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Low resistance ohmic contacts to *n*-GaAs for application in GaAs/AlGaAs quantum cascade lasers

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This paper reports on the results of optimization of ohmic contacts for GaAs/AlGaAs quantum cascade lasers (QCLs). Technological parameters during optimization concerned surface preparation, evaporation method, and thermal treatment. The aim of this research was to obtain low resistance and time stable ohmic contacts. The average specific contact resistance was 6×10^{-7} Ωcm^{-2} with record value below 3×10^{-7} Ωcm^{-2}. It appears that the crucial role in contact formation is played by the *in-situ* surface pretreatment and thermal processing. Circular transmission line method (CTLM) was applied for electrical characterization of Ni/AuGe/Ni/Au metallization system. Secondary ion mass spectroscopy (SIMS) was used for determination of Au diffusion into semiconductor. The system presented was used in fabrication of pulse operating QCLs. The lasers mounted with diamond heat spreaders on copper block cooled by liquid nitrogen (LN) achieved optical powers over 1 W, threshold current density values of 7 kAcm^{-2} and differential efficiencies above 1 W/A.

Keywords: ohmic contacts, sputtering, rapid thermal annealing (RTA), quantum cascade lasers (QCLs).

1. Introduction

Quantum cascade lasers (QCLs) are unipolar sources of mid and far infrared radiation (IR) [1, 2]. QCLs require high voltage for device polarization and high current density for achieving threshold of lasing action. This indicates the demand for low resistance ohmic contacts in order to reduce serial resistance for such devices. What is more, such contacts should be characterized by thermal stability, low depth of metal diffusion into semiconductor layers and lateral uniformity of metal–semiconductor interfaces.

According to Schottky–Mott theory in order to obtain ohmic contact to *n*-type semiconductor the work function of metal should be smaller than that of the semiconductor. But it has been found experimentally that the barrier height may be almost independent of the choice of metal. It was suggested that such phenomena is caused by surface states at the metal–semiconductor interface.

It is known that *n*-type GaAs has acceptor-like surface states [3]. In such a case, in order to obtain ohmic contacts all states should be filled or emptied. There are two ways of accomplishing this, either by heavy doping of semiconductor layer or by diffusion of metal from contact layer into semiconductor. Since the level of doping of GaAs during molecular beam epitaxy (MBE) growth is limited, the thermal processing of metallic layers plays a crucial role in contact formation. However, it cannot be forgotten that deep diffusion of metal into epitaxial layers can damage a device.

In conventional diode lasers ohmic contacts to *n*-type GaAs are on the substrate site, whereas on the epi-site there is a *p*-type contact. That is the reason why shallow *p*-type ohmic contacts are quite well investigated [4]. In the case of *n*-type contact there was not much concern about the range of metal diffusion into *n*-type semiconductor because in most cases it was the thick layer of the substrate the contact was deposited on. Metallic system AuGe/Ni/Au is commonly used for ohmic contacts for *n*-type GaAs [5, 6]. However adding a layer of Ni between GaAs and AuGe improves metal adhesion [7] and results in the formation of diffusion barrier for Ge and Au [8]. This allows such a system to be applied as *n*-type ohmic contact to epitaxial layers.

The aim of this work was to optimize the technology of fabrication of ohmic contacts for QCLs with minimal specific resistance and long-term thermal stability. We have investigated the 5 nm Ni/100 nm AuGe/35 nm Ni/300 nm Au system. The technological control and optimization were concerned with a few process and design parameters. The most important were the contact annealing temperature, evaporation method and surface pretreatment. The rapid thermal annealing (RTA) process and annealing in conventional furnace were compared for sputtered and thermally evaporated metallization.

2. Experimental details

The experiment consisted in preparation of metallization on epitaxial wafers of *n*-type GaAs Si doped to 2×10^{18} cm^{-3}. The metallization whose parameters showed the best results was adapted for forming ohmic contacts on epitaxial GaAs (*n*-type Si doped to 5×10^{18} cm^{-3}) which was used as plasmon waveguide for GaAs/AlGaA QCLs. More details concerning the device can be found in [2].

