GaAs-AlGaAs heterostructures for personalized medicine devices

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Abstract

The investigations of the processing factors combination have been carried that provide to make the customizable GaAs-AlGaAs heterostructures for personalized medicine devices with high emission power, close tolerance of electroluminescence peak wave length (not more than ±3nm), and high parameters in-use stability.

Key words: liquid phase epitaxy; GaAs-AlGaAs heterostructures, light emitting diodes;

The humanity enters successfully into the era of personalized diagnostics and remote patient health monitoring. Modern personalized medicine devices provide the round-the-clock remote patient health real-time monitoring wherever he located. The blood parameters diagnostics is one of the top requested personalized diagnostics direction.

Currently the leading global manufacturers of medical diagnostics devices make successfully the noninvasive oxygen in blood concentration control devices, improve the design of invasive glucose in blood concentration control devices and are developing the noninvasive devices for this purpose.

The level of oxygen in blood concentration has gone one of main criteria of patient health status and the necessary emergency actions at the COVID 19 pandemic. Now the portable pulse-oxymeter is the integrated accessory as for intensive care units as for emergency doctors.

The noninvasive pulse-oxymeter operating principle is based on the difference in level of IR radiation absorption by blood components at the various wave lengths [1]. In particular the bonded with oxygen hemoglobin (oxyhemoglobin) HbO2 has the better absorption at IR wavelengths range (the main absorption is at the 880-940 nm range), when non-bonded with oxygen hemoglobin (deoxyhemoglobin) Hb has the better absorption at red wavelengths range (the main absorption is at 660 nm). When the tissue (ear lobe or finger) are placed between the wide-range photodiode and two LEDs the measurement of absorption difference at the various wavelength permits to calculate the oxyhemoglobin concentration with relation to the total hemoglobin concentration in blood.

The investigation of the correlation between LEDs parameters and the saturation level measurement accuracy of pulse-oxymeter has been shown that LEDs are the main source of measurement errors. The pulse-oxymeter sensor accuracy is dependent highly on the real wavelength and power values deviation from the normal values according to device design which can be resulted or at the device manufacture or due to operating degradation. Besides most significantly that the wavelength values deviation from the normal values influences more crucially on measurement accuracy as the oxygen saturation in blood is reduced.

Evaluation of LEDs parameters effect on measurement accuracy shows that the 4 nm of LED wave length deviation from normal can refer to measurement error in 7% at the threshold for patient hemoglobin saturation level of 80%[2] .

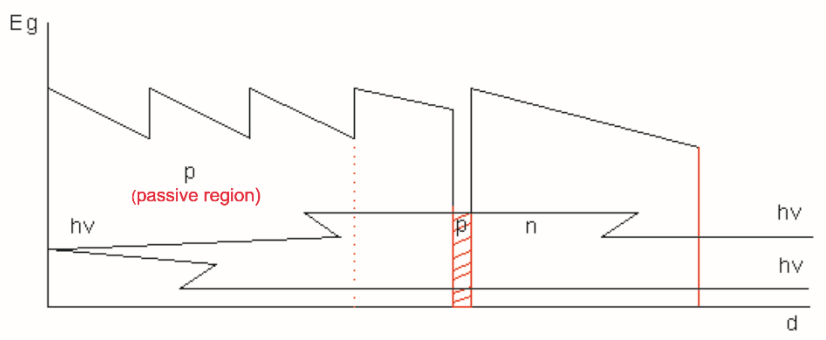
Amid the COVID 19 pandemic that inaccuracy can constitute the life-threatening situation for patient. That is why the more and more hard requirements are placed on the LEDs emitting material for personalized medicine application. That regards both its working parameters precision and its long-term stability.

The personalized medicine devices and in particular the pulse-oxymeter are in need the such customized emitting material as hetero-epitaxial GaAs-GaAlAs structures with peak wave length deviation from normal not more than 3 nm and with high long-term stability of parameters.

