NASA CASE NO. LAR 15184-1-SB

PRINT FIG. 5

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NASA Case No. LAR 15184-1-SB

INCREASED EFFICIENCY LED

AWARDS ABSTRACT

In a semiconductor light emitting diode (LED) a large proportion ofthe light produced will be internally reflected when it strikes the end face ofthe LED at an semiconductor-air interface. This is due to the high index of refraction of most LED semiconductor materials. This problem may be partially overcome by modification of the shape ofthe LED by a reverse taper ofthe sides ofthe LED. Light is redirected by the taper to strike the interface at an angle closer to normal. This allows light to exit the LED that would be totally internally reflected in an untapered LED.

The novelty ofthe present invention lies in the tapering ofthe sides ofthe LED for increased through transmission of light. Prior art devices have made use surface modifications such as roughening, addition of guiding layers, use of index matching materials and hemispherical shaping ofthe emitting end ofthe LED. Current technology LEDs have a transmission efficiency of only a few percent. An increase in this efficiency would be of great value to any technology that makes use of LEDs for light generation. The present invention is related to LAR 15050-SB, Collection of Light from Optical Fibers of NA>1.

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INCREASED EFFICIENCY LED

Origin of the Invention

The invention described herein was jointly made by an employee of the United States Government and a contract employee during the performance of work under NASA Contract No. NAS-1-19236. In accordance with 35 U.S.C. 202, the contractor elected not to retain title.

Background of the Invention

1. Technical Field of the Invention

The present invention relates to increasing the efficiency of light generation in light emitting diodes (LEDs).

2. Discussion of the Related Art

In an LED, light is produced at the p-n junction of the diode. The LED is designed to allow the light produced to escape through an end face. However not all of the light is able to escape a diode in air because a portion is totally internally reflected at the interface between the diode and surrounding air. Due to the very high refractive index of most semiconductor materials, the portion of the light totally internally reflected is very large.

The portion of light transmitted by the LED will depend on the index of refraction of the LED as well as that of the medium in which the LED is placed. Often the medium will be air. Herein the transmitting portion of the LED will be known as the air semiconductor interface, however this should be understood to include any other medium in which an LED may operate. A critical angle, θ_c, measured away from perpendicular, may be defined. Light impinging the air semiconductor interface at an angle less than the critical angle will refract through the interface. Light impinging at an angle greater than the critical angle will be totally internally reflected, remaining in the semiconductor.

One method used to overcome the problem of total internal reflection is to encapsulate the LED in plastic to better match refractive indices and reduce reflection at the interface. This allows a small increase in efficiency.

A second method is to shape the air-semiconductor interface into a hemisphere, thereby altering the angle at which light strikes the interface. This allows a greater portion of the light to be transmitted at the interface. The hemispherical shape, while allowing more light to be transmitted also contributes to diffusion of the light, thereby decreasing intensity.

Bergh, et. al. (US Pat No 3,739,217, herein incorporated by reference) discusses the problem of total internal reflection in an LED. To overcome this problem the semiconductor surface is roughened through chemical or mechanical means. According to Bergh, et. al., light striking the rough surface will pass through at approximately the same rate as it would in an LED having a flat surface. In a rectangular shaped LED any light that impinges on an air-semiconductor interface at an angle that allows total internal reflection will never escape as each interface will be struck at the same angle. However, in a roughened LED that light which is internally reflected has a greater chance of exiting the LED upon striking the rough surface a second or succeeding time. This effect is a result of the random reflection at the rough surface, the light will strike at a random angle and this angle will change with each reflection from the roughened surface. Thus, an overall increase in efficiency is achieved by allowing light that has totally internally refracted to have a chance to escape on subsequent interactions with the air-semiconductor interface.

Yamanaka, et. al. (US Pat No 4,080,245, herein incorporated by reference) also make use of geometric modifications of the emitting surface of an LED for the purpose of increasing light transmission efficiency across the air-semiconductor interface.

Figueroa, et. al. (US Pat No 4,856,014, herein incorporated by reference) makes use of internal channels to guide light to the air-semiconductor interface at an angle less than the critical angle.

Haitz (US Pat No 5,087,949, herein incorporated by reference) geometrically alters the air-semiconductor interface through the use of diagonally cut facets. These facets allow a greater portion of the light produced to strike an interface at an angle less than the critical angle. Additionally, as with the Bergh invention, totally internally reflected light will strike the air-semiconductor interface at a varying angle since the LED is not rectangular, thus allowing light to escape upon striking an interface multiple times.