The contact (5 nm Ni/100 nm AuGe/35 nm Ni/300 nm Au) was deposited by e-beam process and thermal evaporation (system A) and by dc magnetron sputtering system (system B). The fabrication process in the case of system A consisted in cleaning the semiconductor samples in dissolvent and wet etching in order to remove the native oxide. Then, the samples were loaded into a vacuum chamber and the metallic layers were sequentially deposited on GaAs wafers by e-beam deposition (Ni) and thermal deposition (AuGe, Au). The fabrication procedure of system B was divided into two stages; surface pretreatment and deposition of layers. The first step was performed in 4 different versions, *i.e.*, cleaning the samples in dissolvent only (B-unprepared); cleaning the samples in dissolvent and wet etching (B-wet); cleaning the samples in dissolvent and *in-situ* cleaning by Ar^+ plasma (B-ion); cleaning the samples in dissolvent, wet etching and *in-situ* cleaning by Ar^+ plasma (B-mix). In the second step, the metallic layers Ni/AuGe/Ni/Au were sequentially deposited on GaAs wafers by dc magnetron sputtering using a Leybold L400sp system.

The samples were annealed in a gas-flow furnace, in the temperature range from 400 °C to 450 °C or were processed with RTA. Long-term thermal stability was investigated by annealing the samples in a gas-flow furnace at a temperature of 200 °C for 8 h, 16 h.

Specific resistance was determined by circular transmission line method (CTLM) [9]. The *I–V* characteristics were measured by a Tektronix Tek370 programmable curve tracer. The secondary ion mass spectroscopy (SIMS) depth profiles of metallic layers were recorded on CAMECA IMS6F.

3. Results and discussion

The TEM cross-section micrograph for 5 nm Ni/100 nm AuGe/35 nm Ni/300 nm Au is shown in Fig. 1. The Ni layer between AuGe and GaAs improves both the contact resistance and the coverage of semiconductor structure [8].

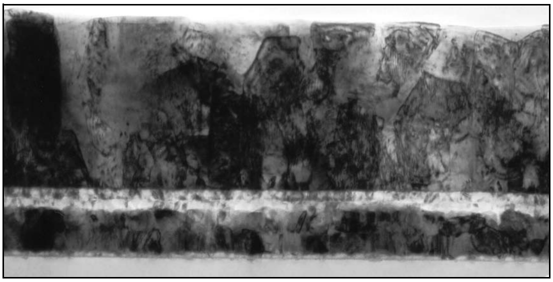

Fig. 1. TEM photo of Ni/AuGe/Ni/Au contact on GaAs [10].

The SIMS profile for such a contact without subsequent thermal processing is shown in Fig. 2. At this stage of contact fabrication, it is quite easy to recognize interfaces between particular layers. Despite the fact that such metallic system consists of metallic layers of very good quality there was no ohmic character of such metallization observed. In order to create the ohmic contact the thermal treatment was needed.

At the beginning of optimization experiments the results for system A and system B-wet were compared because in both cases surface pretreatment was reduced to

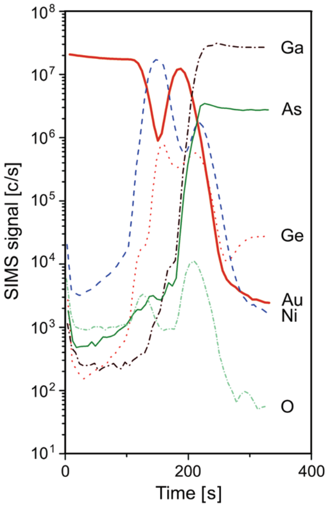

Fig. 2. SIMS depth profile of Ni/AuGe/Ni/Au contact deposited without subsequent thermal processing.

