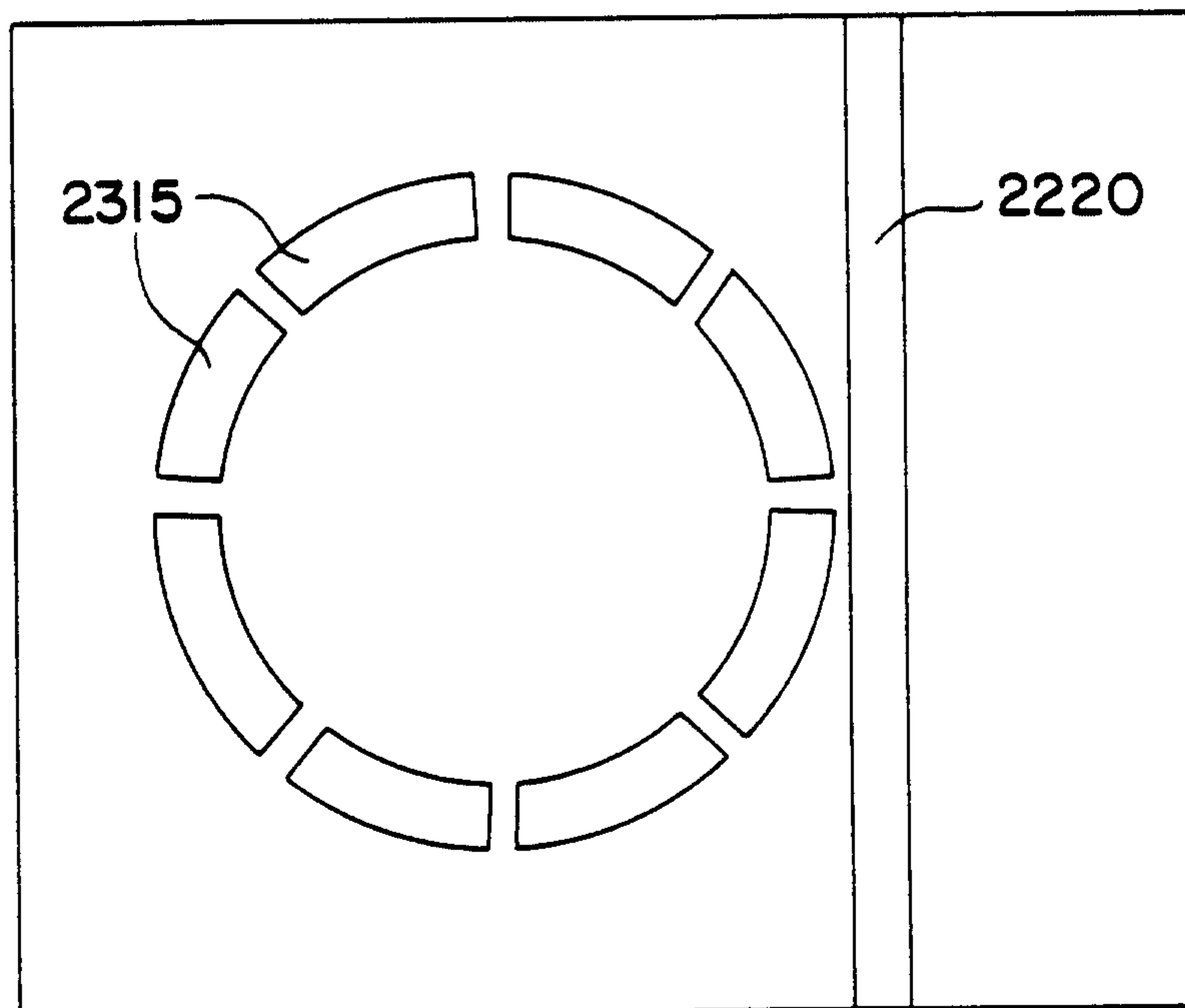


FIG. 37

