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(54) **TWO SECTION BLUE LASER DIODE WITH REDUCED OUTPUT POWER DROOP**

FOREIGN PATENT DOCUMENTS

(75) Inventors: **Michael Kneissi**, Mountain View, CA (US); **Thomas L. Paoli**, Aptos, CA (US)

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(73) Assignee: **Palo Alto Research Center Incorporated**, Palo Alto, CA (US)

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(51) **Int. Cl.**
H01S 5/026 (2006.01)

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(52) **U.S. Cl.** **372/50; 438/48**

Primary Examiner—M. Tran

(58) **Field of Classification Search** **372/50; 438/48**

See application file for complete search history.

(57) **ABSTRACT**

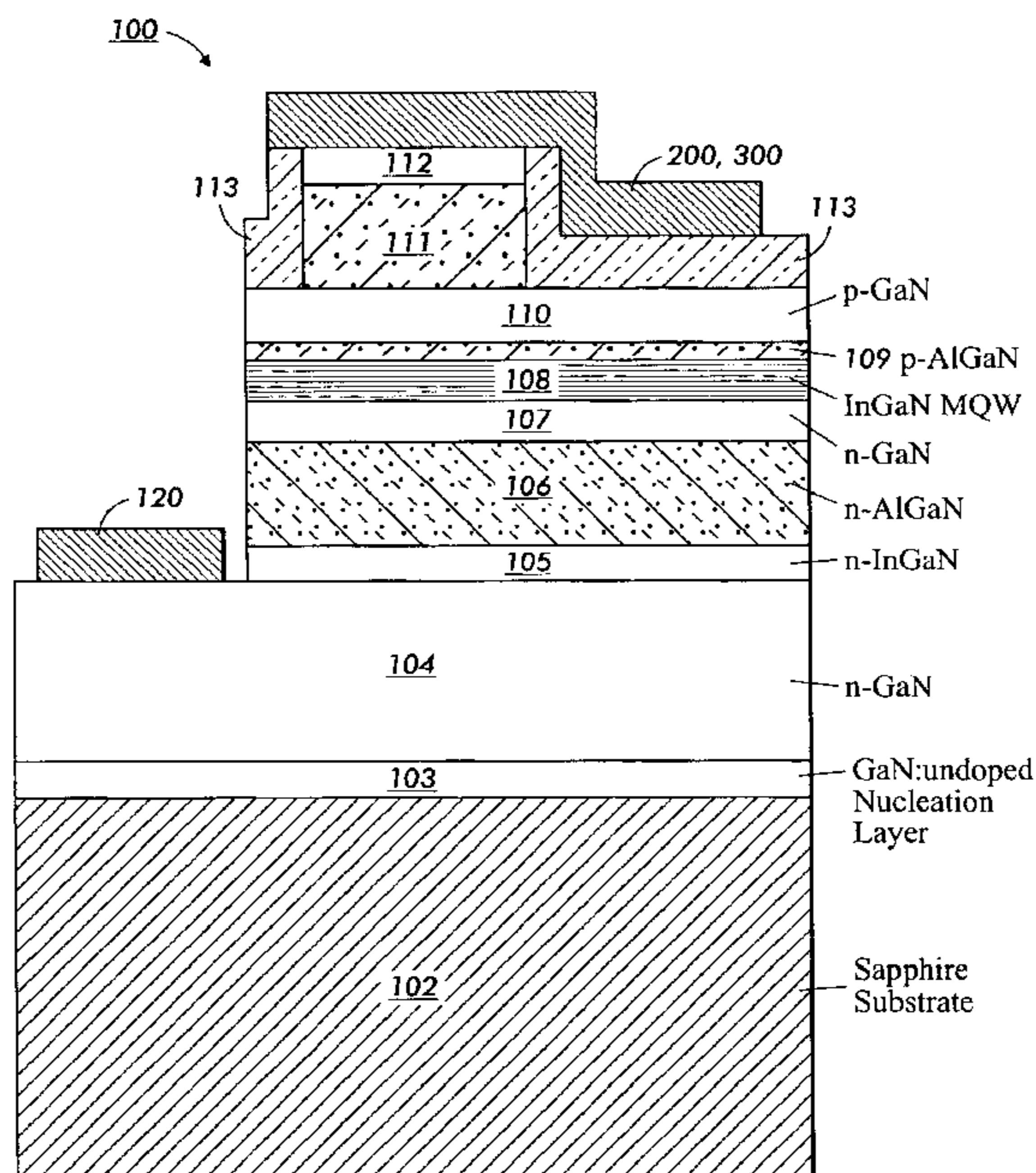
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A III-V nitride blue laser diode has an amplifier region and a modulator region. The amplifier region has a constant current to keep the region near the lasing threshold. The modulator region has a small varying forward current or reverse bias voltage which controls the light output of the laser. This two section blue laser diode requires much lower power consumption than directly modulated lasers which reduces transient heating and "drooping" of the light output.