However the made by usual epitaxial technique heterostructures have the typical peak wave length deviation from normal up to 10 nm. Then the structures with small wave length deviation from normal can be delivered only by means of the grown structures sorting.

The development of the customized GaAs-GaAlAs heterostructures with high emitting power, small wave length deviation from normal (not more than ± 3 nm) and with high long-term stability of parameters would permit the reliability and accuracy of the blood base parameters diagnosis. The present investigation is devoted to this current problem.

Now so-called multi-pass double heterostructures (DDH) are applied in personalized medicine devices, because their design provides the maximum emitting power. The multi-pass heterostructure is the double heterostructure where the active region is between two wide-gap emitters which are transparent for light output, whereas the non-transparent substrate is removed [3]. Due to that the photons after the multiply reflections in crystal make a contribution to light output but don't absorb by substrate. Moreover there aren't the additional absorption losses in active region practically due to their re-emission with the close to 100% internal quantum efficiency. This effect boosts to the sharp rise of external quantum efficiency and as a result the multi-pass double heterostructure quantum efficiency can be five times that of the classic double heterostructure. The multi-pass double heterostructure design schematic view is presented at Picture 1.



Picture 1. — The design of multi-pass double heterostructure

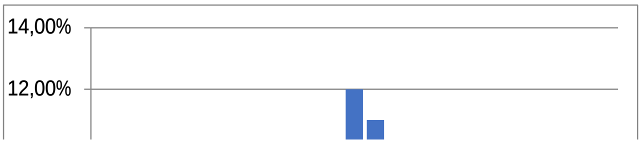
In this investigation the GaAs-AlGaAs heterostructures have been grown at the “Argal” liquid phase epitaxy machine. The growth was processed in the hydrogen atmosphere with dew-point of –80ºC. The graphite cassette of pumping type with successive solution-melt replacement in the substrate-to-substrate narrow gap was used as growing unit. There was the layers growth carried at the chilling temperature of 980—1050°C with the following forced cooling at the 0.2—1.5 ºC/min rate till required temperature. Then the epitaxial growth was interrupted by means of sealing layer forming technique [4]. After epitaxial growth the heterostructure was purified from gallium by ultrasonic cleaning. Key physical parameters of heterostructures were measured on test mesa-diodes with 0.4 mm^2 in area which have been made by photolithography. The light power was measured at 20 mA current and peak wave length was measured at 5 mA current. The measurement of long-term stability of parameters was made on the standard 250x250 micron chips.

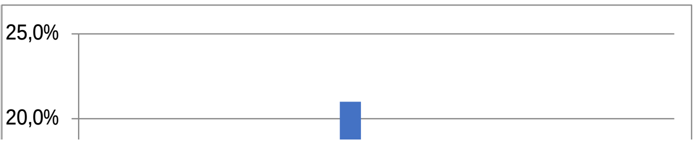
The rather wide wave length band of emission is the specific of LEDs heterostructures. That is why there is the problem of demanded peak wave length achievement. Moreover the peak wave length parameter is very sensitive to the active emitting region composition. The growth of active region in double heterostructure is carried always after forming of layers with higher aluminium concentration. There is the transport of excess aluminium from previous solution-melt to substrate-to-substrate gap within the solution-melt replacement. This process changes locally the effective solution-melt composition that has been designed for active region. All it results in peak wave length deviation from the normal and in its inhomogeneity over the heterostructure surface. In present work the method of solution-melt double-change has been used at the active region forming to stabilize the peak wave length deviation from the normal and its homogeneity. This procedure permits to reduce essentially the excess aluminium transport from previous solution-melt due to its successive removal from substrate-to-substrate gap. As a result the peak wave length deviation from the normal has been reduced till 2—3 nm. The comparative data of peak wave length measurement over the heterostructure surface are presented in Table 1 as for single as for double solution-melt replacement.

Table 1. Data of peak wave length measurement for single and for double solution-melt replacement.

