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Investigation of power IR (850 nm) light-emitting diodes manufacturing by lift-off technique of AlGaAs−GaAs- heterostructure to carrier-substrate

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Development of lift-off technique of AlGaAs/GaAs- heterostructures, grown by the Metalorganic vapour-phase epitaxy, to GaAs carrier-substrate using silver-containing paste or Au-In compound has been carried out. Forming process of frontal ohmic contact to GaAs n-type conductivity based on contact systems Au(Ge)/Ni/Au and Pd/Ge/Au with specific contact resistance $(2-5)\cdot 10^{-6}\,\Omega\cdot\text{cm}^2$ has been investigated. Analyzed was the influence of heterostructure lift-off technique and forming process of frontal ohmic contact on the IR light-emitting diodes parameters: minimum light-emitting diodes ($1\,\text{mm}^2$ square) series resistance was $0.16\,\Omega$. Optical power 270 mW at current 1.5 A has been achieved.

Keywords: AlGaAs/GaAs- heterostructure, light-emitting diode, transfer to carrier-substrate, Au–In- compound, ohmic contacts.

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Introduction

The lift-off technique of the heterostructure to the carrier-substrate is widely used when manufacturing the high-efficient light-emitting diodes [1–5]. This technique makes it possible to form a rear metal reflector directly on the surface of the epitaxial layers, thereby reducing the optical losses of radiation.

The high-efficient IR (800−870 nm) light-emitting diodes based on the AlGaAs/GaAs−heterostructure are manufactured by the MOVPE with subsequent formation of the rear metal reflector, the transfer of the heterostructure to the carrier-substrate and removal of a growth substrate. The rear reflector based on the mirror silver layer is designed to reflect more than 90% of generated isotropic radiation. The reduction of the optic losses makes it possible to increase the external quantum output and the optical power in the AlGaAs/GaAs IR light-emitting diodes with the rear metal reflector. The obtained values of the optical power in the IR light-emitting diodes manufactured as per the described technique were 60 mW [4] at the current 150 mA.

The lift-off technique of the heterostructure to the carrier-substrate is very important for the manufacturing process of the high-efficient light-emitting diodes. An important aspect is the correspondence between the coefficients of thermal expansion of the layers of the heterostructure and the carrier-substrate that provides the reduction of a degradation degree of device during its manufacturing and operation. The optimum option is usage of the silver-containing (Ag) paste [4,5] or the Au-In-compound [6,7] for assembly of the heterostructure to the GaAs carrier-substrate.

The work presents the investigation of the IR light-emitting diodes forming process by means of various lift-off techniques of the AlGaAs/GaAs-heterostructure to the GaAs−carrier-substrate. Analyzed was also the influence of materials of the ohmic contacts on the parameters of the light-emitting diodes.

1. Heterostructure

The AlGaAs/GaAs−heterostructures were grown by the MOVPE (see Table). The active region of the heterostructure includes 6 GaInAs quantum wells comprised between wideband *n*- and *p*-type layers of $Al_xGa_{1-x}As$ (at $x = 0.2-0.4$). The wide bandgap highly-doped layer $nAL_{0.2}Ga_{0.8}As$ of the thickness of $4-6\,\mu$m ensures current spreading over the frontal surface of the light-emitting diode. The highly-doped n^+ and p^+ GaAs-contact layers ensure the low specific contact resistivity when forming the frontal and rear ohmic contacts. The stop-layer $Al_{0.9}Ga_{0.1}As$ has high selectivity when etching the GaAs-substrate in the ammoniac-peroxide etchant and in the solution based on the citric acid and hydrogen peroxide, thereby ensuring high reliability of the chemical process of removal of the growth substrate.