16 Claims, 8 Drawing Sheets



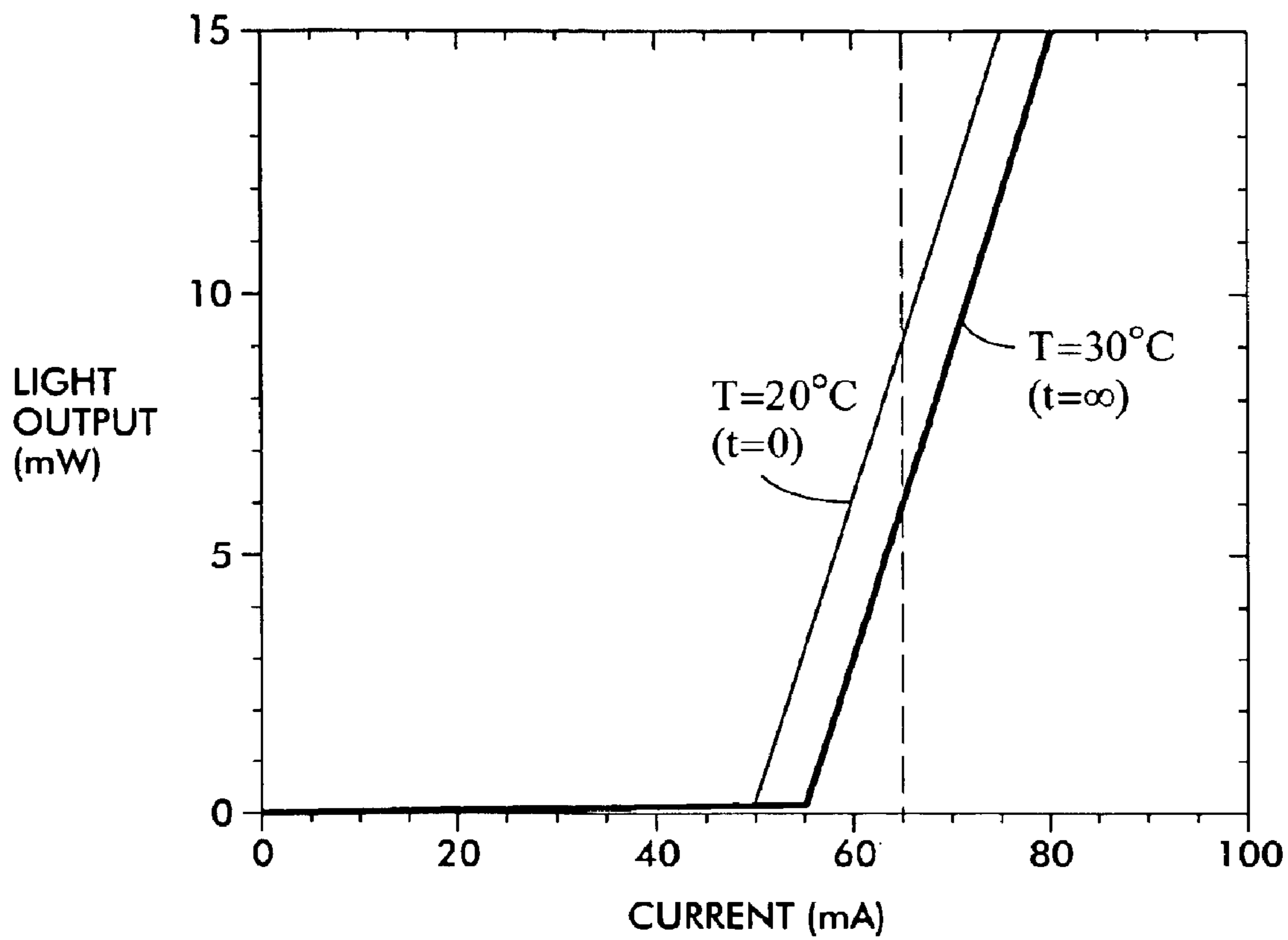


FIG. 1

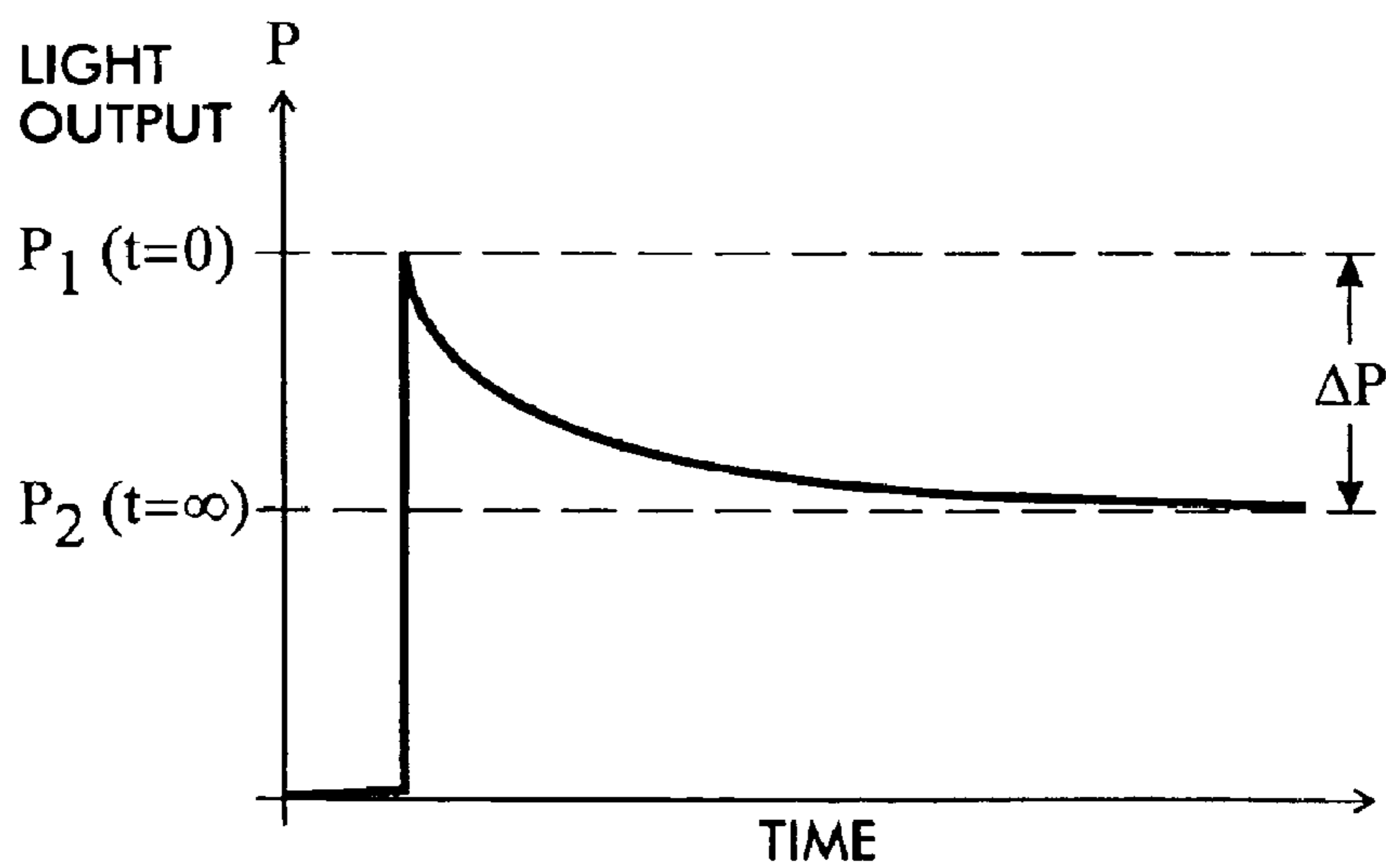


FIG. 2

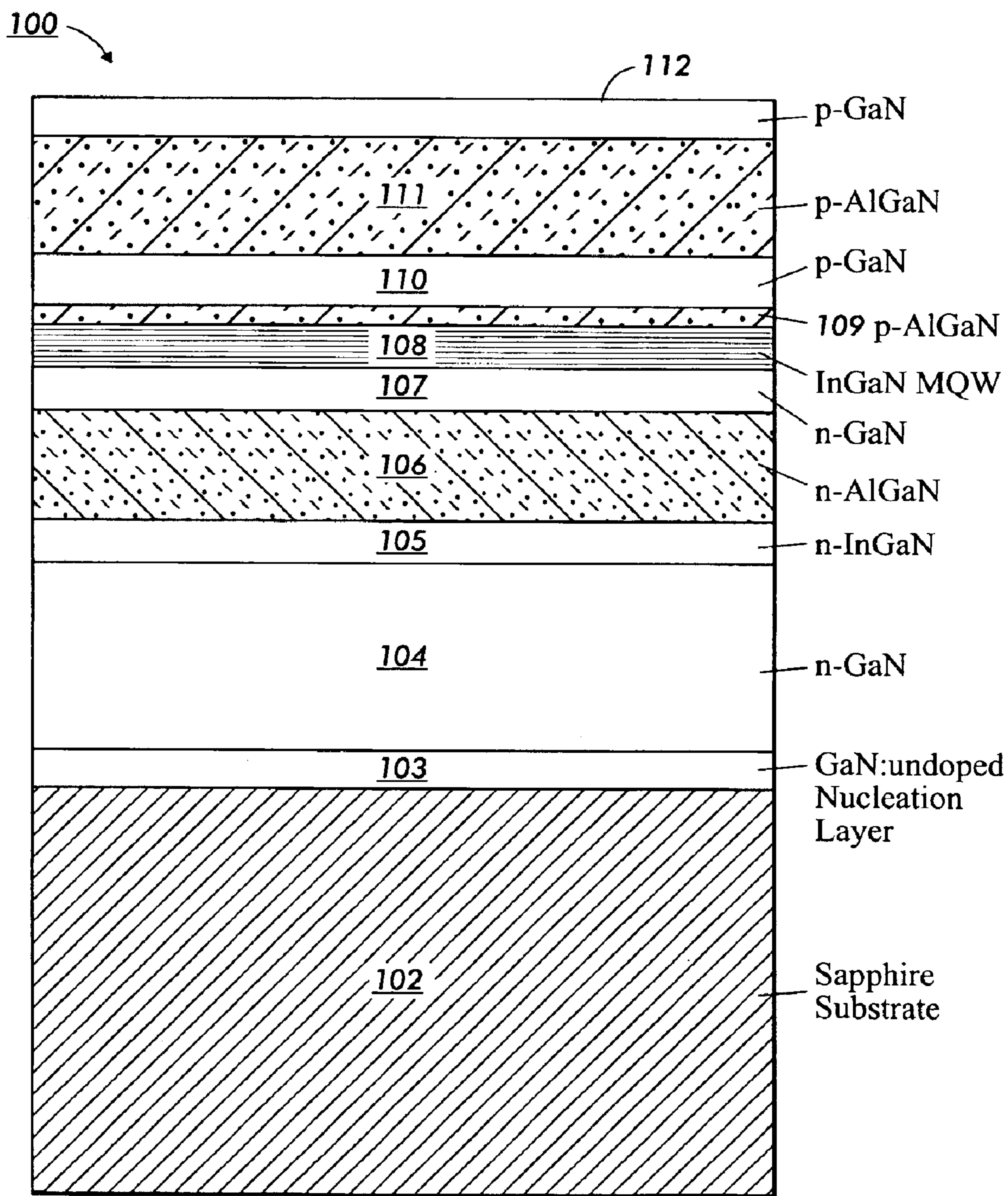


FIG. 3

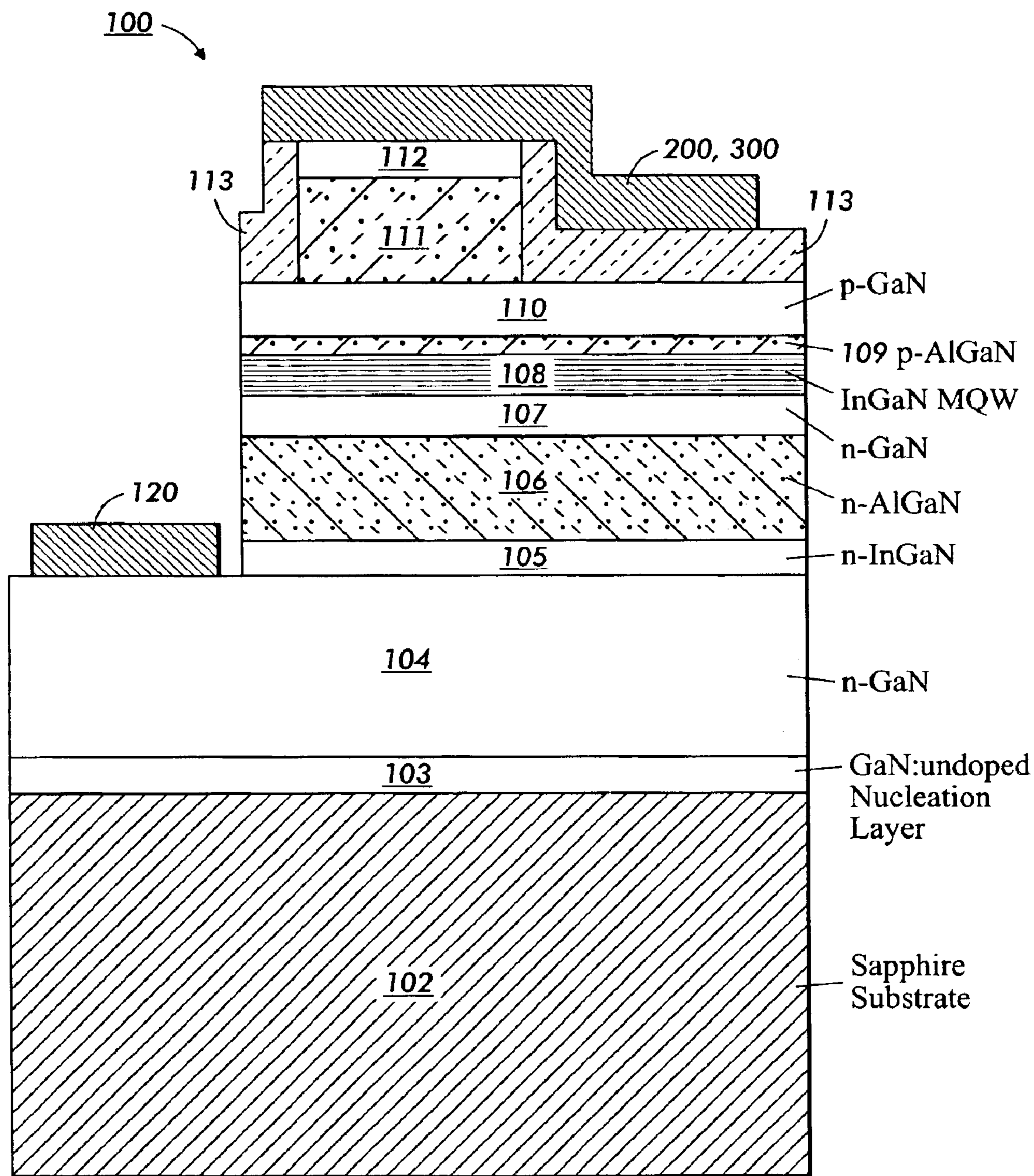


FIG. 4A

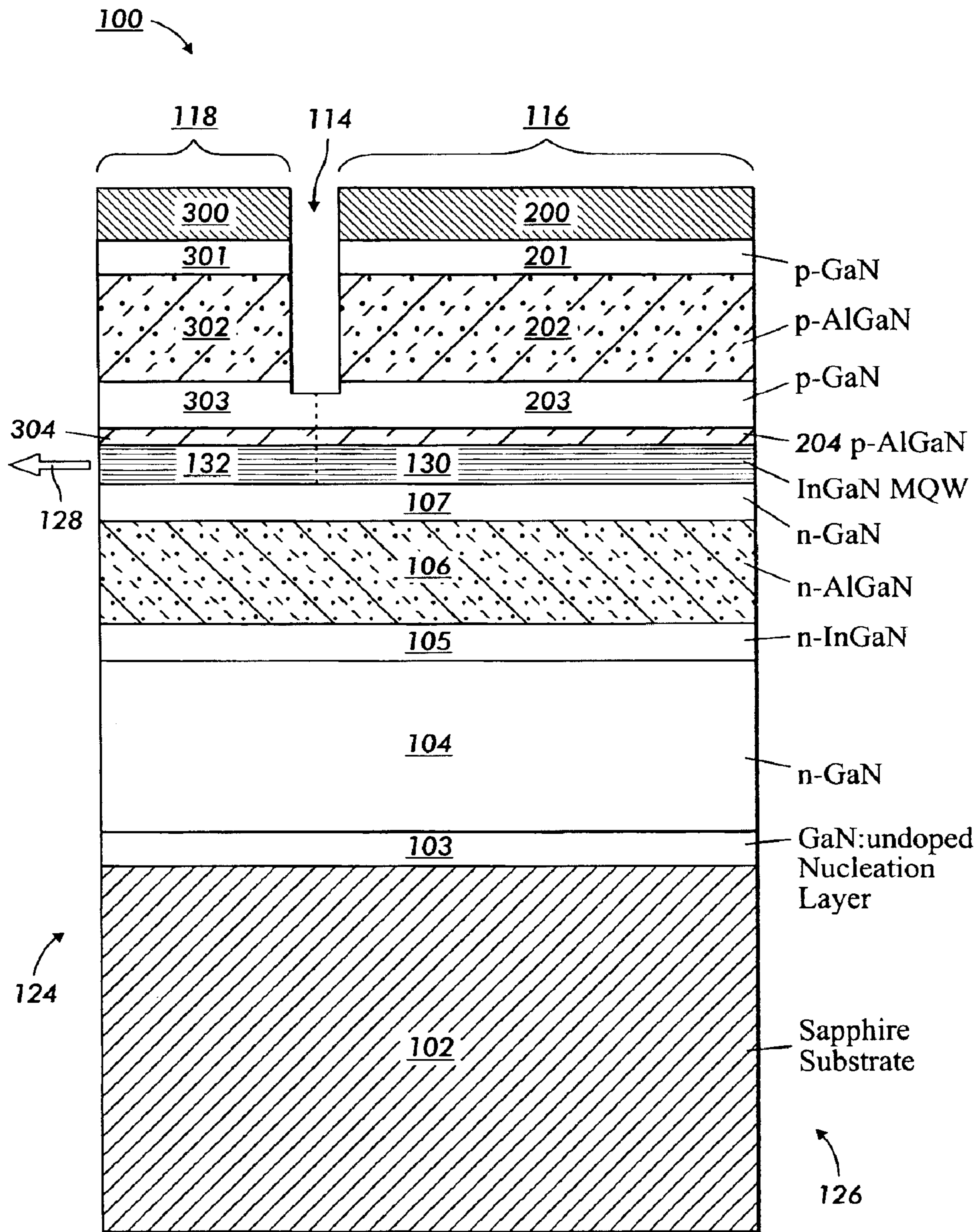


FIG. 4B

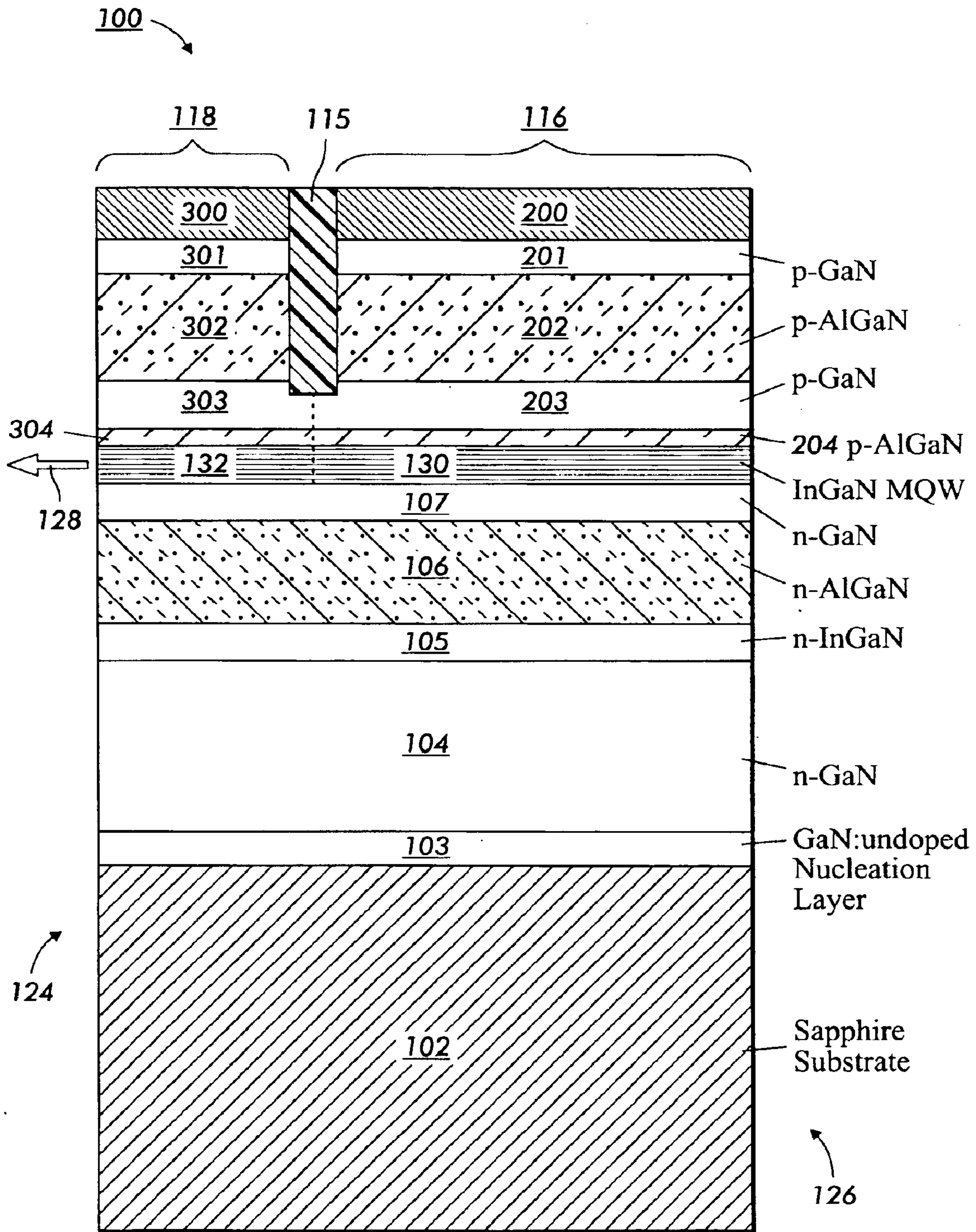


FIG. 4C

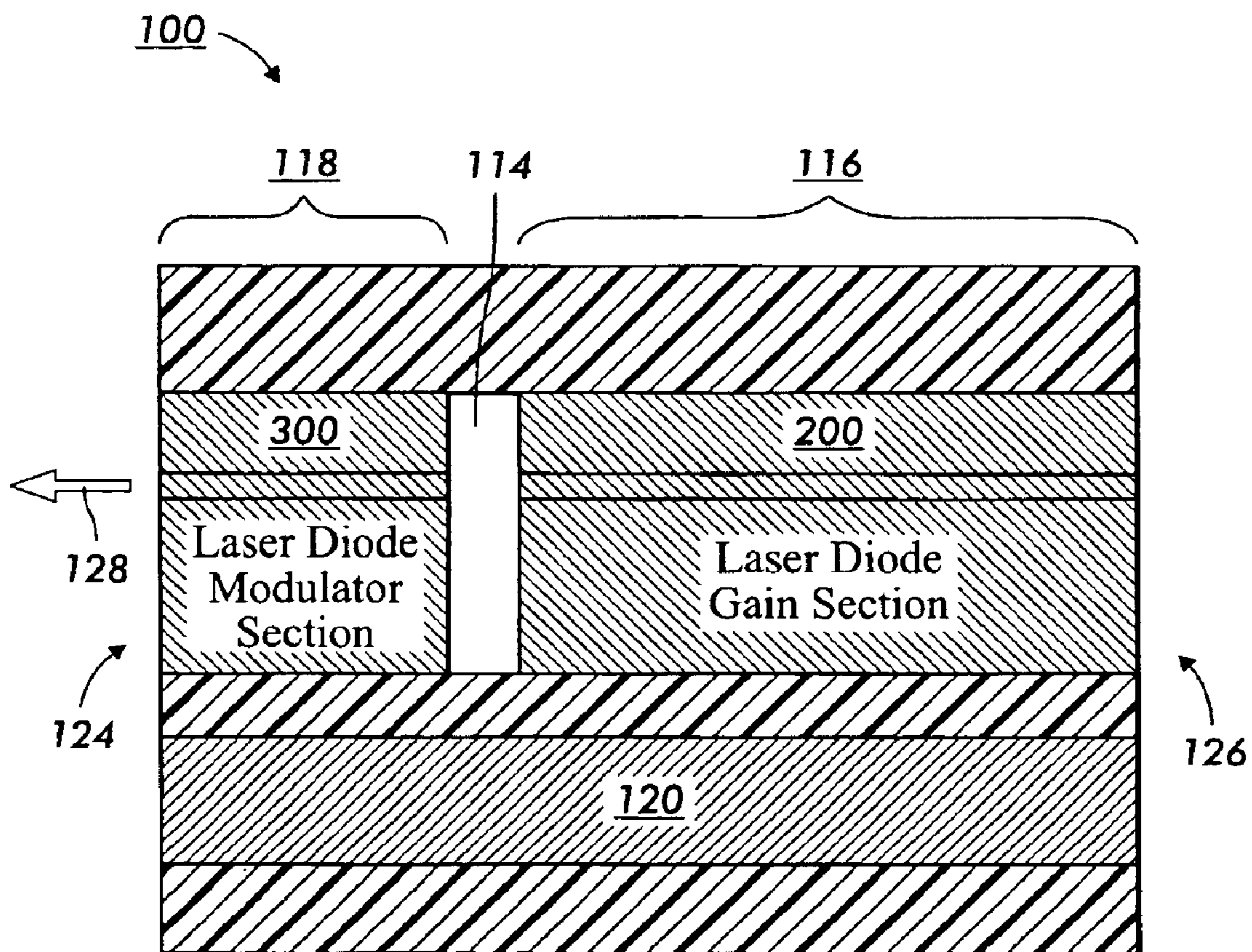


FIG. 5

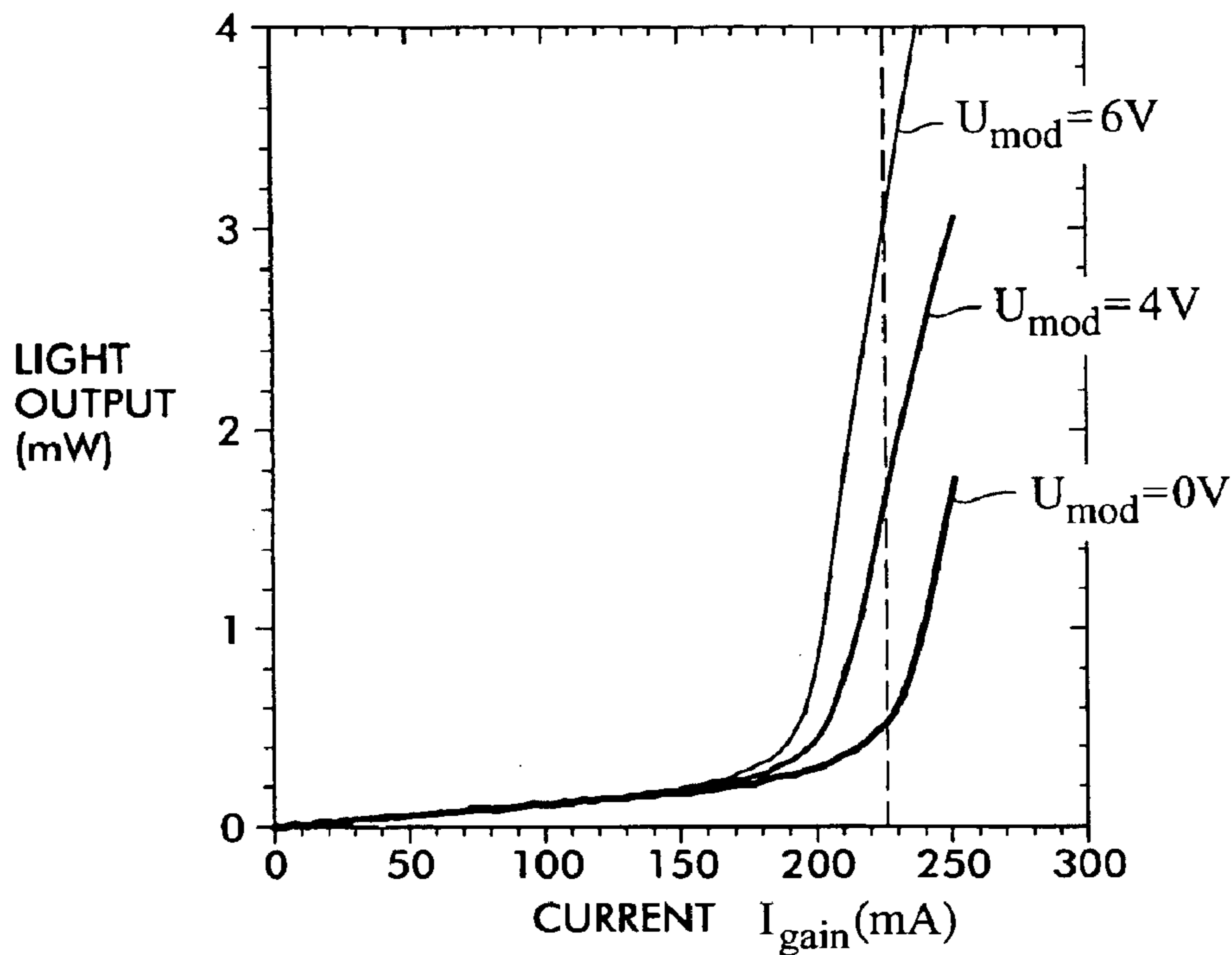


FIG. 6A

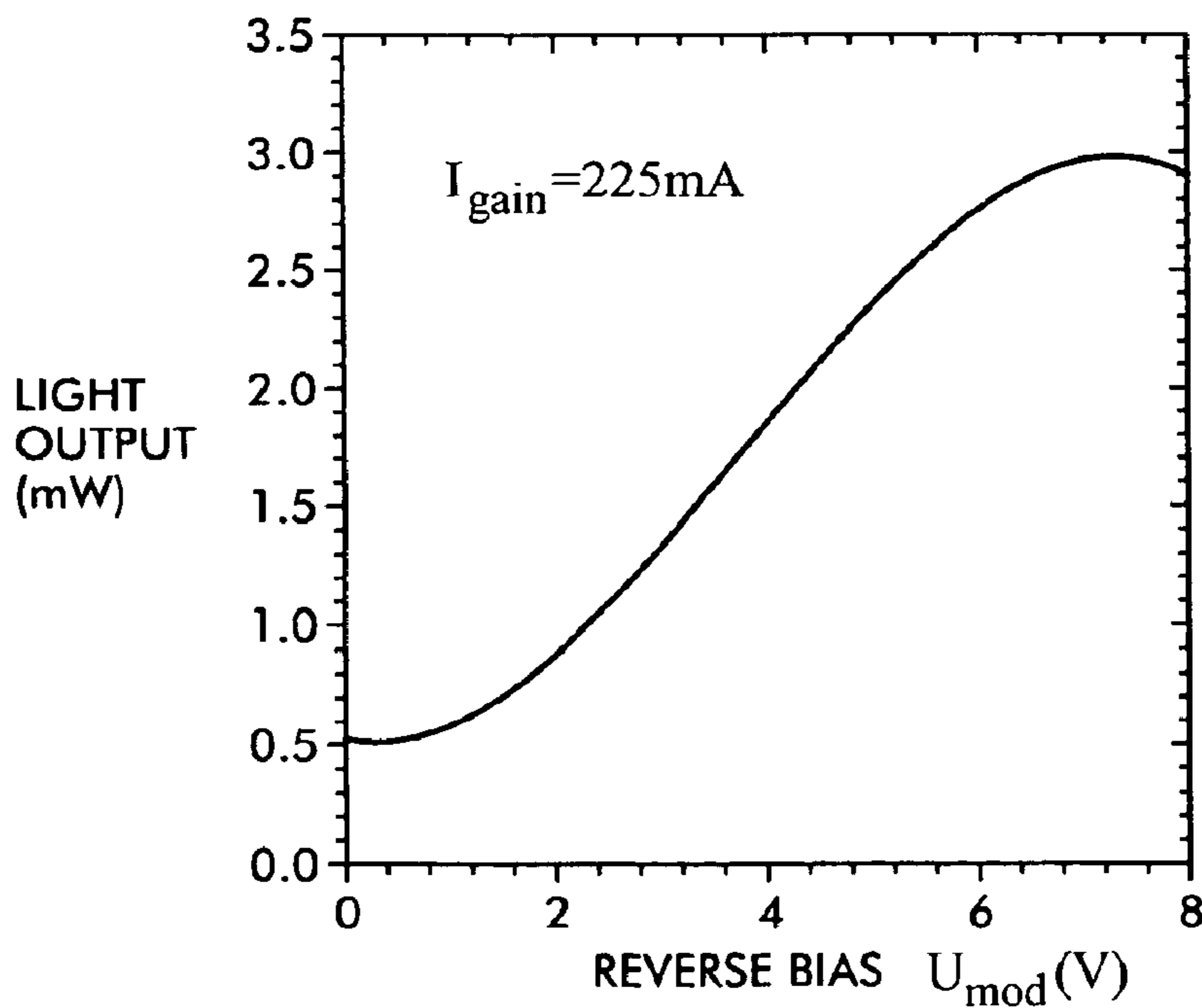


FIG. 6B

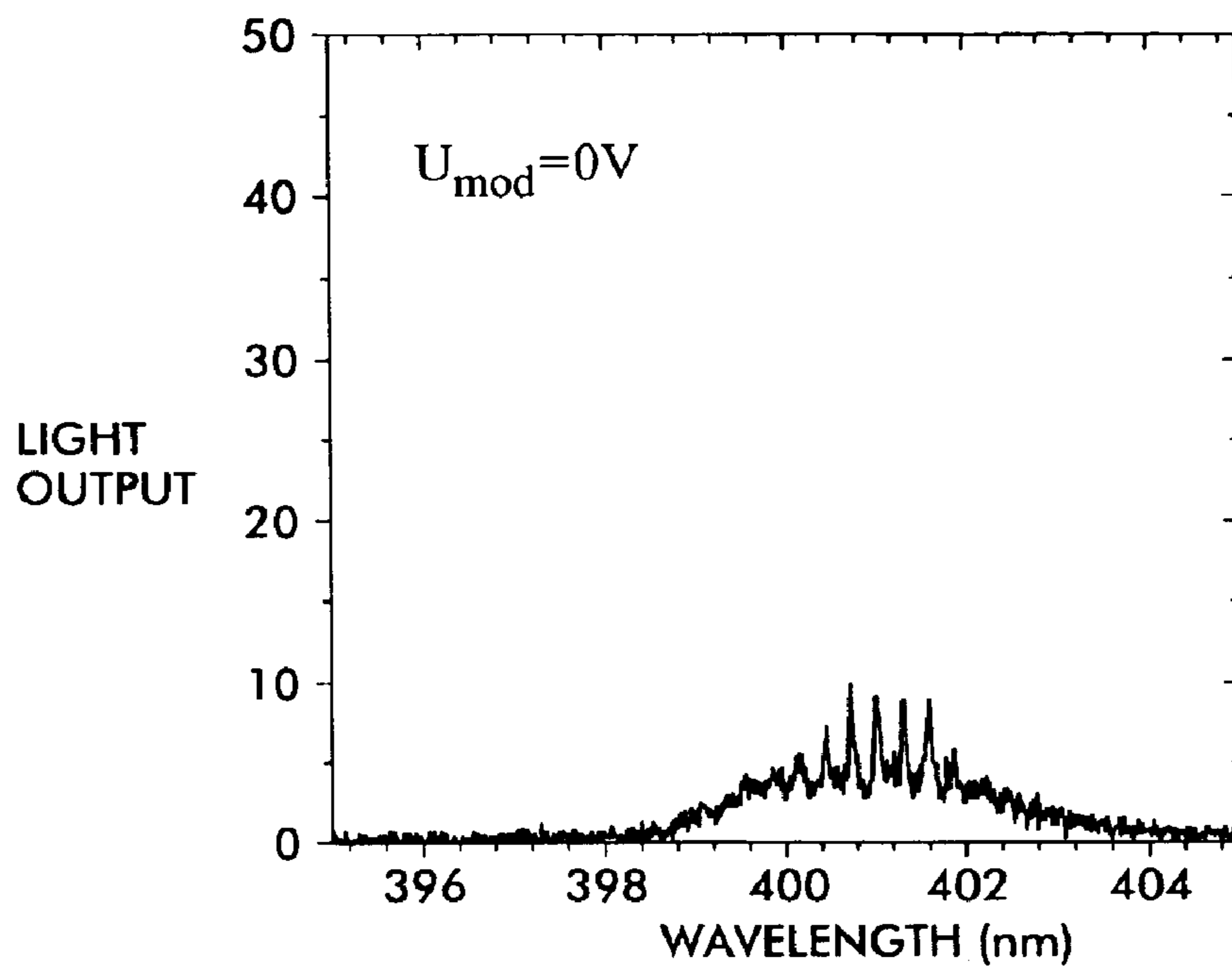


FIG. 7A

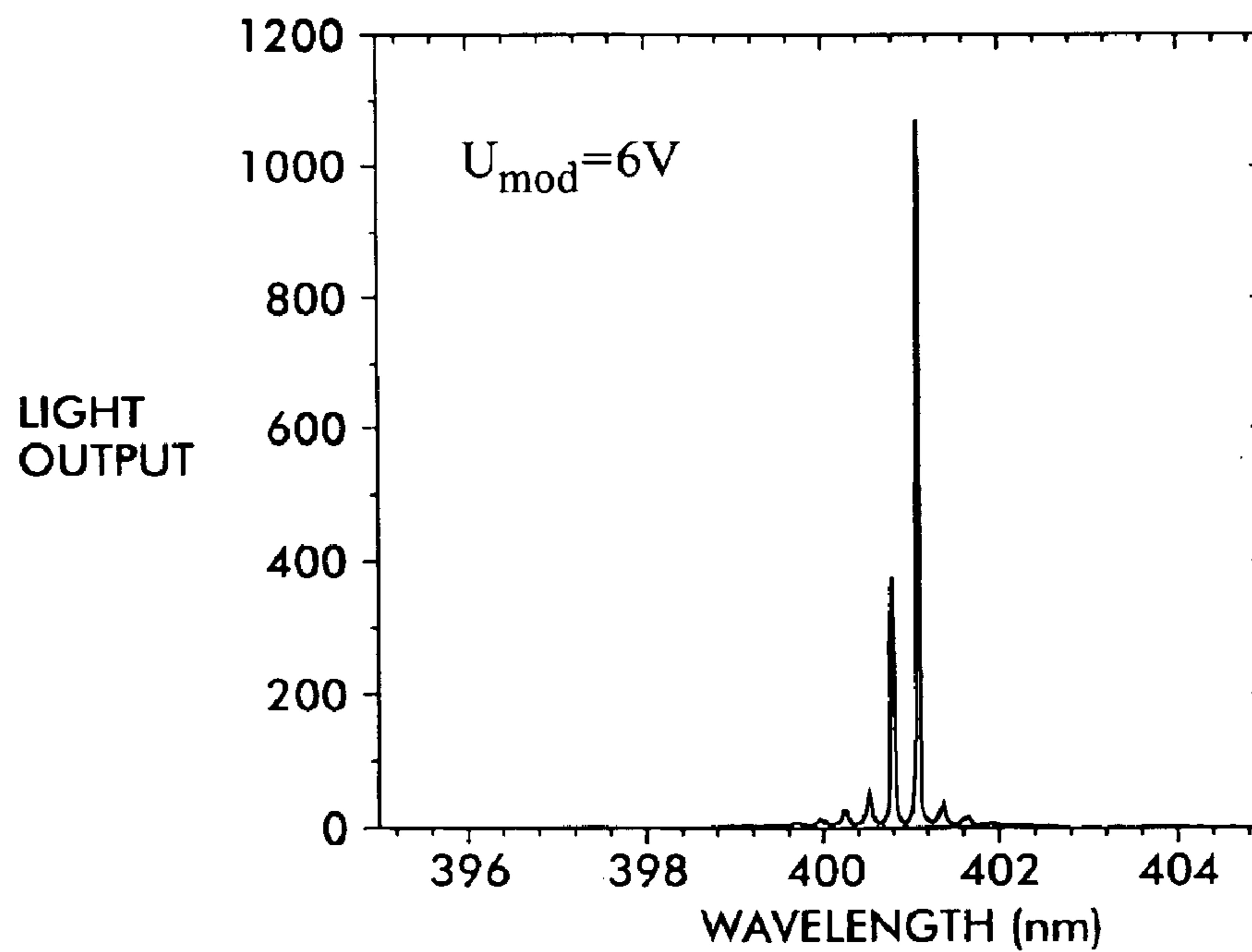


FIG. 7B

TWO SECTION BLUE LASER DIODE WITH REDUCED OUTPUT POWER DROOP

Matter enclosed in heavy brackets [] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue.

BACKGROUND OF THE INVENTION

The present invention relates to a blue laser diode and, more particularly, to a two section blue laser diode with an amplifier region and a modulator region to reduce power output variations.

Solid state lasers, also referred to as semiconductor lasers or laser diodes, are well known in the art. These devices generally consist of a planar multi-layered semiconductor structure having one or more active semiconductor layers bounded at their ends by cleaved surfaces that act as mirrors. The