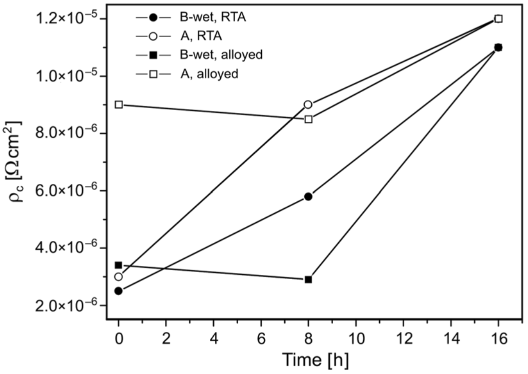

Fig. 3. Specific contact resistance for system A and system B-wet.

the wet etching of the surface before evaporation. The results of resistance measurements are shown in Fig. 3. As can be seen, the specific contact resistance for system B-wet is lower than that for system A, both samples being subject to the same thermal treatment. SIMS profiles suggest that this can be caused by the different character of diffusion of both systems into GaAs layer.

After thermal treatment interdiffusion of elements causes the broadening of SIMS depth profiles, however, it is still possible to estimate layer composition and compare the range of diffusion. In Figure 4, there are SIMS profiles for system A and system B. According to [5], during thermal processing above 400 °C of long-term stable Ni/AuGe/Ni/Au contact first Ni layer reacts with GaAs forming Ni_xGaAs, then Ge from AuGe reacts with Ni and replaces Ga in Ni_xGaAs forming NiAs(Ga, Ge). Ga replaced in Ni_xGaAs diffuses into metallic layers forming a β-AuGa phase. It is impossible to confirm the formation of such phases from SIMS depth profiles, however, the interdiffusion of elements observed on such profiles can suggest that there is high probability of such reactions taking place.

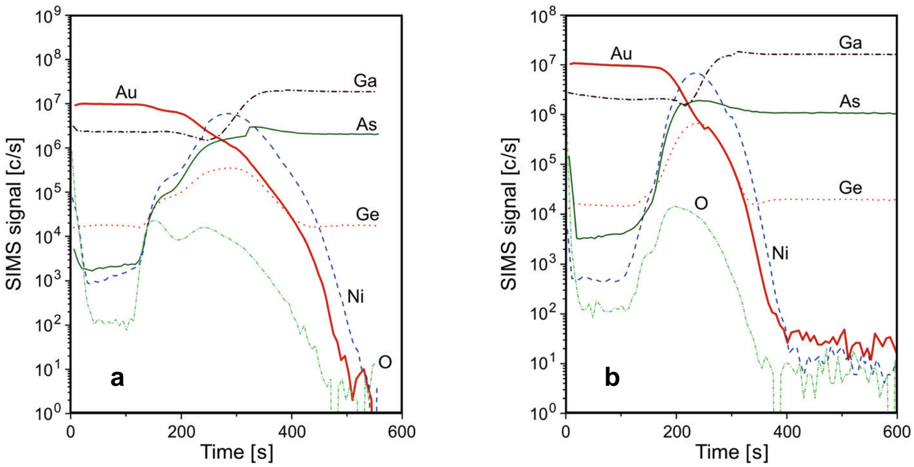

Fig. 4. SIMS depth profile of alloyed contacts: system A (**a**), system B (**b**).

Despite the difference in base pressure before the processes of evaporation in those two methods, 10^{-6} mbar and 10^{-8} mbar, respectively, the amount of oxygen in both contacts is at the same level. The main difference between these profiles is the broadening of spectra, which is much bigger in the case of system A. This indicates that interfaces in system B are much sharper and metallic layers evaporated by sputtering have shorter diffusion range. This can be caused by poor quality of Ni layer deposited by e-beam evaporation. Such a layer is incapable of stopping diffusion of metal into semiconductor. Comparing the profiles of germanium in Figs. 2 and 4 it is seen that in the case of system B there is much less germanium diffused to GaAs layer than in system B. This may be caused by forming NiGe phase during annealing [5]. Also, Au diffusion depth is lower than that of Ni. This proves the possibility of using Ni as a diffusion barrier for AuGe layer. There were no significant differences in SIMS profiles for annealed and RTA processed contacts.

The resistance for both systems with wet pretreatment was too high and thermally unstable. This was the reason for exploring other methods of surface pretreatment. In the case of system B, deposited by magnetron sputtering, it is very easy to perform *in-situ* surface cleaning by Ar^+ ions. This possibility allows for applying even two-stage surface preparation (system B-mix).

