Increasing the emission power of LEDs (λ = 1.7-2.4 μm) by changing the light direction in the GaSb/GaInAsSb/GaAlAsSb heterostructure

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Abstract. Development of a curved reflective surface on the bottom side of the LED chip based on the GaSb/GaInAsSb/GaAlAsSb heterostructure increases the emission power of LEDs in 1.9-2.0 times compared with power of the tradition LED chip. This effect was investigated for the wavelengths of 2.0-2.3 μm. We believe that the improving of LED efficiency is the result of changes of light direction by the reflection from the curved surface formed by the hemispherical pits in the crystal.

1. Introduction

Semiconductor light emitting diodes (LEDs) for the mid-IR spectral range of 1.7 - 2.4 μm are promising for ecological monitoring and medical diagnostics [1]. One of the basic materials for development of LEDs for the spectral range of 1.7 - 2.4 μm is GaSb/GaInAsSb/GaAlAsSb heterostructure system. Though the internal quantum efficiency in the heterostructures can reaches 70% [2], the large refractive index of the semiconductor (n = 3.5 - 3.7) complicates the radiation output from the LED chip volume. This is explained by the fact that only a small portion of the light generated in the crystal falls on the outer surface at an angle less than the total internal reflection angle. As a result, only 8% of the radiation can go beyond of the parallelepiped shape crystal. Therefore one possibility to improve the LEDs efficiency is to find methods to increase the portion of light coming out the crystal.

The different ways of texturing the semiconductor surface are discussed in literature [3-6]. Texturing results in a change in the direction of the light flux within the crystal. As a result, the probability that the light flux will incident on the top side of the chip at a suitable angle is increased. This method was used to increase the output radiation of LEDs both for visible and near-IR spectral range.

Different methods of texturing the surface of semiconductor crystal are also used to increase the external quantum efficiency of LEDs in the mid-IR range (2-5 μm), though multipass is less effective in narrow-band materials than in wideband materials. Low efficiency is explained by the fact that the absorption of radiation by free carriers is proportional to the square of the radiation wavelength.

We investigated the GaSb-based LEDs for the spectral range of 1.8 - 2.4 μm with mesas of cubic and step-pyramid shape in ref. [7]. Theoretical and experimental data have shown that the external quantum efficiency is proportional to the S/V ratio, where S is the area of the surface through which the light is coming out and V is the total volume of the crystal. Once the crystal form is changed from cubic to pyramidal one, the coefficient of radiation coupling can be increased by a factor of 1.5. If LEDs are fabricated in a conical form with a concave surface, the radiation output can be also enhanced by a factor of 1.5, as discussed in [8].

2. Experimental samples

This investigation is a continuation of our investigations on the development of spontaneous sources for the mid-IR spectral range. The aim of this investigation is to study the possibility of increasing the optical power of LEDs based on GaInAsSb/GaAlAsSb heterostructures by changing the direction of the light beams. Such a changing of the light beam direction is achieved by multiple reflections of the photons on the curvilinear surfaces created in the crystal.

We used a GaSb (100) substrate to produce LEDs. It was doped by Tellurium to the carrier concentration of $1.2 \cdot 10^{18}$ cm^{-3}. The n-GaInAsSb 4 µm thick active layer was grown on the substrate by liquid phase epitaxy. The layer was doped by Tellurium to the carrier concentration n~$1.4 \cdot 10^{17}$ cm^{-3}. 3 µm thick wide-bandgap emitter was grown on the active layer. The Emitter was doped by Germanium to the carrier concentration p~$(2\text{-}3)*10^{18}$ cm^{-3}.

Three types of LED chips were developed on the basis of GaSb/GaInAsSb/GaAlAsSb heterostructure (series AV-54) by contact photolithography and wet chemical etching. Designs of these three chip types are shown schematically in Figure 1a. The chips had a square form with the size of 950 x 950 µm. The circular contact was formed by deposition of three layers of Cr/TeAu/Au in the center of the chip on the top side of the structure. The external contact diameter was 770 µm; the inner diameter of the contact was 740 µm.

Three types of LED chips differed by the design of the bottom side contact only. Lateral section schemes are shown in Figure 1 b, c, d.

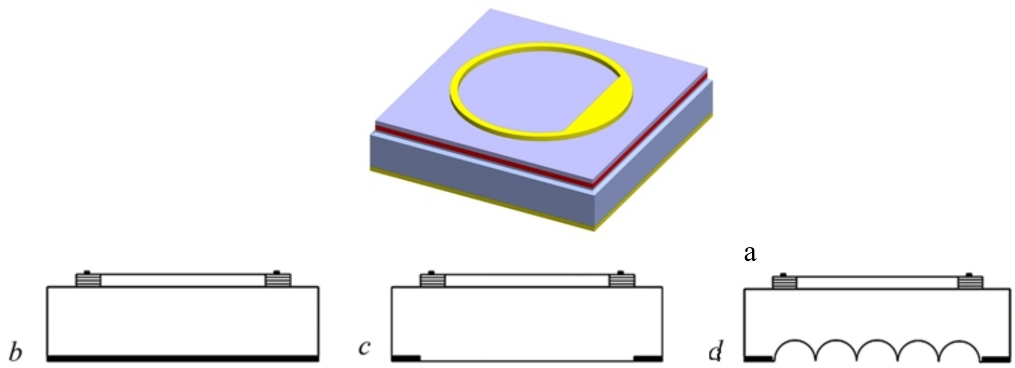

Figure1. LED chips with different geometry of bottom surfaces.
a - LED chip with a top circular contact.
(b, c, d) – lateral view of the LED chips with:
b – solid ohmic bottom contact;
c – bottom contact with a 880 µm diameter window;
d – bottom contact with 120 µm diameter hemispherical pits in the window.