semiconductor layers on one side of the active layer in the structure are doped with impurities so as to have an excess of mobile electrons. The semiconductor layers on the other side of the active layer in the structure are doped with impurities so as to have a deficiency of mobile electrons, therefore creating an excess of positively charged carriers called holes. Layers with excess electrons are said to be n-type, i.e. negative, while layers with excess holes are said to be p-type, i.e. positive.

An electrical potential is applied through electrodes between the p-side and the n-side of the layered structure, thereby driving either holes or electrons or both in a direction perpendicular to the planar layers across the p-n junction so as to "inject" them into the active layers, where electrons recombine with holes to produce light. Optical feedback provided by the cleaved mirrors allows resonance of some of the emitted light to produce coherent "lasing" through the one mirrored edge of the semiconductor laser structure.

Semiconductor laser structures comprising group III-V nitride semiconductor layers grown on a sapphire substrate will emit light in the near ultra-violet to visible spectrum within a range including 360 nm to 650 nm.

The shorter wavelength of blue/violet laser diodes provides a smaller spot size and a better depth of focus than the longer wavelength of red and infrared (IR) laser diodes for laser printing operations and high density-optical storage. In addition, blue lasers can potentially be combined with existing red and green lasers to create projection displays and color film printers.

The III-V nitrides make possible diode lasers that operate at room temperature and emit shorter-wavelength visible light in the blue-violet range under continuous operation. The III-V nitrides comprise compounds formed from group III and V elements of the periodic table. The III-V nitrides can be binary compounds such as gallium nitride (GaN), aluminum nitride (AlN), or indium nitride (InN), as well as ternary alloys of aluminum gallium nitride (AlGaIn) or indium gallium nitride (InGaIn), and quaternary alloys such as aluminum gallium indium nitride (AlGaInIn).

These materials are highly promising for use in short-wavelength light emitting devices for several important reasons. Specifically, the AlGaInN system has a large band-gap covering the entire visible spectrum. III-V nitrides also provide the important advantage of having a strong chemical bond which makes these materials highly stable and resistant to degradation under high electric current and intense light illumination conditions that are present at active regions of

the devices. These materials are also resistant to dislocation formation once grown.

High speed and high resolution printing requires laser devices with little or no fluctuations of the output power. For example, the variation in the laser light output required for red and IR laser diodes for printing applications is smaller than 4% and those requirements would be similar for AlGaInN laser diodes.

Heat is generated through voltages drops across the metal electrode/semiconductor interfaces, which have a finite resistance, and through voltage drops across the resistive semiconductor layers. Energy is also introduced into the active region of the laser by injecting electrons into the conduction band and/or holes into the valence band. Electrons relax into the lowest energy state of the conduction band and holes relax into the lowest energy state of the valence band through non-light emitting processes and release their energy in the form of heat.

When a laser device is switched from the OFF to the ON state, transient heating, or heating that changes over time, can cause the light output of AlGaInN laser diodes to drop significantly.