Fletcher, et. al, (US Pat No 5,233,204, herein incorporated by reference) present an LED having a thick transparent layer overlying the light generation region of the LED. This improvement is directed towards LEDs that make use of an electrically conductive transparent window layer between the light generation region and a top metal contact. The thick transparent layer allows more light to escape from the sides of the LED than would be able to with a thin electrically conductive transparent window. One embodiment of the invention makes use of non-parallel sides for the thick electrically conductive transparent window layer so that more light may refract through the interface between the window and the surrounding medium.

Egalon and Rogowski (US app. ser. no. 08/______, filed ______, herein incorporated by reference) concerns untrapping light in an optical fiber having high numerical aperture. It also makes use of geometric modifications of a reflecting surface to modify the angle of incidence of light so that it may refract through an air interface instead of being totally internally reflected.

Summary of the Invention

It is an object of the present invention to provide a p-n type semiconductor LED capable of efficiently transmitting light produced at the p-n junction through the air-semiconductor interface.

It is a further object of the present invention to do so without the use of plastic encapsulation or difficult machining of the semiconductor material into a hemispherical shape.

To achieve the forgoing objects a LED is presented that makes use of reverse tapering to alter the path of light produced such that more is able to be transmitted through the air-semiconductor interface.

Brief Description of the Drawings

Fig. 1 is a drawing showing the generation of light at the p-n junction of a semiconductor LED.

Fig. 2 is a drawing showing the total internal reflection of a light ray at a air-semiconductor interface in a semiconductor LED.

Fig. 3 is a drawing of light being refracted through a hemispherical interface.

Fig. 4 is a drawing of a semiconductor having a reverse taper, showing a sample light path for a beam being refracted through the interface, dashed lines show how the same beam would be totally internally reflected in an untapered LED.

Fig. 5 is a drawing of a semiconductor LED with tapered sides and the addition of an end face with a refractive index chosen to reduce total internal reflection.

Description of Preferred Embodiments

Making reference to Fig. 1, an n-p semiconductor is shown. At the p-n junction **14** between n type semiconductor region **10** and p type semiconductor region **12** photons **16** are produced when electricity is applied to electrical contacts **18**. Oxide layer **20** serves as an electrical insulator.

Making reference to Fig. 2, total internal reflection is shown in a semiconductor LED similar to that in Fig. 1. A light ray **22** is produced at the p-n junction **14** as in Fig. 1. The light ray travels to the air-semiconductor interface **24** where it is totally internally reflected.

Fig. 3 shows a semiconductor LED in which the air-semiconductor interface **24** is shaped in a hemisphere. Light rays **22** produced at the p-n junction **14** are refracted through the air-semiconductor interface **24**. Note that these light rays are dispersed as a result of refracting through the curved surface.

Fig. 4 shows an LED according to the present invention. As in the LED of Fig. 1 an n-type semiconductor region **10** is surrounded by a p-type semiconductor region **12**. Light rays are produced at the p-n junction **14**. A light ray **22** traveling at angle θ reflects off of the reverse tapered side of the LED **26** and continues to the air-semiconductor interface **24**. It strikes the interface **24** at an angle ϵ and refracts through. Dashed lines **26'** show the sides of an untapered LED. Dashed arrows **22'** represent the path of the same light ray in an untapered LED. Light ray **22'** strikes the interface **24** at an angle ϵ' (not shown) and is totally internally reflected. Angle α is the angle at which the sides of the LED are reverse tapered. Making reference now to Fig. 5, another embodiment of the present invention is shown. As in the LED of Fig. 1 an n-type semiconductor region **10** is surrounded by a p-type semiconductor region **12**. In addition to the tapered side of the LED **26** as in Fig. 4 another layer **28** is added between the surface of the semiconductor and the air **30**. This layer **28** is chosen to have an index of refraction lower than that of the semiconductor materials. The use of a lower index of refraction material in the interface region helps to reduce total internal reflection.

In the examples are shown an n-p type LED, that is an n-type semiconductor is surrounded by a p-type semiconductor. This arrangement may be preferable because the refractive index of a p type semiconductor may be made slightly lower than that of an n type semiconductor, providing a waveguide configuration. However a p-n type LED may also be used with the reverse taper surface to some advantage. As the difference in refractive indices is generally small between n and p type semiconductors the waveguiding effect would tend to be small.