Normal peak wave length λ_0, nm	Solution-melt change procedure	Measured peak wave length for structure mesa diodes λ_n, nm					Average deviation from normal, nm	Maximal deviation from normal, nm
		λ_1, nm	λ_2, nm	λ_3, nm	λ_4, nm	λ_5, nm		
660	Single	669	666	658	668	662	-4,6	-9,0
	Double	663	662	659	662	660	-1,2	-3,0
800	Single	812	808	805	808	807	-8,0	-12,0
	Double	802	802	801	802	800	-1,4	-2,0
900	Single	910	906	902	907	905	-6,0	-10,0
	Double	903	901	900	901	902	-1,4	-3,0

The comparative histograms of the peak wave length deviation from 660 nm normal distribution for mesa diodes of heterostructures shipment both for single and for double solution-melt replacement are presented at Picture 2a) and 2b).





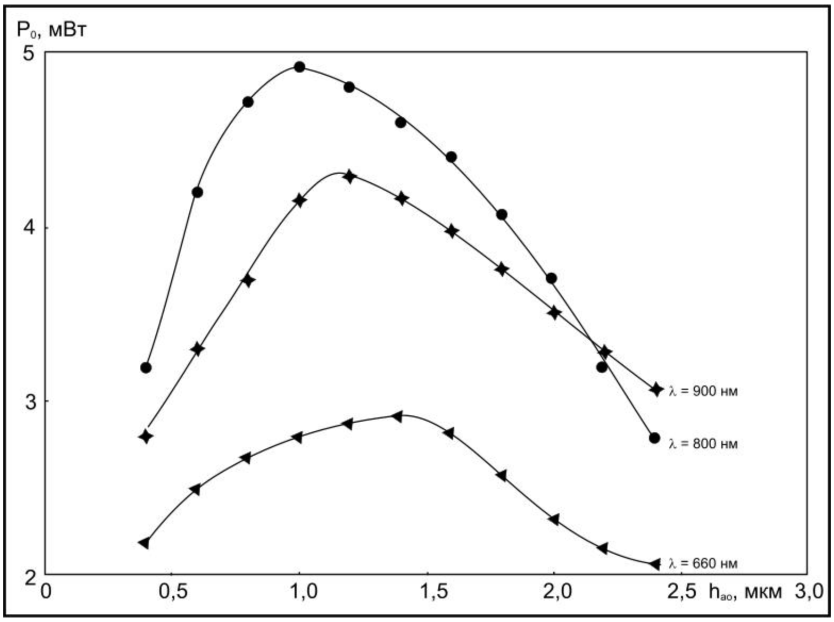
a) b)

Picture 2. — The comparative distribution histograms of the peak wave length deviation from 660 nm normal for mesa diodes of heterostructures shipment both for single a) and for double b) solution-melt replacement

The following experiments have shown than the output power depends essentially upon active region thickness. These results are presented at Picture 3. It has been found that most suitable active region thickness depends upon the normal peak wave length.

The active region thicknesses which provide the maximal output power are the following;

- there is 1.4 micron for heterostructures with l = 660 nm;
- there is 1.0 micron for heterostructures with l = 800 nm;
- there is 1.2 micron for heterostructures with l = 900 nm.

