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Low-resistance p-type ohmic contacts for high-power InGaAs/GaAs-980 nm CW semiconductor lasers

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Abstract

In this paper, the optimization of ohmic contacts for semiconductor lasers based on InGaAs/GaAs/GaAlAs layers is reported. Transmission electron microscopy (TEM) and electrical methods were used to study extensively the Pt/Ti/Pt/Au metallization system. The contact fabrication technology was optimized towards achieving the lowest electrical resistance. The technological control and optimization concerned the contact annealing temperature and thickness of metallic layers that form the contact. The average specific contact resistance was below $5\times10^{-6}\,\Omega\,\mathrm{cm}^2$ (with the record value of $8\times10^{-7}\,\Omega\,\mathrm{cm}^2$) for the 10 nm Pt/20 nm Ti/30 nm Pt/150 nm Au system. The presented system was used in fabrication of continuous wave (CW) operated laser diodes. The chips mounted on passively cooled copper block achieved optical powers over 1 W, threshold current density values of 140–160 A/cm^2 and differential efficiencies above 1 W/A. The value of the characteristic temperature T_0 for discussed lasers varied in the range of 180–200 K.

Keywords: Ohmic contacts; Semiconductor laser; TEM; *I–V* characteristic

1. Introduction

One of the most important requirements the high-power laser fabrication technology has to fulfill is achievement of low series resistance of the devices. This is a necessary prerequisite for low threshold voltage and minimization of the amount of heat generated in the laser [1]. The ohmic contacts in semiconductor lasers should also be thermally stable, as well as characterized by good lateral uniformity and shallow diffusion depths. The materials widely used to make ohmic contacts to p-type semiconductors are alloyed and Schottky-type metals. However, the Au-based alloyed contacts are thermally stable and uniform only at relatively low temperatures. During the chemical reaction between Au and GaAs, the geometrically inhomogeneous spikes [2,3] form and the current flow is concentrated in the area of the low-resistance pyramidal pits. Once the alloy spikes reach the active region, dark spot defects are formed. The Au may act as nonradiative recombination centers in the laser active region and hence may also decrease the device efficiency [4]. In spite of this, Au is used to connect the low-resistance contact layer with the external circuit. This explains why it is necessary to interpose a diffusion barrier between the contacting metals and the Au overlayer [2,5]. The advantage of using such a diffusion barrier between GaAs and the contacting metals is the enhanced uniformity of the surface morphology after the heat treatment, in contrast to the case when this barrier is absent [2]. The Pt layer acts as an excellent diffusion-preventing barrier for gold migrating into the semiconductor, as well as for outdiffusion of the semiconductor volatile components, even up to 450 °C [6]. There are several advantages of the Pt-based ohmic system use, especially for semiconductor lasers. First of all, it is possible to obtain low ohmic contact resistivities without a highly doped p-layer due to the high work function of Pt ($\Phi_m = 5.65$) [5]. Additionally, the platinum layer has relatively low reaction temperatures with III–V semiconductors. The metal reacts with GaAs in the temperature range of 300–500 °C, and after complete reaction a laterally uniform GaAs/$PtAs_2$/PtGa layered structure is observed, which stays in the thermodynamic equilibrium. According to this, Pt-based contacts to GaAs may be laterally more

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uniform than the contacts based on the other later transition metals [2]. Another advantage is the stability of Pt-based ohmic contact [6,7].

The most popular ohmic p-type contacts for semiconductor lasers are composed of Ti/Pt/Au metallic layers [8] or Cr/Au [9] systems. In this work, we propose modification of the first contact, relying on addition of an extra Pt layer, which plays a critical role in reducing the potential barrier between the semiconductor and metallization. The resulting Pt/Ti/Pt/Au system was characterized by TEM and electrical methods. The ohmic contacts to p-GaAs of a similar type were used for AlGaAs/GaAs high-performance heterojunction bipolar transistors (HBTs) by Okada et al. [7]. The contact fabrication technology was optimized towards obtaining the lowest possible resistance. The technological control and optimization concerned a few process and design parameters. The most important were the contact annealing temperature and the thickness of metallic layers building the contact. Transmission electron microscopy (TEM) was used to characterize the material morphology. The electrical parameters of the contacts were assessed by the transmission line method (TLM). The current–voltage (*I–V*) characteristics were compared for the two different contact systems, i.e. the standard and the optimized ones, as used for fabrication of semiconductor lasers. The optimized contact was used for manufacturing the room-temperature (RT) continuous wave (CW) strained layer QW InGaAs/GaAs lasers.