The index of refraction of region **10** is given to be n_1, the index of refraction of region **12** is given as n_2, and the index of refraction of the medium surrounding the LED is given as n_0. Light impinging the air-semiconductor interface will refract through the interface if the critical condition is met. For light in region **10** this is that $\sin \epsilon < n_0 / n_1$, that is, light striking the interface at an angle closer to the normal angle than ϵ will refract through, and light striking the interface at an angle closer to parallel than ϵ will be totally internally reflected. Light in region **12** must meet the condition $\sin \epsilon < n_0 / n_2$. In the case where the LED is in air, $n_0 = 1$, generally n_1 and n_2 are both much higher than 1. In addition, as noted above, n_1 is approximately equal to n_2 so in a first approximation the conditions for the two regions may be considered to be the same.

The above conditions may be used to determine an advantageous choice for α, the angle of taper of the sides of the semiconductor, for purposes of this discussion only n_1 will be used, n_2 may be trivially substituted when necessary, however here we take them to be equivalent:

$$0 < \sin \epsilon < (n_0/n_1) \qquad (1)$$

where:

$$\epsilon = (\pi/2-\theta) \text{ when } (\pi/2-\theta) \leq \alpha \qquad (2)$$

and,

$$\epsilon = 2\alpha - (\pi/2-\theta) \text{ when } (\pi/2-\theta) > \alpha \qquad (3)$$

and,

$$0 < \theta < \pi/2 \qquad (4)$$

Equation one gives the critical conditions for light to refract through the air-semiconductor interface as discussed above. Equation two merely states that light traveling at an angle that does not cause it to intersect with the tapered sides will not have any dependance on α. Note that the angle θ is measured from the normal angle to the side of an untapered semiconductor. Thus, $(\pi/2-\theta)$ gives ϵ which is measured from the normal angle to the air-semiconductor interface. Equation three shows the dependance on α of light traveling at an angle θ such that it intersects with the tapered sides of the semiconductor. Note here that since the distance from the production of light at the p-n junction to the tapered sides of the semiconductor is non-zero, the given conditions for intersection do not strictly hold over small distances. That is, in an LED having a short optical path from the p-n junction to the air-semiconductor interface compared with the width of the LED, the conditions given in Eqns. 2 and 3 are only approximations. Some light having $(\pi/2-\theta) < \alpha$ will obey Eqn. 2 rather than Eqn. 3. The angle α may therefore be chosen by optimizing Eqns. 1 and 3. This optimization will depend on the ratio of width to height of the LED as well as factors such as the rate of absorption of light by the LED material, and the values of n_1 and n_0.

In optimizing equations 1 and 3 for α it may become apparent that a single value of α is not the best solution. Instead, a varying α, providing a curved taper rather than a straight reverse taper may enable a larger amount of light to be untrapped.

Other applications and modifications of the present invention will be apparent to those skilled in the art. The above embodiments are not exhaustive but rather given by way of example. It is understood that the present invention is capable of numerous modifications within the scope of the following claims.

INCREASED EFFICIENCY LED

Abstract of the Disclosure

In an LED a large portion of the light produced is lost due to total internal reflection at the air-semiconductor interface. A reverse taper of the semiconductor is used to change the angle at which light strikes the interface so that a greater portion of the light is transmitted.