The high amount of heat which is generated during QCL operation demands stability of contacts for such devices. Long-term thermal stability of contacts was investigated by annealing at a temperature of 200 °C in a furnace with gas flow. The results are shown in Figs. 5 and 6.

Poor thermal stability and high specific contact resistance for system A are comparable with system B-unprepared or B-wet. This shows the necessity for *in-situ* surface cleaning before deposition of metalilztaion. system B-ion and B-mix have comparable resistances but in the case of RTA processing B-mix tends to have better resistance than B-ion and better long-term stability with lower changes of resistance.

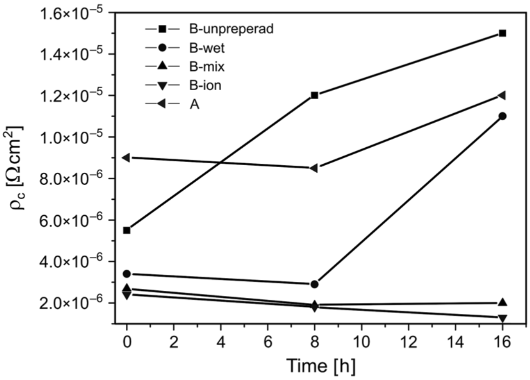

Fig. 5. Specific contact resistance versus time for thermally annealed contacts.

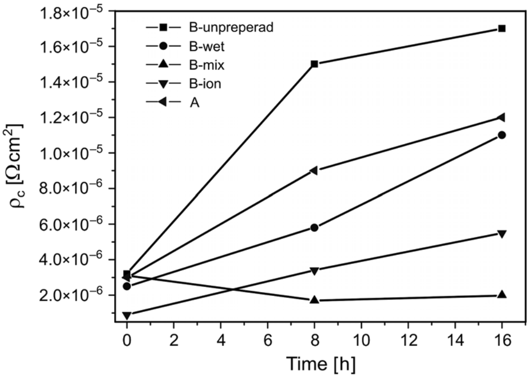

Fig. 6. Specific contact resistance versus time for RTA processed contacts.

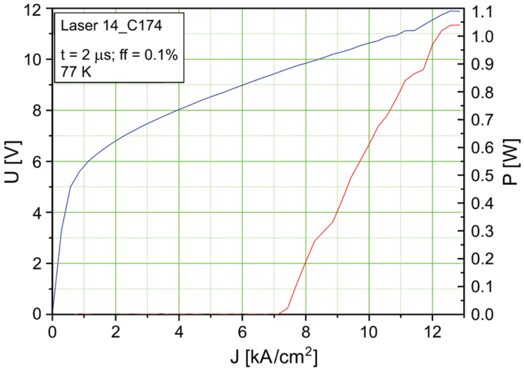

Fig. 7. *I*–*V* and *P*–*I* characteristic of QCL with 5 nm Ni/100 nm AuGe/35 nm Ni/300 nm Au contact.

This shows the importance of removing native oxide from the surface of semiconductor for contact formation. Despite the minor changes in results for contacts thermally processed in different ways, measurements confirm low resistance and long thermal stability of 5 nm Ni/100 nm AuGe/35 nm Ni/300 nm Au contacts.

An optimized process of contact formation was applied during the processing of pulsed operating, liquid nitrogen cooled QCLs. Examples of *I*–*V* and *P*–*I* characteristics for such a device are shown in Fig. 7.

4. Conclusions

We have investigated Ni/AuGe/Ni/Au metallization system for quantum cascade lasers. The average specific contact resistance achieved was about $6\times10^{-7}\,\Omega\mathrm{cm}^{-2}$ (GaAs:Si 5×10^{18} cm^{-3}). It was confirmed that Ni layer between AuGe and GaAs can be a good diffusion barrier. The diffusion of metals into semiconductor layers was observed. The preparation of contacts without pretreatment or with wet etching results in a high specific resistance and poor thermal stability. The advantage of mixed pretreatment is reported only in the case of RTA processing. The optimized ohmic contacts were applied during fabrication of quantum cascade lasers. Typical threshold current densities obtained were of the order of 7 kAcm^{-2}.

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