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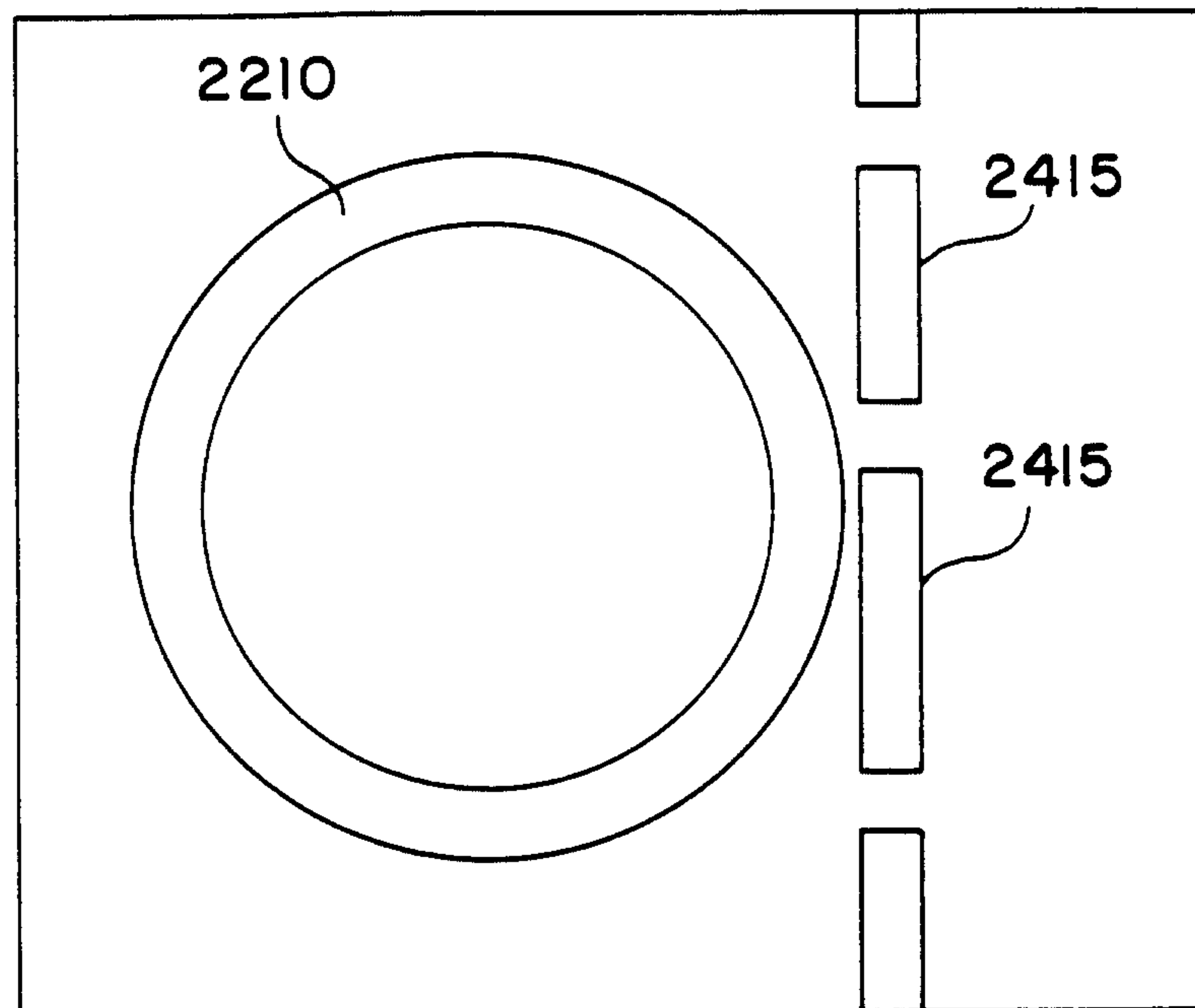