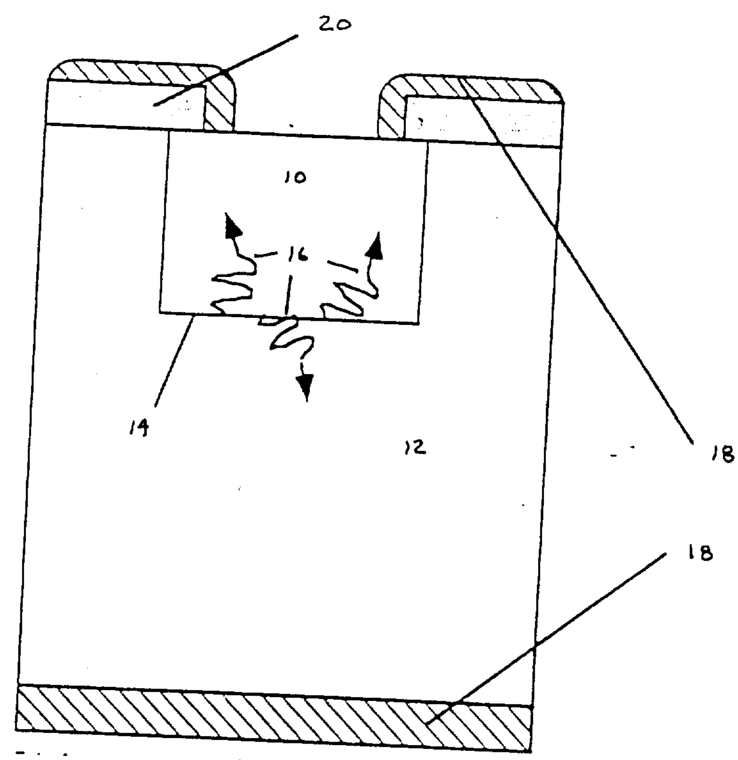

Fig. 1

Prior Art

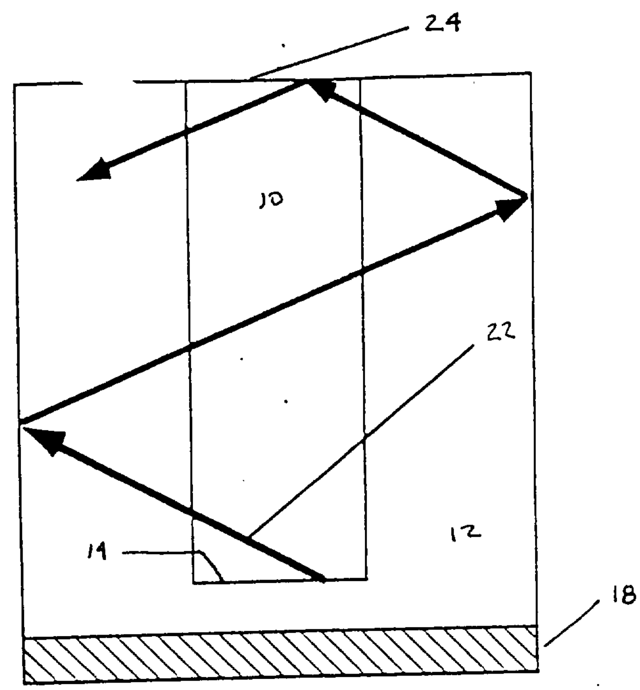

Fig. 2

Prior Art

