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AlNiGe AS A NEW DEDICATED MATERIAL FOR CONTACTS TO n–GaAs

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Al(150 nm)/Ni(30 nm)/Ge(40 nm) layers have been deposited onto n–type GaAs by thermal evaporation. The samples have been annealed for 20 minutes in flowing forming gas H_2:N_2 (30%:70%). The alloying behaviour of the specimens has been investigated by electron microscope. The contacts show a bilayer structure in the case of as–deposited samples. The top layer is pure Al and the second one is Ni–Ge. The metal–semiconductor interface is sharp. Annealing at 400 °C resulted in the formation of florets on the surface assumed to be AlGe eutectic; meanwhile, randomly distributed pits of size 10 nm have been grown into the GaAs. The samples annealed at 450 °C show bilayer structure. The top layer is pure Ge and the second one consists of Al–Ni(Ge). On samples annealed at 500 °C thick alloyed layer has been found with deep pyramidal pits of size 0.25 μm. The interface region between GaAs and the pits contains substantial amount of Al. Contrary to the published results, $I - V$ (current–voltage) characteristics of the annealed specimens show that the contacts remained rectifying at each applied annealing process. The temperature dependence of parameters evaluated from either current–voltage or capacitance–voltage characteristics prove that the characteristic form of conductance is the anomalous thermionic–field emission.

1. Introduction

The widely used gold–based ohmic contacts have some technological disadvantages. Since the gold and germanium have an eutectic composition with a low melting point of 365 °C, the thermal degradation of the Au/Ge based contacts begins at rather low temperature. An other problem leading to the search for new contact materials is the reactive nature of gold [1] that causes a very rough, inhomogeneous interface.

The substitution of the gold with aluminium, firstly proposed by the authors [2–4], should have numerous advantages. The first point is that AlGe has higher eutectic temperature than AuGe; so better reliability parameters can be predicted. The second is that Al does not dissociate the $A^{III}B^{V}$ [5] as it can be seen studying the Al/$A^{III}B^{V}$ systems applying evolved gas analysis (EGA) method [6].

The unambiguous advantages of Al based contact metallization was also recognised by other scientific groups [7–12]. Different heat treatment processes were applied and ohmic contacts were obtained both to p-type GaAs [10,11] and to n–type GaAs [7,11,12]. The preparation of Al/Ni/Ge contacts described in the above mentioned articles differs very much from our original proposal [2-4], where a high–temperature, rapid thermal annealing (RTA) process was successfully applied. Electrical characterization and the structural investigation of the Al/Ni/Ge-nGaAs contacts prepared by this type of heat–treatment were carried out to study the possibility of application of an open–tube furnace annealing.

2. Experiment

To prepare samples, an n–type epitaxial layer doped by sulphur of $N_d = 8\times10^{15}$ cm^{-3} with 6 μm layer thickness was grown by Effer–Nozaki type VPE reactor on n^{++}–GaAs (100).

The samples were carefully degreased, then the lift–off patterns were prepared using Shipley AZ-1450J resin. Prior to the metal deposition, the surface was etched by the mixture of NH_4OH:H_2O_2:H_2O with the ratio 1:1:100 at 0 °C for 10 seconds, followed by a rinse with 18 MΩ water and blown dry with filtered dry nitrogen. The chemical treatment of the surface was finished with an etch by NH_4OH:H_2O with the ratio 1:10 at 25 °C for 30 seconds and blown dry with filtered dry nitrogen. Ge(40 nm), Ni(30 nm) and Al(150 nm) layers were deposited by thermal evaporation at room temperature in an oil–free vacuum system. The evaporation rates were 0.4, 0.2 and 1 nm/s, respectively. The pressure was kept lower than 10^{-4} Pa at the beginning of the Ge deposition and did not exceed 10^{-3} Pa during the whole process. The metallization was patterned by the lift–off technique; the contacts have circular dot shape with diameter of size 250 to 110 μm. The samples have been annealed at 20 minutes in flowing forming gas (H_2 (30%):N_2 (70%)) at three different temperatures: 400 °C, 450 °C and 500 °C. The patterned samples were encapsulated using AuGe eutectic on their back side and Al wire bonding on the studied contacts. Special care was taken to reduce and minimize the thermal shock originating from the encasing process.

Temperature dependent current–voltage and capacitance–voltage characteristics were measured using Keithley 230 Programmable Voltage Source, Keithley 236 Source and Measure Unit and a Hewlett–Packard 4271B CV Meter.

The structural characterization was carried out by cross–sectional transmission electron microscope (XTEM) equipped with energy dispersive system (EDS); the surface was studied by scanning electron microscope (SEM).

The samples studied by XTEM and EDS were prepared as described in Ref. 15. The XTEM pictures were taken at 200 keV, using a Philips CM 20 microscope; EDS analysis was done by Noran microprobe; the SEM study was carried out by JEOL JSM-T20 at 20 keV.