As an illustrative example, an AlGaInN blue laser diode is forward biased with a constant current above the lasing threshold current. At the initial time $t=0$, with a constant current of 65 mA, the blue laser diode will have a first output power P_1 of 9.5 mW with a laser structure temperature of 20 degrees C., as shown in FIG. 1.

However, as time increases with the blue laser diode above lasing threshold with the constant current, the temperature of the laser structure increases. This increased temperature results in a decreased output power for the AlGaInN laser diode.

At a subsequent time $t=\infty$, still with a constant current of 65 mA, the blue laser will have a second output power P_2 of 6.2 mW with a laser structure temperature of 30 degrees C., as shown in FIG. 1. The second output power P_2 is lower than the initial output power P_1 . Thus, the plot of output power versus time of FIG. 2 shows an initial output power of P_1 at turn-on, "drooping" to the second lower output power P_2 as the blue laser diode is operated.

Thermal fluctuations are especially deleterious to maintaining constant optical power output, especially during pulsed modulation. In virtually all of the applications of these lasers, it is necessary to modulate the output of the laser into a series of pulses.

Transient heating during a sequence of pulses can have a cumulative effect on the temperature depending on the number and frequency of the pulses. For example, if the time between successive pulses is large, the laser diode will be given sufficient time to cool, so that the application of the driving current has a large temperature effect (i.e., a large droop in output power will occur at turn-on of the next pulse). The shorter the time between pulses, the less time the laser diode has to cool between one pulse and the next, leading to a sustained increase in the temperature of the laser. This sustained temperature increase results in a further decrease in the output pulse obtained with a constant level of input current.

Another related consequence of transient heating of a laser is wavelength variation during a pulse and over long streams of pulses. Essentially, the operating wavelength of a laser diode is dependent on the temperature of the laser diode. If the temperature varies, the wavelength of operation will vary. The effect of this variation of wavelength, for example in the laser xerography application, is to vary the

energy that can be written onto the photoreceptor. This can also translate directly into variations in the spot size and pattern on the photoreceptor.

Digital printing requires accurate control of the optical energy delivered in each pulse. In systems currently known to those skilled in the art, a predetermined amount of energy is delivered in each pulse by turning on the optical beam to a desired power level for a fixed time interval. This approach requires that the laser output power be reproducible from pulse to pulse and constant during a pulse, in order that the optical energy delivered in each pulse be accurately controlled. Accurate control is especially important in printing with different grey levels formed by varying the number of exposed spots or when exposing very closely spaced spots in order to control the formation of an edge.

Due to the poor thermal conductivity of the sapphire substrate and the relatively high electric power consumption of III-nitride baser laser devices, transient heating is an issue to AlGaInN devices. For example, AlGaInN laser devices have threshold currents in the order of 50 mA and operating voltages of 5 V (compared to about 15 mA and 2.5 V for red lasers).

It is an object of the present invention to provide a blue laser with reduced power output variations due to transient heating.

SUMMARY OF THE INVENTION

According to the present invention, an III-V nitride blue laser diode has an amplifier region and a modulator region. The amplifier region has a constant current to keep the region near the lasing threshold. The modulator region has a small varying forward current or reverse bias voltage which controls the light output of the laser. This two section blue laser diode requires much lower power consumption than directly modulated lasers which reduces transient heating and "drooping" of the light output.

The light output of the laser diode is controlled by absorption changes in the modulator region. Absorption changes can be induced using field effects (e.g. QCSE) or carrier effects (e.g. band filling or field screening) which require much lower power consumption than directly modulated lasers.

Since only a small section of the laser diode is used to control the output power, the resulting lower capacitance should also be beneficial for achieving higher modulation speeds.

Other objects and attainments together with a fuller understanding of the invention will become apparent and appreciated by referring to the following description and claims taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete appreciation of the invention and many of the attendant advantages thereof will be readily obtained and understood by referring to the following detailed description and the accompanying drawings in which like reference numerals denote like elements as between the various drawings. The drawings, briefly described below, are not to scale.

FIG. 1 is a plot of power output versus input current for a blue laser diode showing the effect of transient heating of the laser diode.

FIG. 2 is a plot of power output versus time for the blue laser diode of FIG. 1 showing power output "droop".

FIG. 3 is a cross-sectional side view of the blue laser diode of the present invention after III-V nitride film growth.

FIG. 4a is a cross-sectional front view of the two section ridge-waveguide blue laser diode with gain region and modulator region of the present invention.

FIG. 4b is a cross-sectional side view of the two section blue laser diode with gain region and modulator region of the present invention separated by an etched trench.

FIG. 4c is a cross-sectional side view of the two section blue laser diode with gain region and modulator region of the present invention separated by an electrically insulating ion implanted region.

FIG. 5 is a top view of the two-section blue laser diode of FIG. 4.

FIG. 6a shows the measured light output vis. current characteristic for a blue two-section laser diode for different modulator section reverse bias voltages.

FIG. 6b shows the measured light output vs. reverse bias voltage characteristic for a blue two-section laser diode at a constant gain section current.

FIG. 7a shows the measured two-section laser diode emission spectra at a modulator section voltage of 0 V (OFF state).

FIG. 7b shows the measured two-section laser diode emission spectra at a modulator section voltage of 6 V (ON state).

DESCRIPTION OF THE INVENTION

In the following detailed description, numeric ranges are provided for various aspects of the embodiments described. These recited ranges are to be treated as examples only, and are not intended to limit the scope of the claims hereof. In addition, a number of materials are identified as suitable for various facets of the embodiments. These recited materials are to be treated as exemplary, and are not intended to limit the scope of the claims hereof.

Reference is now made to FIG. 3 wherein is described the basic two section III-V nitride based semiconductor alloy diode laser **100** of the present invention. The semiconductor laser structure **100** has a C-face (**0001**) or A-face (**1120**) oriented sapphire (Al_2O_3) substrate **102** on which a succession of semiconductor layers is epitaxially deposited. The laser structure **100** includes a thin buffer layer **103**, also known as a nucleation layer, formed on the sapphire substrate **102**. The buffer layer **103** acts primarily as a wetting layer, to provide smooth, uniform coverage of the top surface of the sapphire substrate **102**. The buffer layer **103** can comprise any suitable material. Typically, the buffer layer **103** is formed of a binary or ternary III-V nitride material, such as, for example, GaN, AlN, InGaN or AlGaIn. The buffer layer **103** typically has a thickness of from about 10 nm to about 30 nm. The buffer layer **103** is typically undoped.

A second III-V nitride layer **104** is formed on the buffer layer **103**. The second III-V nitride layer **104** is an n-type GaN or AlGaIn layer. The second III-V nitride layer **104** acts as a lateral n-contact and current spreading layer. The second III-V nitride layer **104** typically has a thickness of from about 1 μm to about 10 μm . The second III-V nitride layer **104** is typically n-type GaN:Si or AlGaIn:Si.

A third III-V nitride layer **105** is formed over the second III-V nitride layer **104**. The third III-V nitride layer **105** is a defect reducing layer. The third III-V nitride layer **105** typically has a thickness of from about 25 nm to about 200

nm. The third III-V nitride layer **105** is typically n-type InGaN:Si with an In content smaller than the InGaN quantum well(s) in the active region **108**.

A fourth III-V nitride layer **106** is formed over the third III-V nitride layer **105**. The fourth III-V nitride layer **106** is an n-type cladding layer. The fourth III-V nitride layer **106** typically has a thickness of from about 0.2 μm to about 2 μm . The fourth III-V nitride layer **106** is typically n-type AlGaIn:Si with an Al content larger than the third or the second III-V nitride layer.

A fifth III-V nitride layer **107**, which is a waveguide layer, is formed over the fourth III-V nitride layer **106**. The fifth III-V nitride layer **107** is typically n-type In GaN:Si, GaN:Si, InGaIn:un or GaN:un with an In content smaller than the InGaIn quantum well(s) in the active region **108**. The overall thickness of the fifth III-V nitride layer **107** is typically from about 0.05 μm to about 0.2 μm .

On top of the fifth III-V nitride layer **107**, the InGaIn quantum well active region **108** is formed, comprised of at least one InGaIn quantum well. For multiple-quantum well active regions, the individual quantum wells typically have a thickness of from about 10 \AA to about 100 \AA and are separated by InGaIn or GaN barrier layers which have typically a thickness of from about 10 \AA to about 200 \AA . The InGaIn quantum wells and the InGaIn or GaN barrier layers are typically undoped or can be Si-doped.

A sixth III-V nitride layer **109**, which is a carrier confinement layer, is formed over the InGaIn (multiple) quantum well active region **108**. The sixth III-V nitride layer **109** has a higher band gap than the quantum well active region. The sixth III-V nitride layer **109** is typically p-type $\text{Al}_x\text{Ga}_{1-x}\text{N:Mg}$ with an Al content in the range from $x=0.05$ to $x=0.4$. The overall thickness of the sixth III-V nitride layer **109** is typically from about 5 nm to about 100 nm.

A seventh III-V nitride layer **110**, which is a waveguide layer, is formed over the sixth III-V nitride layer **109**. The seventh III-V nitride layer **110** is typically p-type InGaIn:Mg or GaN:Mg with an In content smaller than the InGaIn multi-quantum well(s) in the active region. The overall thickness of the seventh III-V nitride layer **110** is typically from about 50 nm to about 200 nm.

An eighth III-V nitride layer **111** is formed over the seventh III-V nitride layer **110**. The eighth III-V nitride layer **111** serves as a p-type cladding layer. The eighth III-V nitride layer **111** typically has a thickness of from about 0.2 μm to about 1 μm . The eighth III-V nitride layer **111** is typically AlGaIn:Mg with an Al content larger than the seventh III-V nitride layer.

A ninth III-V nitride layer **112** is formed over the eighth III-V nitride layer **111**. The ninth III-V nitride layer **112** forms a p-contact layer for the minimum-resistance metal electrode, to contact the p-side of the heterostructure **100**. The ninth III-V nitride layer **112** typically has a thickness of from about 10 nm to 200 nm.