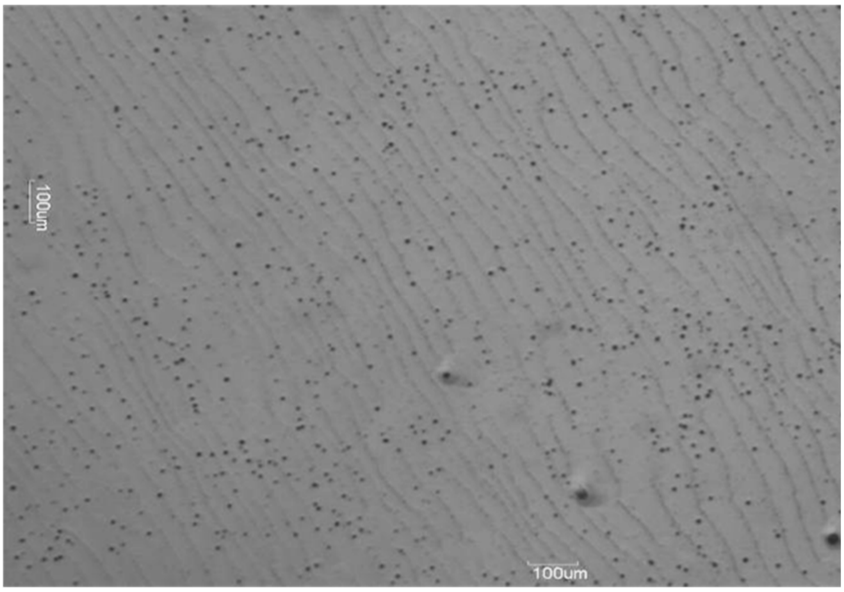


Picture 3. — Dependence of power emission P_0 vs active region thickness h_{ar} for heterostructures with normal peak wave length of 660, 810 and 900 nm.

Moreover the method of background impurity gettering was used to improve the power emission by means of rare earth elements doping into solution-melt. In this investigation ytterbium was used due to its workability and the high efficiency for solution-melt purification [5]. At the usage in epitaxial growth of GaAs-AlGaAs layers rare earth elements have the specific tendency to form the minor phase [6]. As a result various defects have arisen in epitaxial layers. That is why it was necessary to find the acceptable level of ytterbium doping.

At the experiments it has been found that power emission increases monotone with the ytterbium concentration increase in solution-melt. But upon 0.35 atomic % of ytterbium concentration reaching the intensive defects formation starts. The typical view of defective surface is presented at Picture 4.

As a result the ytterbium concentration of 0.3 atomic % has been taken as optimal in view of the necessary technological reserve.



Picture 4. — The view of heterostructure surface at 0.35 atomic % of Yb concentration in solution-melt

That level of ytterbium concentration in solution-melt provides as high quality of heterostructure surface as the noticeable rise of power for all studied heterostructure types with l = 660nm, 800 nm and 900 nm correspondently up to 11%, 16% and 14% in average.

The power rise is due to the non radiative recombination centers concentration reducing. There was the long-term stability of heterostructure parameters improvement together with power rising at the ytterbium addition into solution-melt.

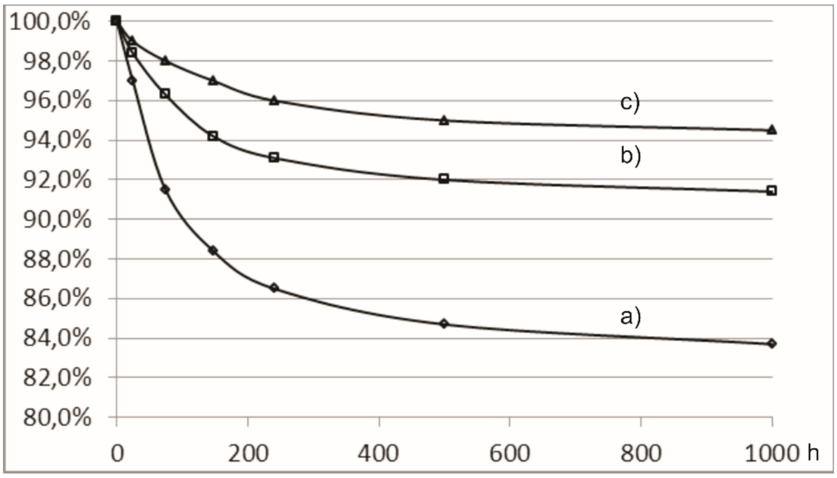
There have been made the investigations of the heterostructures structural perfection on degradation process.