2. Post-growth lift-off technique of the heterostructure to the carrier-substrate

The post-growth technique of manufacturing of the IR light-emitting diodes includes the following operations:

— the surface of the heterostructure is processed to form the point contacts of the diameter $10\,\mu$m of the *p*-type of

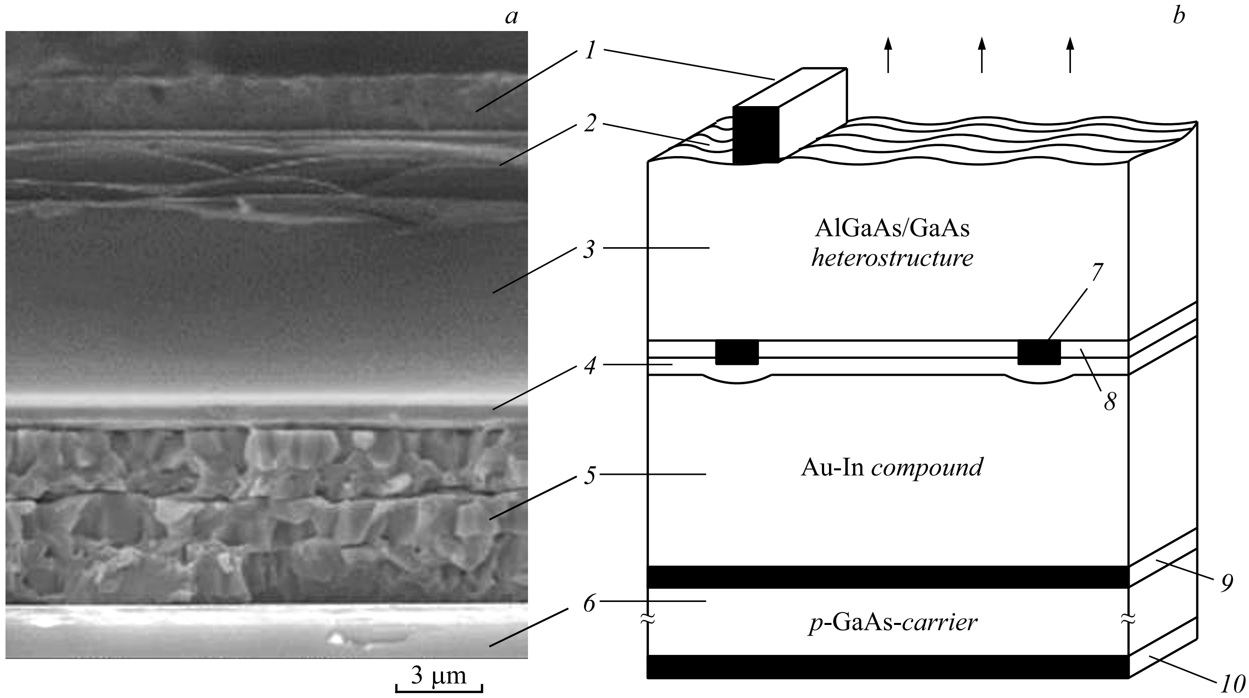

Figure 1. *a* — Cross section image of the light-emitting diode AlGaAs/GaAs heterostructure after transfer to the *p*-GaAs-carrier-substrate using the Au−In-compound; *b* — the structure of the light-emitting diode: *1* — the frontal strip ohmic contact, *2* — the textured surface of the light output layer, *3* — the *n*−*p*-AlGaAs/GaAs-heterostructure, *4* — the rear silver reflector, *5* — the Au−In-compound, *6* —the *p*-GaAs-carrier-substrate, *7* — the rear point contact to the heterostructure, *8* — the dielectric coating of TiO_x/SiO_2 or Si_3N_4, *9, 10* — the two-sided ohmic contacts to the *p*-GaAs-carrier-substrate.