The laser structure **100** can be fabricated by a technique such as metalorganic chemical vapor deposition (MOCVD) or molecular beam epitaxy as is well known in the art. MOCVD growth is typically performed on 2-inch or 3-inch diameter sapphire substrate wafer. The substrate **102** can be a C-face (0001) or A-face (1120) oriented sapphire (Al_2O_3) substrate. The sapphire substrate wafers are of standard specifications including an epitaxial polish on one side and a typical thickness of 10-mil to 17-mil. Other examples of substrates include, but are not limited to 4H-SiC, 6H-SiC, AlN or GaN. In case of growth on a GaN substrate, the second III-V nitride layer **104** can be directly

formed on top of the substrate **102** without the deposition of a nucleation layer **103**. The substrate temperatures during growth are typically 550 degrees C. for the GaN nucleation layer, 1000 degrees C. to 1100 degrees C. for the GaN and AlGaIn layers and 700 degrees C. to 800 degrees C. for the InGaIn layers. In addition, the reactor pressure may be controlled between 50 Torr and 740 Torr. As organometallic precursors for the MOCVD growth TMGa (trimethylgallium), TMAI (trimethylaluminum), TMIIn (trimethylindium) and TEGa (triethylgallium) are used for the group III elements and NH_3 (ammonia) is used as the nitrogen source. Hydrogen and/or nitrogen are used as carrier gas for the metalorganic sources. For the n-doping, 100 ppm SiH_4 diluted in H_2 is used, and for the p-doping, Cp_2Mg (cyclopentadienylmagnesium) is used. Other examples of p-type dopants include, but are not limited to, Mg, Ca, C and Be. Examples of n-type dopants include, but are not limited to, Si, O, Se, Te and N-vacancies.

After MOCVD growth, the Mg p-doping in (Al)GaIn:Mg layers is activated by RTA (rapid thermal annealing) at 850 degrees Celsius for 5 minutes in N_2 ambient. A ridge waveguide structure is formed by dry-etching into the p-GaN waveguide layer **110** with CAIBE (chemical assisted ion beam etching) or RIE (reactive ion beam etching) in an Ar(argon)/ Cl_2 (chlorine)/ BCl_3 (borontrichloride) gas mixture as shown in FIG. 4a.

In order to form the gain and the modulator section of the device, an isolation trench **114** is etched into the ridge-waveguide as shown in FIG. 4b. The isolation trench **114** can be formed in the same step as the ridge-waveguide etch or can be formed in a separate step in order to obtain a different etch depth. An electrically insulating layer (e.g., silicon-oxy-nitride or SiO_2 or Si_3N_4) (not shown in the Figure) can be deposited, e.g. by plasma-enhanced chemical vapor deposition (PE-CVD), into the trench in order to reduce the disturbance of the optical mode and serve as passivation layer for the exposed surfaces.

Dry-etching using CAIBE (chemical assisted ion beam etching) or RIE (reactive ion beam etching) in an Ar/ Cl_2 / BCl_3 gas mixture is used to access the GaIn:Si layer **104** for n-contact formation. An n-contact **120** is formed over the second III-V nitride layer **104**, which is functioning as a lateral contact layer.

The n-electrode **120** of FIG. 4a is common to both the amplifier region **116** and the modulator region **118**. The n-contact metal can be deposited by thermal evaporation, electron-beam evaporation or sputtering. Typically Ti/Al, Ti/Au or Ti/Al/Au are used as n-metal contacts. The n-contacts are annealed in N_2 ambient at 500 degrees Celsius in order to reduce the contact resistance. A dielectric isolation layer **113** (e.g. silicon-oxy-nitride or SiO_2 or Si_3N_4) is deposited by plasma-enhanced chemical vapor deposition (PE-CVD) on top of the ridge-waveguide. Alternatively polyimide can also be used for isolation. Windows for p-contact formation are etched into the dielectric isolation layer using RF plasma etching in a CF_4/O_2 ambient.

In FIGS. 4a and 4b, a p-electrode **200** is deposited on top of the amplifier contact layer **201** for the amplifier region **116**. A p-electrode **300** is deposited on top of the modulator contact layer **301** for the modulator region **118**. The two p-electrodes **200** and **300** are separate and distinct and allow for independent addressability of the amplifier region **116** and the modulator region **118**. Ni/Au, NiO/Au, Pd/Au, Pd/Au/Ti/Au, Pd/Ti/Au, Pd/Ni/Au, Pt/Au or Pd/Pt/Au can be deposited as p-contact metal by thermal evaporation, electron-beam evaporation or sputtering.

The laser facets can be formed either by cleaving or dry-etching (e.g. CAIBE). A $\text{SiO}_2/\text{TiO}_2$, $\text{SiO}_2/\text{Ta}_2\text{O}_5$ or $\text{SiO}_2/\text{HfO}_2$ high reflective coating can be deposited on the backside of laser diode facets **126** by e-beam evaporation in order to enhance the mirror reflectivity. A SiO or SiO_2 anti-reflective coating can be deposited on the front side of the laser diode facet **124** using e-beam evaporation.

As seen in FIGS. **4b** and **5**, the trench **114** separates the laser structure **100** into an amplifier region **116** and a modulator region **118**. The amplifier region **116** has a metal p-contact **200**, a p-contact layer **201**, an upper cladding layer **202**, an upper waveguide layer **203** and an upper confinement layer **204**. The modulator region **118** has a metal p-contact **300**, a p-contact layer **301**, an upper cladding layer **302**, an upper waveguide layer **303** and an upper confinement layer **304**.

The amplifier p-contact layer **201** is separate and distinct from the modulator p-contact layer **301** but both are formed from the p-contact layer **112** before the groove **114** is etched. The amplifier upper cladding and waveguide layers **202** and **203** are separate and distinct from the modulator upper cladding and waveguide layers **302** and **303** but both are formed from the upper confinement and waveguide layer **110** and **111** before the groove **114** is etched. The amplifier upper confinement layer **204** is separate and distinct from the modulator upper confinement layer **304** but both are formed from the p-upper confinement layer **109** before the groove **114** is etched.

The active quantum well layer **108**, the lower waveguide layer **107**, the lower cladding layer **106**, the defect reducing layer **105**, the thick (Al)GaN current spreading layer **104**, the buffer layer **103** and the substrate **102** are common to both the amplifier region **116** and the modulator region **118**.

The optimum depth of the isolation trench **114** will depend on whether complete electric isolation is desired or minimum disturbance of the optical mode. Complete electric isolation is obtained if the trench **114** is etched through all the p-type layers and may even reach into or beyond the MQW active region **108**. This might, however, disturb the optical mode traveling between the modulator and the gain section of the device and lead to scattering losses. If the trench is only partially etched into the p-type layers some electric connection between the gain and modulator section remains. The cross-talk between these two section, however, is expected to be quite small, because of the high lateral resistance of the p-type GaN and AlGaIn layers. For example, if the trench **114** is only etched into the p-AlGaIn cladding layer **111** (as shown in FIG. **4b**), the remaining GaN:Mg waveguide layer **110** and p-AlGaIn layer **109** would yield a series resistance of about 3 M Ω between the modulator and the gain section (assuming a waveguide thickness of 100 nm, a trench width of 10 μm and a ridge-waveguide width of 2 μm , a hole concentration of 10^{18} cm^{-3} and a mobility of 1 cm^2/Vs). The trench can also be refilled with an electrically insulating dielectric layer (e.g. silicon-oxy-nitride or Si_3N_4) (not shown in the Figure), which can be deposited by plasma-enhanced chemical vapor deposition (PE-CVD) in order to improve the optical coupling between the modulator and the gain section.

Alternatively, electric isolation between the modulator and gain section can be obtained by ion implantation and without the etching of a trench. Ion implantation of the area **115** between the modulator and the gain section for example with protons (H^+) or oxygen ions would make this area electrically insulating and have the additional benefit that the optical waveguide would not be disturbed. An example of

such a structure is shown in FIG. **4c**. The ion implanted region could reach into or beyond the InGaIn MQW active region in order to prevent and carriers from the gain section leaking into the modulator section of the device.

The light beam **128** emitted by the laser structure **100** is emitted from the mirror **124** adjacent to the modulator region **118** in order to minimize any spontaneous emission from the amplifier region **116** in the OFF state.

For this invention, the active layer **108** under the amplifier region **116** is the amplifier active layer **130** and the active layer **108** under the modulator region **118** is the modulator active layer **132**.

In the two region blue laser structure **100**, the amplifier region **116** is strongly pumped with current to serve as a light emitting region, and the modulator region **118** is pumped with a lower current level than the amplifier region to allow high frequency modulation. Alternatively the modulator region can be also reverse biased, which also enables high frequency operation.

The amplifier region **116** is of much greater length than the modulator region **118**. Accordingly, the active layer **130** of the amplifier region **116** provides essentially all of the gain required to produce the desired output intensity. The active layer **132** of the modulator region **118** controls the output of laser **100** by switching the internal loss from a high value to a low value.

The amplifier region **116** will be forward biased by an input current applied through the p-electrode **200** and the n-electrode **120**. The current will cause electrons to flow from the n-doped layers of the current spreading layer **104**, the defect reducing layer **105**, the lower cladding layer **106** and lower waveguide layer **107** into the amplifier active layer **130**. The current also causes holes to flow from the p-doped layers of the amplifier contact layer **201**, the amplifier upper cladding layer **202**, the amplifier upper waveguide layer **203** and the amplifier upper current confinement layer **204** into the amplifier active layer **130**. Recombination of the electrons and holes in the amplifier active layer **130** at a sufficient current will cause stimulated emission of light **128**.

The current applied to the amplifier region **116** is adjusted so that enough gain is generated in the amplifier active layer **130** to overcome the total optical loss including the mirror loss and the optical loss from of the entire active layer **108** in the two section laser structure **100**, when the modulator section **118** is in the ON state (ON state=the modulator active layer **132** is in the low-loss-state) but is not exceeding the total optical loss including the mirror loss and the loss of the entire active layer **108** if modulator region **118** is in the OFF state (OFF state=the modulator active layer **132** is in the high-loss-state). The amplifier current is kept constant. The two-section laser structure **100** modulates the laser emission and laser output power by varying the optical loss in the active layer **132** of the modulator section of the laser device. If the modulator section is its high-loss-state (OFF state), the gain produced in the amplifier section is not large enough to overcome the total optical loss and therefore lasing is prohibited. If the modulator is switched to its low-loss-state (ON state) the optical gain produced in the amplifier section will be large enough to overcome the total optical loss and lasing will be allowed. The optical loss in the modulator section can be either varied by applying a forward current or by applying a reverse bias voltage to the modulator region **118**.