In GaAs-AlGaAs heterostructures epitaxial layers the structural defects level depends upon dislocations, the main source of which are the starting arsenide-gallium substrates. The substrates dislocation pattern works principally on concentration and distribution of dislocation in epitaxial layers, especially at the initial stage of layer forming due to the dislocation propagation from substrate into layer.

There were used the substrates from GaAs single crystals which have been made by two main industrial growth techniques to study the single crystals growth technique influence on defects formation in epitaxial layers of LEDs heterostructures. There have been used GaAs single crystals made by Liquid Encapsulated Czochralski (LEC) technique for first type of substrates and made by Vertical Gradient Freeze (VGF) technique for second type of substrates. The main difference of these GaAs single crystals consist in contrasting levels of dislocation density (N_d). So LEC GaAs single crystals have N_d of (2—4)•10^4 cm^{-2} when VGF GaAs single crystals have Nd of (2—5)•10^3 cm^{-2} only.

The examination of parameters long-term stability was carried at working current of 20 mA within 1000 h. The investigation results are presented at Picture 5 both for heterostructures on substrates of two these types and in addition for heterostructure that has been grown on VGF substrate from solution-melt with Yb doping.

One can see that high dislocation density reduces long-term stability of heterostructures. It can therefore be concluded that the substrates from VGF GaAs single crystals usage has unmatched advantage for manufacture of heterostructures with high long-term stability of power.



Picture 5. — The power emission degradation dependence vs operation time for heterostructures with peak wave length of 660 nm which have been grown: a) — on LEC substrates, b) on VGF substrates, c) — on VGF substrates with Yb doping

Conclusion

Thus within the fulfilled investigation it has been found out the key conditions for technology of customizable GaAs-GaAlAs heterostructures with the parameters which are satisfied a requirements of personalized medicine devices.

These key conditions include such procedure as:

- the usage of double solution-melt replacement method at the active region forming stage;
- the background impurity gettering in solution-melt by Yb;
- the usage of optimal active region thickness;
- the usage of the substrates from VGF GaAs single crystals.

The practical realization of these results has provided the peak wave length deviation from normal reducing from ±8 nm to ±3 nm as over surface of heterostructure as from one to the next heterostructure in shipment, the power emission rise at 11—16% depending of heterostructure type and the rise of long-term stability of power at 1000 h from 82—89% to 94—97%.

References

1. Rogatkin D.A. Fizicheskie osnovy opticheskoi oksimetrii / Rogatkin D.A. // Meditsinskaya fizika. 2012. №2. P. 97-114. (in Russian)

2. «Clinical Impact of LED Performance in Pulse Oximetry». Electrode Company Ltd./ http://www.electro.co.uk/pdfs/clinical_implications.pdf

3. Alferov Zh.I. Mnogoprokhodnye geterostruktury. II. Vneshnii kvantovyi vykhod izlucheniya /Alferov Zh.I., Agafonov V.G., Garbuzov D.Z.// FTP. 1976. Tom 10. Vyp. 8. P.1497-1506. (in Russian)

4. Kryukov V.L., Kryukov E.V., Meerovich L.A., Nikolaenko A.M., Strel'chenko S.S., Titivkin K.A. Sposob polucheniya mnogosloinykh geteroepitaksial'nykh struktur v sisteme AlGaAs metodom zhidkofaznoi epitaksii// Patent RF № 2639263. 2017. Byul. №35 (in Russian)

5. Grym J. Role of rare-earth elements in the technology of III-V semiconductors prepared by liquid phase epitaxy/ Grym J. [et al]// Semiconductor Technologies. InTech. 2010. №S. P. 297-320

6. Kurkovskii S. I. Svoistva epitaksial'nykh sloev GaAs, legirovannykh redkozemel'nymi elementami/ Kurkovskii S. I., Syvorotka N. Ya.// Tekhnologiya i konstruirovanie v elektronnoi apparature. 2007. №2. P. 47-51. (in Russian)