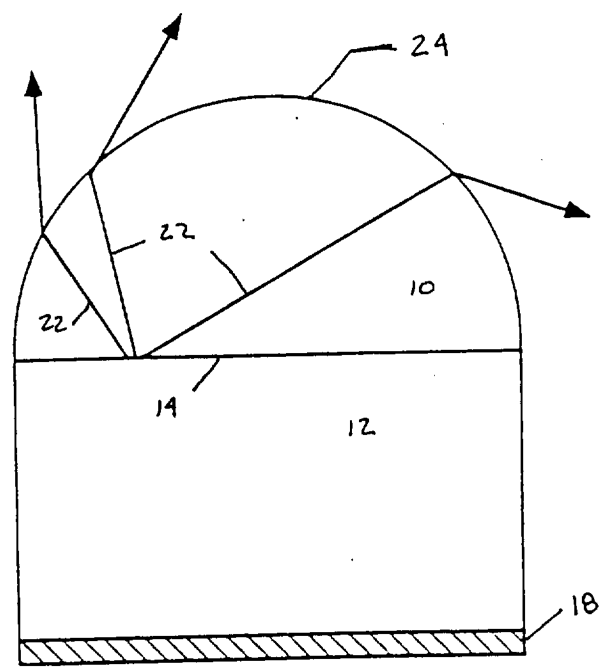

Fig. 3

Prior Art

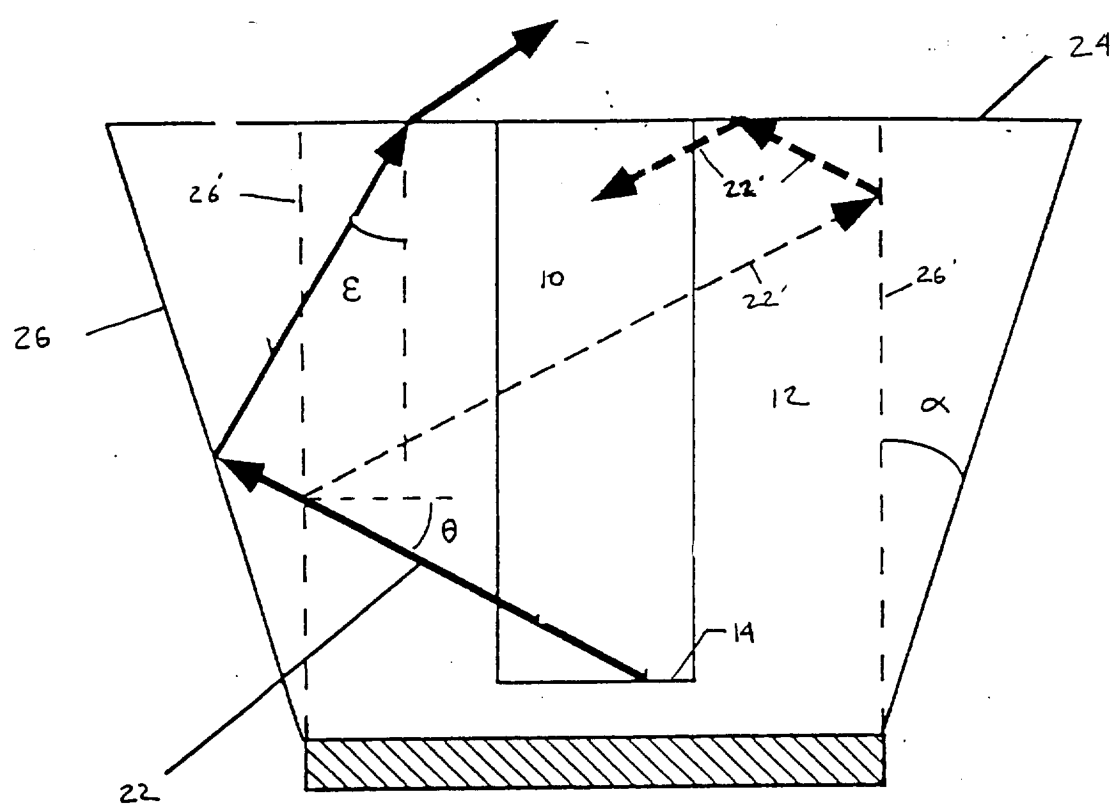

Fig. 4

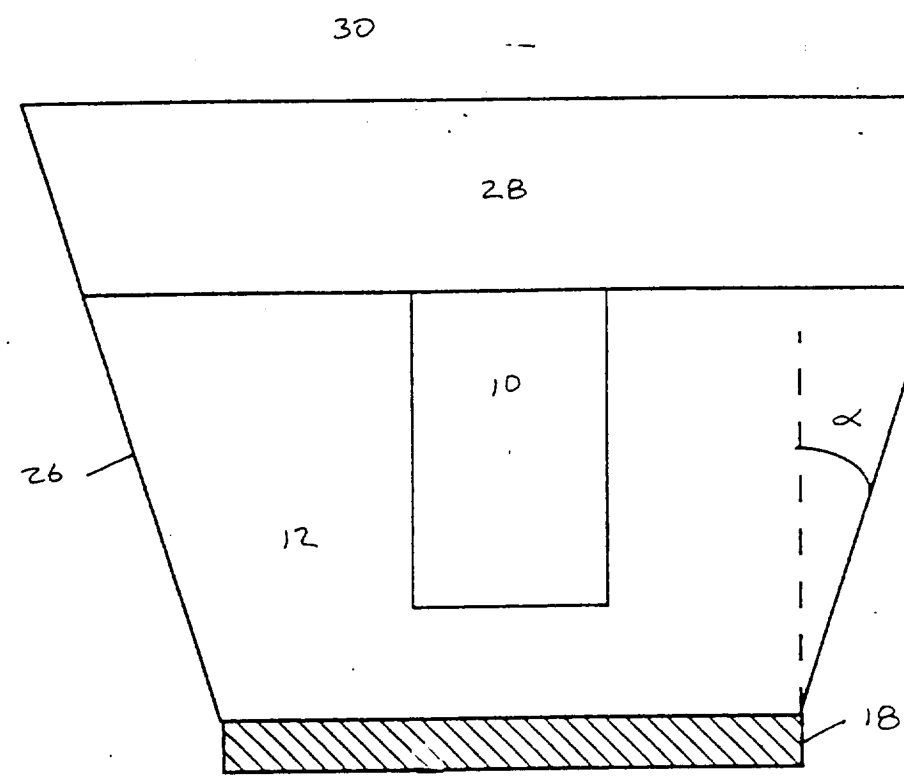

Fig. 5