Description of the layers of the AlGaAs/GaAs-heterostructure

Heterostructure elements	Conductivity type	Layer composition
Contact layer	p^+	GaAs
Cladding /barrier layer	p	$Al_{0.2-0.4}Ga_{0.6-0.8}As$
Active layer (6 pairs of quantum wells)	–	InGaAs
	–	$Al_{0.2}Ga_{0.8}As$
Barrier layer /wide bandgap window	n	$Al_{0.2-0.4}Ga_{0.6-0.8}As$
Contact layer	n^+	GaAs
Stop-layer of etching	–	$Al_{0.9}Ga_{0.1}As$
Substrate	n	GaAs

conductivity based on the NiCr/Ag/Au layers (item *7* of Fig. 1) with the distance between the point contacts 75 μm;

— the dielectric coating is deposited in places with no point contact based on the TiO_x/SiO_2 or Si_3N_4 layers (item *8* of Fig. 1);

— the continuous rear reflector (item *4* of Fig. 1) based on the NiCr (1 nm)/Ag/Au layers is formed on the surface of the dielectric coating;

— the heterostructure is transferred to the *p*-GaAs-carrier-substrate (with the pre-applied two-sided ohmic contacts) using the Ag-paste or the Au–In-compound (item *5* of Fig. 1);

— the *n*-GaAs-growth substrate is etched in the ammoniac-peroxide etchant to emergence of the stop-layer $Al_{0.9}Ga_{0.1}As$ and in the etchant based on the citric acid and hydrogen peroxide until full removal of the substrate;

— the stop layer $Al_{0.9}Ga_{0.1}As$ is etched in the hot hydrochloric acid to the GaAs contact layer;

— the light output surface of the light-emitting diode is textured (item *2* of Fig. 1);

— the frontal antireflection coating based on the TiO_x/SiO_2 or Si_3N_4 layers is formed;

— the frontal strip ohmic contact is evaporated to the GaAs-layer of the *n*-type of conductivity based on Au(Ge)/Ni/Au or Pd/Ge/Au;

— the Ag/Ni/Au contact materials are electrochemically deposited (item *1* of Fig. 1);

— the mesa-structures of the light-emitting diodes of the area of 1 mm^2 are formed.

The two lift-off techniques of the heterostructure to the *p*-GaAs-carrier-substrate have been investigated: using the Ag-paste and the Au−In-compound.

The Ag-paste is applied directly to the surface of the rear metal reflector (item *4* of Fig. 1). Then, the *p*-GaAs-carrier-substrate with the pre-formed two-sided solid ohmic contacts is assembled on the paste surface and the assembled structure is thermally processed at the temperature $\sim 200^\circ$C.

The Au–In-compound (item *5* of Fig. 1) is formed in several steps:

— the Au layer of the thickness $\sim 3\,\mu$m is applied to the surface of the rear reflector;

— layers of Au with a thickness of $\sim 1\,\mu$m and In with a thickness of $\sim 3\,\mu$m with an adhesive sublayer of chrome and a protective layer of tin are applied successively on the *p*-GaAs-substrate-carrier with ohmic contacts

— the heterostructure with the applied Au layer ($\sim 3\,\mu$m) is assembled to the carrier-substrate onto the Cr/In/Sn layers ($\sim 3\,\mu$m);

— the assembled structures are thermally annealed (baked) in a hydrogen ambient at the temperature 200°C during 30 min.

During the thermal annealing, at the temperature above the indium melt temperature indium diffuses into the gold layers to form an intermetallic monolith Au-In compound designed to reliably assemble the structures.

3. Characteristics of the rear mirror bases on the NiCr(1 nm)/Ag/Au multi-layer structure

The heterostructure is assembled to the carrier-substrate using the Au–In-compound with melting of indium and its diffusion towards the substrate and towards the rear metal reflector, which can result in degradation of the reflector parameters. In order to evaluate the influence of the lift-off technique of the heterostructure on the reflectance of the silver-based metal reflector, the following investigation has been performed. Just after thermal annealing of the structures the layers of the AlGaAs/GaAs-heterostructure have been locally etched to open the reflector surface with subsequent measurement of its characteristics. The reflectance of radiation from the open surface of the reflector was 92–93% at the wavelength 750–850 nm, thereby fully complying with the parameters of the silver reflector obtained in its development [4].

4. Frontal bus-bar contact

The influence of the parameters of the frontal metal contact to the GaAs layer of the n-type of conductivity on the characteristics of the IR light-emitting diodes has been investigated.