Thus, one portion of the radiation from the active layer was directed outside the crystal through the near surface region (top side) of the chip, whereas the other portion of the radiation was directed towards the bottom side of the chip through the substrate 200 μm thick transparent for radiation.

Let us consider three types of the chip design.

The chip of the first type is characterized by a solid ohmic contact formed on the bottom side of the chip (Figure. 1 a). After alloying the contacts eutectic alloy was formed on the surface of semiconductor. This alloy adsorbs part of radiation directed to the bottom side of the chip.

The light flux is passed through the substrate transparent for radiation from active area to the bottom side of the chip. The large portion of the light flux is adsorbed at the interface between the substrate and ohmic contact in the eutectic alloy.

To form the chip of the second type a window with the diameter of 880 μm was formed in the ohmic contact (Figure. 1 b). Light flux impinged on the bottom side of the chip was reflected from the area free of metallization. Such a reflection allowed to increase the light flux reflected from the bottom side of the chip inside the crystal. However, light flux cannot change the angel of incidence and the reflection angle in the crystal.

In the LED chips of the third type the hemispherical pits with the radius of 60 μm were formed on the bottom side in the area free of metallization. In this case the radiation generated in the crystal is reflected repeatedly from the curved surface formed by the hemispherical pits (Figure. 1 c). As a result, the direction of light flux is changed by reflection from a curvilinear surface and much of it was extracted through surface on the top side of the chip.

LED chips were mounted on the TO-18 frame. Bottom side of the chip was adjoined to the diode frame.

3. Measuring the characteristics and discussion

Spectral characteristics were studied by an automated setup based on a monochromator DK-480 (CVI Laser Corp.) with 300g/mm diffraction lattice. An optical radiation was detected on the monochromator exit by InSb photo detector (Judson Technologies) with sensitive platform with the diameter of 4 mm. The signal from the photo detector was detected by digital selective amplifier SR-810 (Stanford Research Systems) after pre-amplification. The resulting digital signal was transmitted to a computer. This computer implemented a control of the measurement process.

An electroluminescence was excited by rectangular current pulses with a filing factor of 50 % and a 521 Hz repetition rate. Pulse amplitude was varied from 20 mA to 220 mA. Negative potential was applied to the GaSb substrate and positive potential was applied to the covering layer.

The dependence of the emission spectra and radiation power on the current density flowing though the LED chip was investigated. Emission spectra for three types of LED chips are shown in Figure 2. These spectra were measured at a current of 250 mA. All the emission spectra obtained have similar shape but different intensity of radiation. Maximum radiation intensity was observed in the LED chips with the hemispherical depressions formed on the bottom side of the chip. Minimal radiation intensity was observed in the chips containing a solid ohmic contact. Dependence of the output optical power on the current for three types of the LED chips is shown in Figure 3. The steepest dependence of the radiation power on the current was observed for the LED chips containing the hemispherical depressions on the bottom side of the chips. The most flat dependence was observed for the chip containing the solid ohmic contact. The increase in output power by a factor of 1.7 was observed for LED chips of the second type compared with the chips of the first type (at the current of 200 mA). The double increase in the output power was observed for the chips of the third type compare with the chips of the first type. The increase of the output power for LED chips with spherical etched pits on the bottom side of the chip provides a changing of the direction of the light beams by reflections on a curved surface.

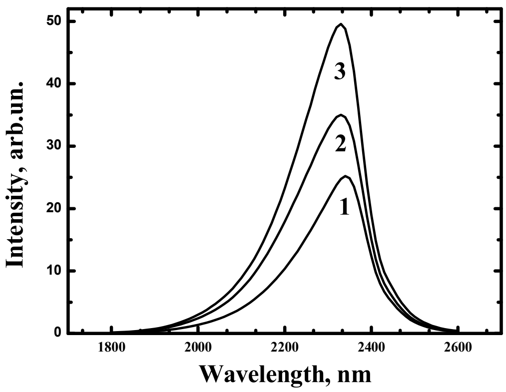

Figure 2 Emission spectra of LED chips with:
1 – solid ohmic bottom contact;
2 – bottom contact with a 880 μm diameter window;
3 – bottom contact with 120 μm diameter hemispherical pits in the window.

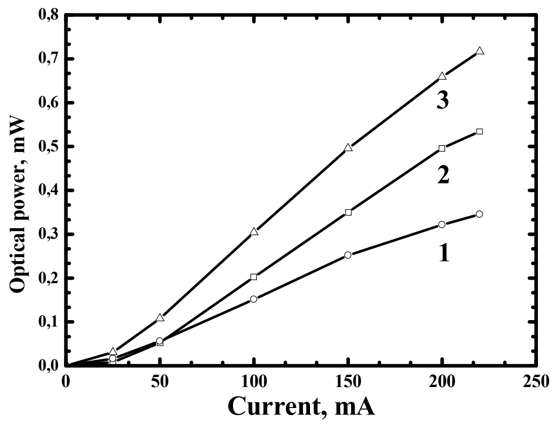

Figure 3. Dependence of the output optical power on the current for the LED chips with:
1 – solid ohmic bottom contact;
2 – bottom contact with a 880 μm diameter window;
3 – bottom contact with 120 μm diameter hemispherical pits in the window.

4. Conclusion

Thus, in this study a new way of increasing the emission power of LEDs for mid-infrared spectral range was proposed. For the LED chips of the third type with structured bottom surface an increase of the emission power by a factor of 1.9 is observed in the entire spectral range of 1.7-2.5 μm.

Implementation of the curved reflective surfaces in developed LED chip is an effective method for increasing the emission power of LEDs for the mid-IR spectral range.

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