FIG. 38

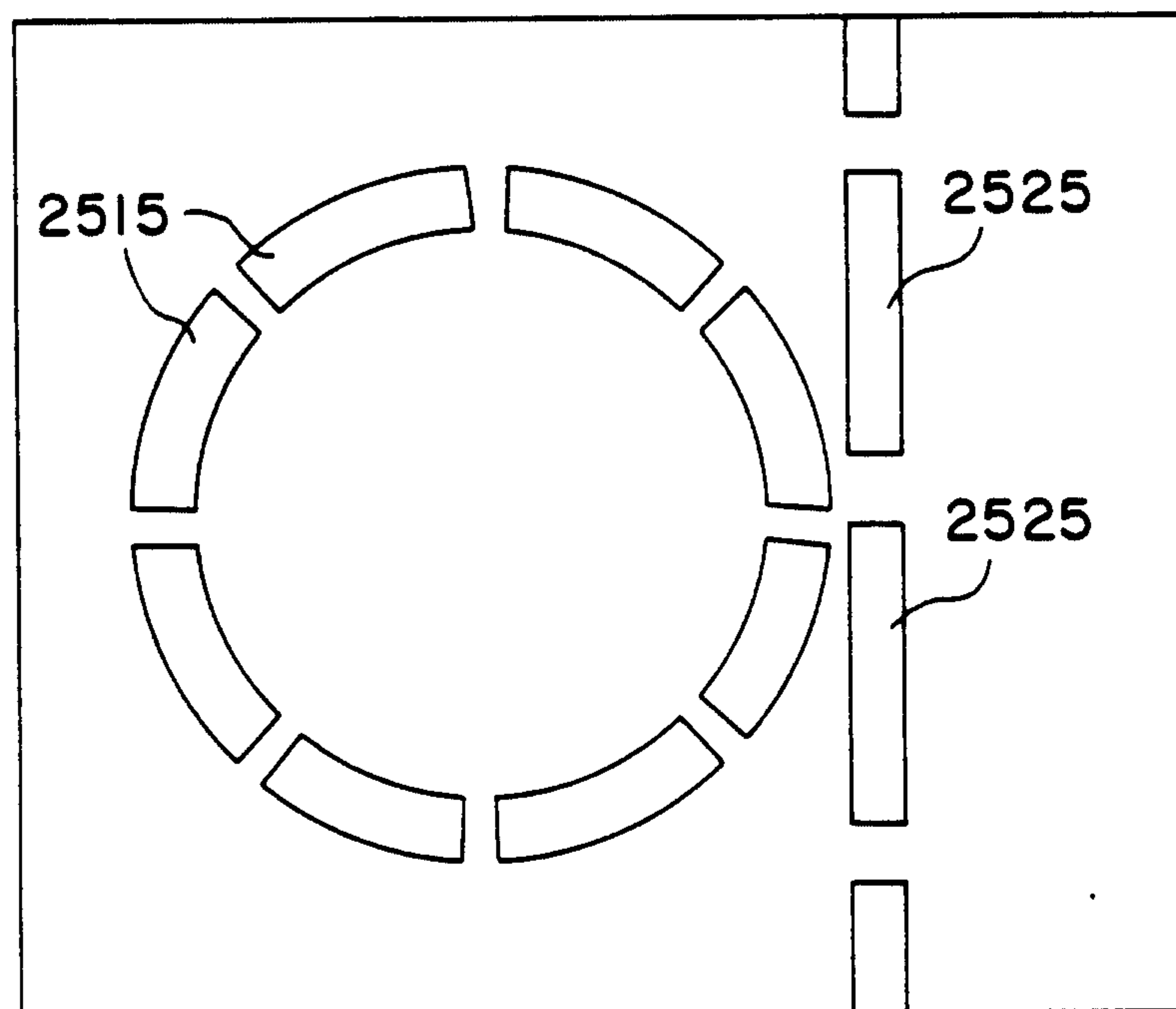


FIG. 39

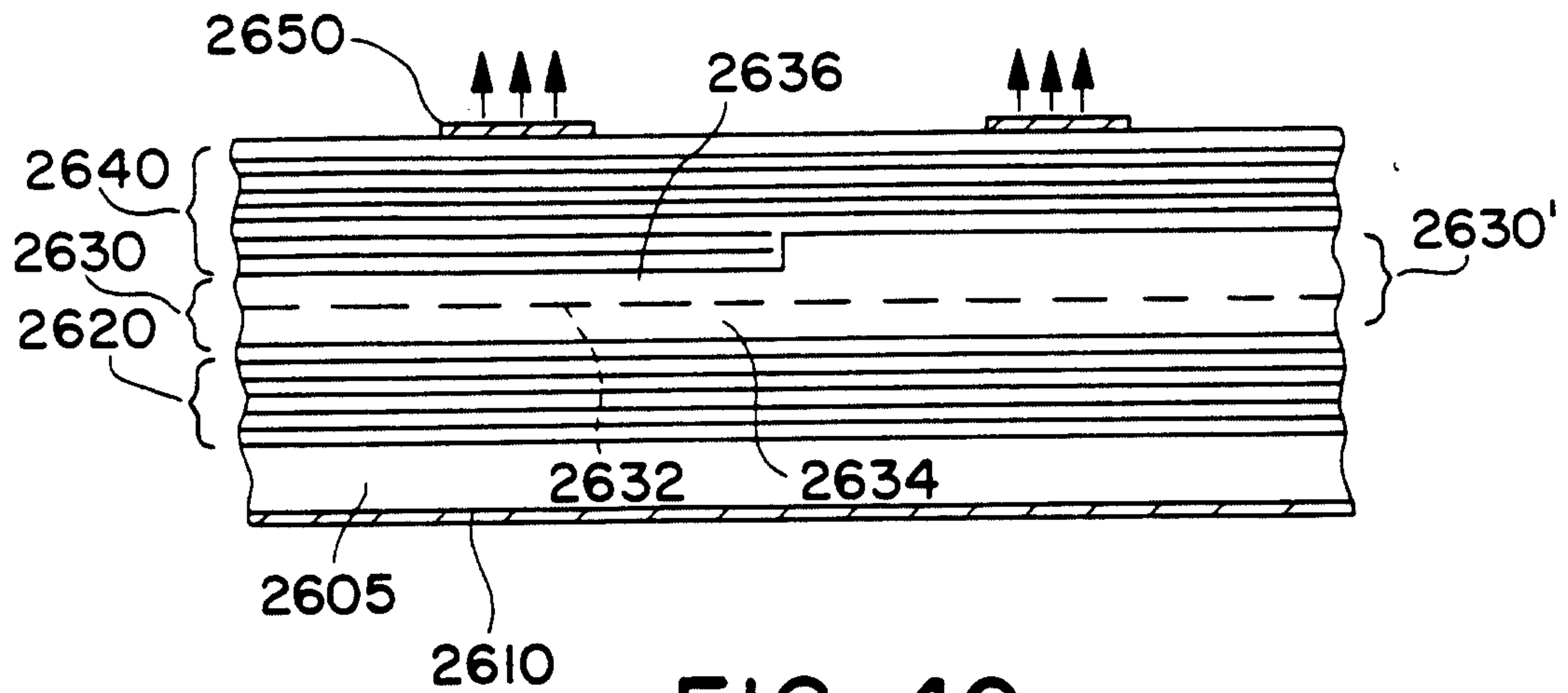