The two options of the contact system have been considered: based on the AuGe/Ni/Au and Pd/Ge/Au layers, which provide the value of the specific contact resistance $\sim 2{-}5 \cdot 10^{-6}\,\Omega\cdot\text{cm}^2$ [8–10] at the annealing temperature, which is 400°C for AuGe/Ni/Au and 185°C for Pd/Ge/Au. Using the high-temperature annealing of the heterostructures after transfer to the carrier substrate results in defects due to the difference of the coefficients of thermal expansion of the AlGaAs/GaAs materials and the Ag-paste or the Au–In-compound. A mechanical stress also occurs at the heterointerface of the structure with the rear metal reflector, thereby resulting in reduction of the radiation reflectance and, as a consequence, reduction of the device efficiency. The measurements of the parameters of the IR light-emitting diodes based on the AlGaAs/GaAs heterostructure have shown substantial reduction of the output of the operable instruments after thermal annealing at the high temperature 400°C during 1 min.

The influence of the materials of the contact systems has been evaluated by carrying out measurements of the series resistance (Rs) of the devices, which includes the rear contact-semiconductor resistance the resistance of the semiconductor structure and the frontal contact-semiconductor resistance. The heterostructure was transferred to the carrier-substrate by Au-In compound, rear point contacts to GaAs the p-type of conductivity with the NiCr/Ag/Au contact structure with the contact resistivity $\sim (6{-}9) \cdot 10^{-6}\,\Omega\cdot\text{cm}^2$. The only difference in the technique of device manufacturing was selection of the materials of the frontal bus-bar contact to the GaAs-layer of the *n*-type of conductivity.

The series resistance of the light-emitting diode has been evaluated by measuring the current-voltage (I-V) characteristics of the light-emitting diodes (the curves *1* and *2*, Fig. 2) and approximation of the idealized (at $R_s = 0\,\Omega$) I-V characteristics (the curve *3*). The results of the measurements have shown that the devices with the Pd/Ge/Au contact have a lower resistance of $R_s = 0.16\,\Omega$, whereas the instruments with the Au(Ge)/Ni/Au contact have $R_s = 0.21\,\Omega$ with the light-emitting diodes' area of $1\,\text{mm}^2$. Thus, using the Pd/Ge/Au contact system ensures

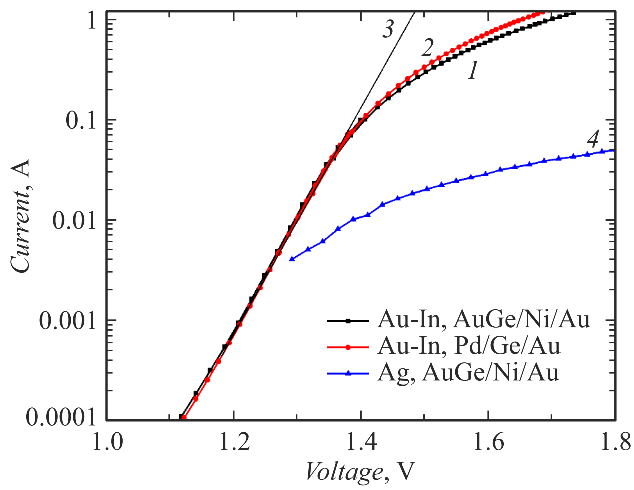

Figure 2. I-V characteristics of the IR (850 nm) light-emitting diodes at transfer of the heterostructure to the carrier-substrate using the Au–In-compound (the curves *1, 2*) and the Ag-paste (the curve *4*) with different materials of the frontal contacts to the GaAs-layer of the *n*-type of conductivity: Au(Ge)/Ni/Au (the curves *1, 4*) and Pd/Ge/Au (the curve *2*); approximation of the idealized I-V characteristics (the curve *3*).