There are two basic modes of modulation for the two-section blue laser structure **100** of the present invention.

One mode, called the "forward current modulation mode", is one in which the amplifier region **116** is suffi-

ciently forward biased to cause stimulated light emission and a negligible minimal forward bias current is applied to the modulator region. The modulator region **118** can be forward biased by an input current applied through the p-electrode **300** and the n-electrode **120**. The current will cause electrons to flow from the n-doped layers of the current spreading layer **104**, the defect reducing layer **105**, the lower cladding layer **106** and lower waveguide layer **107** into the modulator active layer **132**. The current also causes holes to flow from the p-doped layers of the modulator contact layer **301**, the modulator upper cladding layer **302** and the modulator upper waveguide layer **303**, and the modulator current confinement layer **304** into the modulator active layer **132**. If no current is applied, the modulator section **118** is in the high-loss-state and lasing is prohibited (OFF state). Injection of the electrons and holes in the modulator active layer **132** at a sufficient current will reduce the loss in the modulator active layer **132**. As the modulator region **118** is in its low-loss-state, the gain from the amplifier section **116** will be sufficiently high to overcome the total loss and lasing is permitted (ON State).

Another mode, called the “reverse bias modulation mode”, also has the amplifier region sufficiently forward biased to cause stimulated emission, but has a reverse bias voltage applied to the modulator region.

The reverse bias input voltage to the modulator region **118** can be applied through the p-electrode **300** and the n-electrode **120**. By applying a reverse bias to the modulator region p-n junction formed by the lower waveguide layer **107**, the InGaN MQW active region **1132** and the upper current confinement layer **304**, the electric field in the modulator section p-n junction can be changed. If no voltage is applied, the modulator section **118** is in the high-loss-state and lasing is prohibited (OFF state). As the modulator section **118** is in its low-loss-state, by applying an external reverse bias, the gain from the amplifier section **116** will be sufficiently high to overcome the total loss and lasing is permitted (ON state).

Examples of the measured laser diode characteristics of devices operating in the “reverse bias modulation mode” are shown in FIGS. **6** and **7**. The amplifier region in this example has a length of 700 μm , the modulator region has a length of 100 μm and the ridge-waveguide has a width of 3 μm . Amplifier and modulator region are separated by a 20 μm wide trench, which was etched into the upper GaN waveguide layer **110**. FIG. **6a** shows the light output vs. current characteristic for such a two-section laser device with different reverse bias voltages applied to the modulator section. With no voltage applied to the modulator section, the loss in the modulator section is high resulting in a high threshold current ($I_{th} \sim 225$ mA). If a reverse bias voltage is applied to the modulator section the loss in the modulator section is reduced leading to a reduction of the threshold current. For example at a modulator voltage of $U_{mod} = 6$ V the threshold current is reduced to $I_{th} \sim 190$ mA). In the “reverse bias modulation mode”, the laser is operated with the current in the gain (amplifier) section set to a constant current of $I_{gain} = 225$ mA (indicated by the dotted curve in FIG. **6a**). The light output vs. modulator voltage characteristic of the same two-section laser diode is shown in FIG. **6b**. The current in the gain (amplifier) section was set to a constant current value of $I_{gain} = 225$ mA. As the reverse bias voltage applied to the modulator section increases, the loss in the modulator section is reduced and the light output increases from 0.5 mW (at zero bias) to ~ 3 mW (at $U_{mod} = 7.2$ V). The corresponding laser diode emission spectra are shown in FIGS. **7a** and **7b**. At a modulator section voltage $U_{mod} = 0$ V the loss in

the modulator section is high, thus prohibiting lasing (as shown in FIG. **7a**). If the modulator section reverse bias U_{mod} is raised to 6 V, the loss the modulator section is reduced and consequently lasing is permitted, as can be seen in the spectra of FIG. **7b**.

The varying modulator region current and the varying dissipated electric power in the modulator region is significantly smaller in comparison to the constant current and the dissipated electric power in the amplifier region. For example, if the two-section laser diode is operated in the “forward current modulation mode”, the current density necessary to modulate the absorption in the modulator section (typically 100 A/cm² to 1000 A/cm²) is only a fraction of the current density necessary to produce sufficient gain in the amplifier section (typically 2000 A/cm² to 5000 A/cm²). Furthermore the length of the modulator section is much smaller (typically 1/10 to 1/5 of the length of the amplifier section) and therefore the current to switch the modulator section is even smaller. In the case when the two-section laser diode is operated in the “reverse bias modulation mode”, the dissipated electric power in the modulator region will be even smaller. Since the modulator section is operated in reverse bias, no current is injected in the modulator section active region. The only current flowing in the modulator section is the photocurrent, which is induced by the absorbed light from the amplifier region. Accordingly, the laser structure **100** operates at an elevated but constant temperature due to the constant amplifier region current. The varying modulator region current will have minimal temperature effect to the laser structure **100**. Modulating the laser from the non-light emitting, or OFF state, to the light emitting, or ON state, does -only result in a small increase in the operating temperature of the laser.

Since only the smaller modulator region **118** is used to control the output power of the emitted laser beam, the resulting lower capacitance will help achieve higher modulation speeds for the blue laser diode **100**.

The laser diode structure according to the invention described above can be applied to any device requiring compact laser structures, including high resolution laser printing devices, digital printers, display devices, projection displays, high density optical storage devices, including magneto-optical storage devices, including CD-ROM and DVD's whereby data is stored on a magneto-optical disk, fiber-optic communications devices, including for fiber optic emitters and repeaters and undersea communications devices (sea water is most transparent in the blue-green spectrum). The LED structure according to the invention can also be applied to any device requiring compact LED structures, including illumination devices and full color displays, including monolithically integrated pixels for full color displays.

While the invention has been described in conjunction with specific embodiments, it is evident to those skilled in the art that many alternatives, modifications and variations will be apparent in light of the foregoing description. Accordingly, the invention is intended to embrace all such alternatives, modifications and variations as fall within the spirit and scope of the appended claims.

What is claimed is:

1. A semiconductor laser structure comprising:

a sapphire substrate;

a plurality of III-V nitride semiconductor layers formed on said sapphire substrate such that at least one of said plurality of III-V nitride semiconductor layers forms an active layer;

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a first active region formed in said active layer, including at least one junction between p-type and n-type material, for functioning as an amplifier;
 a second active region formed in said active layer, including at least one junction between p-type and n-type material, for functioning as an optical modulator;
 wherein a sufficient forward bias is applied to said first active region such that stimulated emission is caused to occur therein, a portion of said stimulated emission being directed into said second active region, and the optical loss of said second active region is varied to cause lasing from said semiconductor laser structure.

2. The semiconductor laser structure of claim 1 wherein said optical loss of said second region of said semiconductor laser structure is varied by applying a forward bias current to said second active region.

3. The semiconductor laser structure of claim 1 wherein said optical loss of said second region of said semiconductor laser structure is varied by applying a reverse bias voltage to said second active region.

4. The semiconductor laser structure of claim 1 further comprising

a trench formed in at least one of said plurality of III-V nitride semiconductor layers, said trench forming said first active region and said second active region.

5. The semiconductor laser structure of claim 2 further comprising

a trench formed in at least one of said plurality of III-V nitride semiconductor layers, said trench forming said first active region and said second active region.

6. The semiconductor laser structure of claim 3 further comprising

a trench formed in at least one of said plurality of III-V nitride semiconductor layers, said trench forming said first active region and said second active region.

7. The semiconductor laser structure of claim 4 wherein said trench is formed in said plurality of III-V nitride semiconductor layers to said active layer.

8. The semiconductor laser structure of claim 1 wherein said semiconductor laser structure emits light with a wavelength within a range including 360 nm to 650 nm.

9. A semiconductor laser structure comprising:

a substrate;

a plurality of III-V nitride semiconductor layers formed on said substrate such that at least one of said plurality of III-V nitride semiconductor layers forms an active layer;

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a first active region formed in said active layer, including at least one junction between p-type and n-type material, for functioning as an amplifier;

a second active region formed in said active layer, including at least one junction between p-type and n-type material, for functioning as an optical modulator;

wherein a sufficient forward bias is applied to said first active region such that stimulated emission is caused to occur therein, a portion of said stimulated emission being directed into said second active region, and the optical loss of said second active region is varied to cause lasing from said semiconductor structure.

10. The semiconductor laser structure of claim 9 wherein said optical loss of said second region of said semiconductor laser structure is varied by applying a forward bias current to said second active region.

11. The semiconductor laser structure of claim 9 wherein said optical loss of said second region of said semiconductor laser structure is varied by applying a reverse bias voltage to said second active region.

12. The semiconductor laser structure of claim 9 further comprising:

a trench formed in at least one of said plurality of III-V nitride semiconductor layers, said trench forming said first active region and said second active region.

13. The semiconductor laser structure of claim 10 further comprising:

a trench formed in at least one of said plurality of III-V nitride semiconductor layers, said trench forming said first active region and said second active region.

14. The semiconductor laser structure of claim 11 further comprising

a trench formed in at least one of said plurality of III-V nitride semiconductor layers, said trench forming said first active region and said second active region.

15. The semiconductor laser structure of claim 12 wherein said trench is formed in said plurality of III-V nitride semiconductor layers to said active layer.

16. The semiconductor laser structure of claim 9 wherein said semiconductor laser structure emits light with a wavelength within a range including 360 nm to 650 nm.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

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APPLICATION NO. : 10/737669
DATED : April 8, 2008
INVENTOR(S) : Michael A. Kneissl et al.

Page 1 of 1

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Cover Page, after “(73) Assignee”:

replace Palo Alto Research Center Incorporated, Palo Alto, CA (US)

with: Xerox Corporation, Norwalk, CT (US)

Signed and Sealed this

Twenty-fourth Day of March, 2009



JOHN DOLL
Acting Director of the United States Patent and Trademark Office