FIG. 40

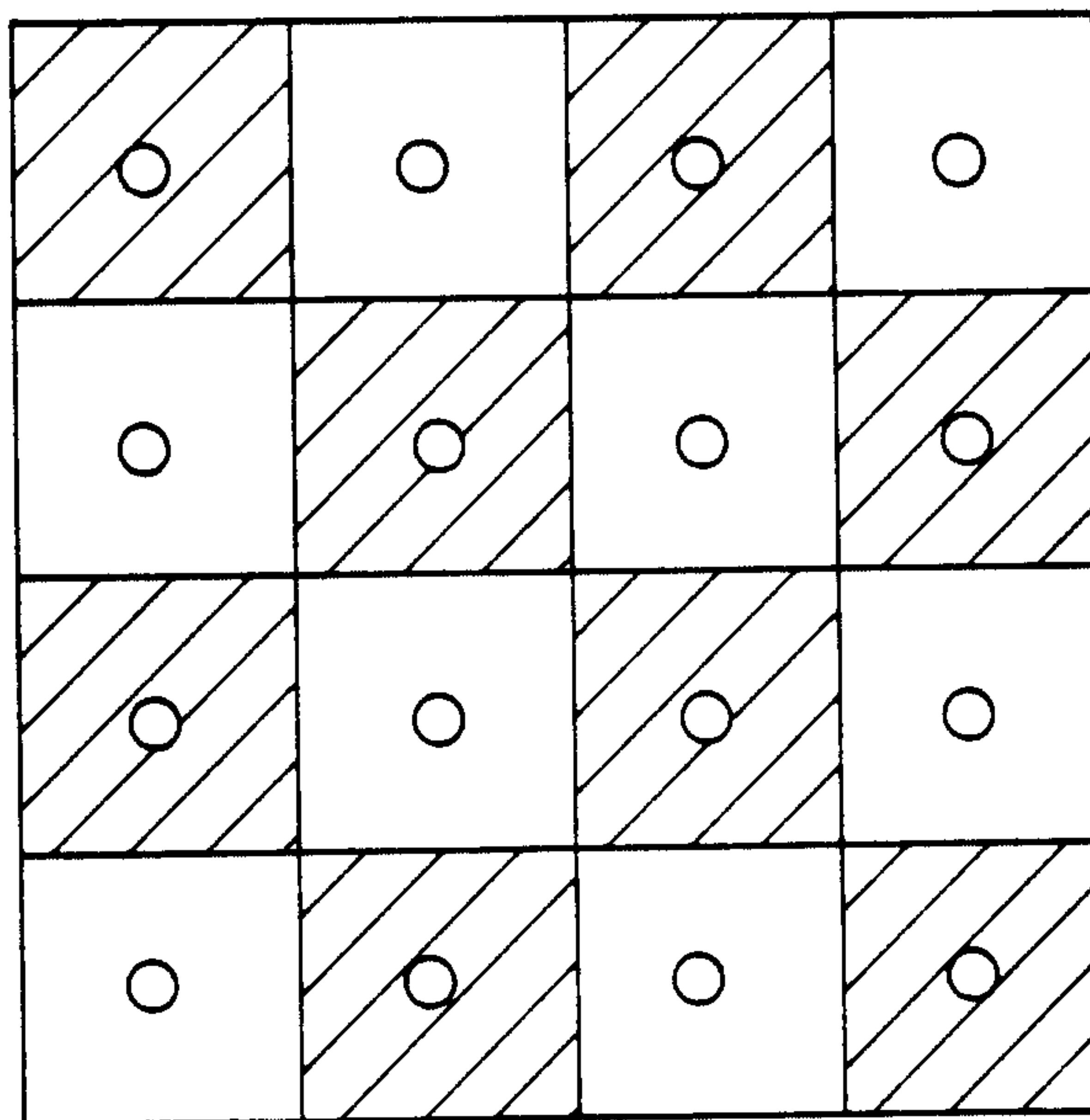


FIG. 41