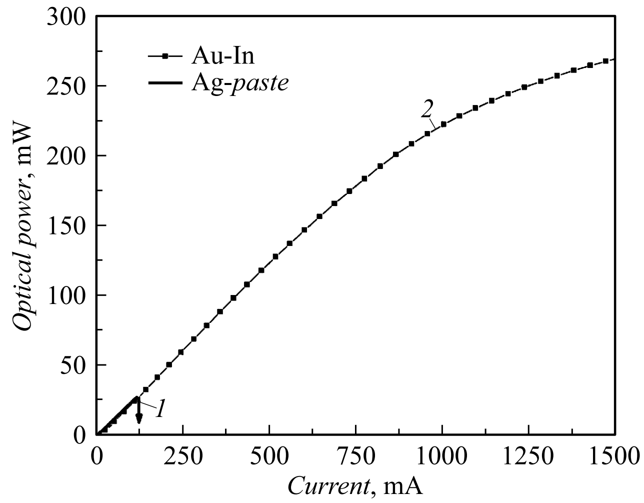

Figure 3. Dependence of the optical power of the IR (850 nm) light-emitting diodes on the current when baking the structures by the Ag-paste (the curve *1*) and the Au−In-compound (the curve *2*).

the increased output of the operable devices and reduction of their series resistance.

5. Influence of the lift-off technique on I-V characteristics and the optic power of the IR (850 nm) light-emitting diodes

The lift-off techniques of the AlGaAs/GaAs–heterostructure to the GaAs–carrier–substrate using the Ag-paste or Au−In-compound substantially affect the efficiency of operation of the semiconductor devices.

Using the Ag- paste makes it impossible to form a monolith compound of the heterostructure and the carrier-substrate, as baking causes a porous structure. The high chemical activity of the silver-containing pastes complicates the post-growth process of device manufacturing and makes it impossible to provide device resistance to exposure of the environmental parameters. These light-emitting diodes exhibit significant increase of the ohmic losses when the operating current is increasing (the curve *4*, Fig. 2). The baking of the heterostructure and the carrier substrate using gold and indium results in formation of the crystal intermetallic Au-In compound, thereby reducing the series resistance of the device and the degradation degree of the parameters with the current increase (the curves *1, 2*, Fig. 2).

The parameters of the IR light-emitting diodes produced using the Ag-paste and the Au−In-compound have been compared before the step of formation of the hemispherical optical element (Fig. 3). It is found that it is the lift-off technique of the heterostructure to the carrier substrate that substantially affects the values of the achieved optical power of the light-emitting diodes. The maximum optical power of radiation of the light-emitting diodes manufactured using the Ag-paste for transfer of the heterostructure to the carrier substrate was $P = 30$ mW at the current 120 mA. In the light-emitting diodes manufactured using the Au−In-compound $P = 100$ mW at the current 400 mA. The more substantial difference of the parameters of the light-emitting diodes is observed when increasing the operating current to at least 1 A: the light-emitting diodes with the Ag-paste irreversibly degrade at the current above 150 mA (the curve *1*, Fig. 3), while the light-emitting diodes with the Au−In-compound ensure attaining the optical power above 270 mW at the current above 1.5 A (the curve *2*, Fig. 3).

The formation of the optical element as a silicone hemisphere on the light-emitting diode will ensure increase of the optical power in about 1.5 times — to the values above 400 mW at the current above 1.5 A.

Conclusion

It has developed the technique of formation of the high-efficient powerful IR light-emitting diodes based on the AlGaAs/GaAs–heterostructure by transferring the heterostructure to the carrier substrate using the Au−In compound. It has optimized the step of formation of the frontal bus-bar ohmic contact to the GaAs-layer of the *n*- type of conductivity based on the low-temperature Pd/Ge/Au contact system, thereby ensuring the increased output of the operable instruments and the decreased series resistance of the light-emitting diodes of the area 1 mm^2 to the value 0.16 Ω. The attained optical power in the IR light-emitting diodes manufactured using the developed technique was 270 mW at the current 1.5 A without using the silicone hemisphere.

Conflict of interest

The authors declare that they have no conflict of interest.

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