2. Experimental

On the basis of experimental optimization made on the set of test metallized structures, the best type of contact was found. The experimental studies consisted of preparation of different ohmic contacts deposited on a 0.25 μm thick GaAs p-type Be doped to $1\times10^{19}\,\mathrm{cm}^{-3}$ layer, which was used as the cap layer in InGaAs/GaAs/AlGaAs epitaxial laser structures. The graded index separate confinement heterostructure (GRINSCH) lasers used in this work designed for emission at 980 nm at RT, were grown by molecular beam epitaxy (MBE) on (1 0 0) n+ GaAs:Si substrates. The details of heterostructure design are presented elsewhere [10]. The procedure of contact fabrication was as follows: The native oxides from the cap GaAs:Be layer were dissolved in the diluted HCl, prior to cleaning the surface of the wafer by Ar+ plasma. The metallic layers (varied d_{Pt})Pt/20 nm Ti/30 nm Pt/150 nm Au were sequentially deposited on GaAs wafers by dc magnetron sputtering using the Leybold L400sp system. The thickness d_{Pt} of the Pt layer deposited directly on GaAs:Be layer was 10, 20 and 30 nm and resulting contacts are denoted A, B and C, respectively. The samples were annealed in a gas-flow furnace, at N_2 ambient, in the temperature range 430–490 °C. One of the most popular systems used in fabrication of semiconductor lasers, i.e. 20 nm Ti/30 nm Pt/150Au, also tested in this work and denoted D, was annealed at 450 °C for 5 min. The TLM [11] was used to measure the specific contact resistance, while the cross-sectional TEM was used to observe the microstructure of the ohmic contact after annealing. The samples for TEM were prepared by the method described in [12] and were studied using a JEM-200CX TEM operating at 200 kV. The *I–V* characteristics of the semiconductor lasers were measured at CW conditions as well as at pulsed mode, with the following parameters of supply: maximum current amplitude $I_{\mathrm{ps}} = 2\mathrm{A}$; pulse filling factor $\mathrm{ff} = 0.1\%$; pulse duration $\tau = 500\,\mathrm{ns}$; pulse frequency $v = 2\,\mathrm{kHz}$. Although Be doping in the range of 1×10^{14}–$6\times10^{19}\,\mathrm{cm}^{-3}$ is fully controllable, the very rapid interstitial Be diffusion may already occur for doping levels $>1\times10^{19}\,\mathrm{cm}^{-3}$ [13]. This phenomenon may dramatically decrease the reliability of the high-power lasers. This explains why the $5\times10^{18}\,\mathrm{cm}^{-3}$ level of p-type doping was finally chosen for the optimized laser structures. The specific contact resistance and *I–V* characteristics were measured for these structures. The fabricated test lasers were of the broad contact (100 μm stripe width) ridge-waveguide type.

3. Result and discussion

The average specific contact resistance ρ_c as a function of Pt layer thickness d_{Pt} measured for samples A, B and C is displayed in Fig. 1. The well-pronounced increase of the value of this parameter with increase in thickness of the inner Pt layer, deposited directly on GaAs:Be, is clearly observed. The average value of ρ_c in a large number of processing runs was consistently below $5\times10^{-6}\,\Omega\,\mathrm{cm}^2$ for the 10 nm Pt/20 nm Ti/30 nm Pt/150 nm Au system. The cross-section TEM micrographs for systems A, B and C annealed at 450 °C are shown in Fig. 2. As a result of the annealing, the intermixed layer is created, composed of Pt (from the inner layer), Ga and As. We suppose that the layered structure consisting of Pt/PtGa/$PtAs_2$/GaAs forms due to the rapid diffusion of Ga in Pt, coupled with the high stability of the $PtAs_2$ compound formed at the GaAs side. Similar phenomenon was reported in papers [5,14].

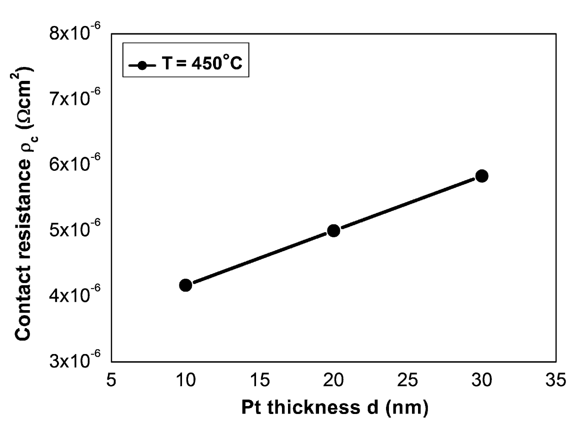

Fig. 1. The average specific contact resistance ρ_c of A, B, C systems annealed at 450 °C for 5 min.