3. Results

The as–deposited sample was heat–treated at 180 °C during the standard XTEM sample preparation technique [15]. This sample had a bilayer structure (Fig. 1a).

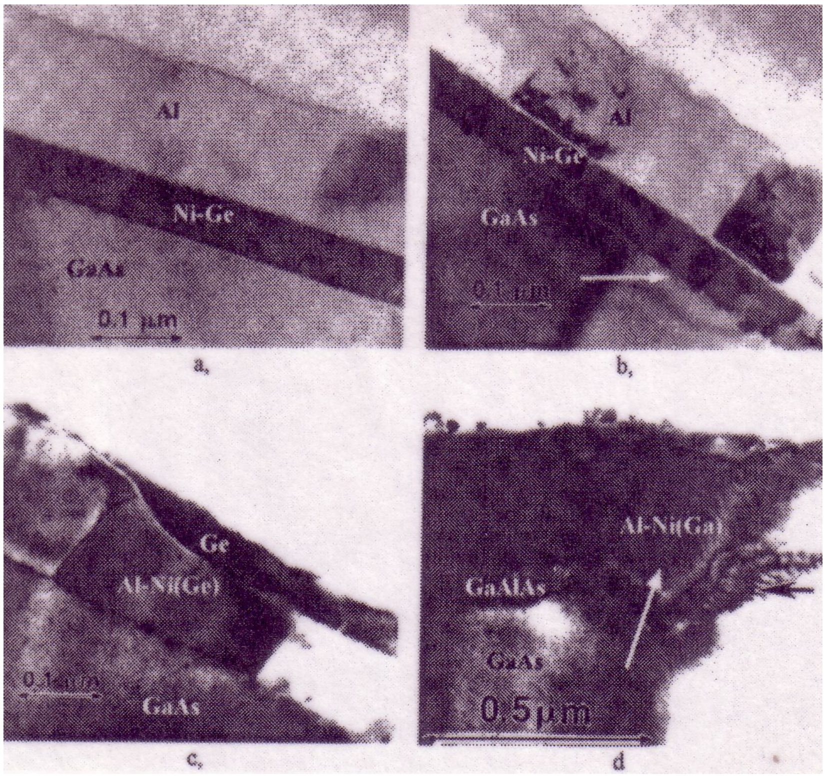

Fig. 1. XTEM image of the Al/Ni/Ge–nGaAs *contact. The sample was heat–treated: at a)* 180 °C *during the XTEM sample preparation; b)* 400 °C*; c)* 450 °C*; d)* 500 °C.

The metal/semiconductor interface was sharp. The traces of the original Ge/Ni interface have been preserved within the Ni–Ge mixed layer. EDS measurements carried out with small pot size in TEM proved that the composition of the upper and bottom part of the Ni–Ge layer is the same.

The SEM investigation of samples heat–treated at 400 °C showed floret formation on the sample surface. The size of the florets was in the 10 μm range with an average distance of 30 μm. Between the florets, the surface seemed to be rather homogeneous. The XTEM investigations showed a bilayer structure with 10 nm size protrusions into the GaAs crystal (marked with arrow in Fig. 1b).

Increasing the heat–treatment temperature either up to 450 °C or above, the florets disappeared and a rather rough surface could be seen on SEM images.

Samples annealed at 450 °C showed a bilayer structure (Fig. 1c), where the inner layer was Al–Ni with a detectable amount of Ge and the covering layer was pure Ge.

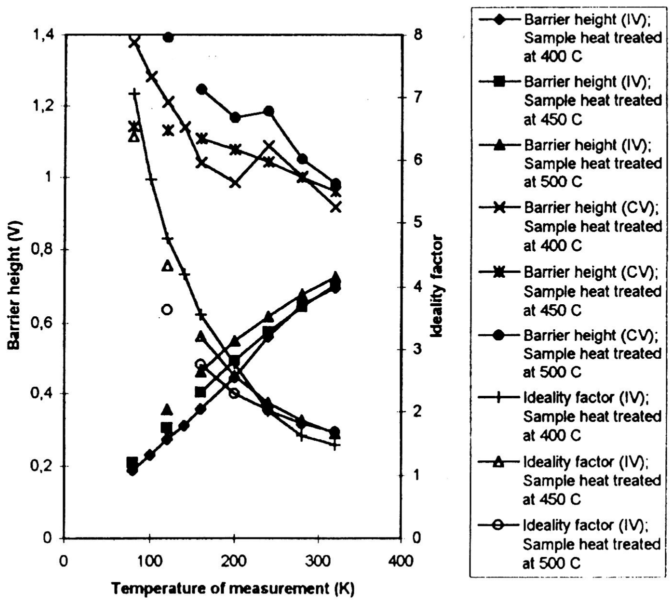

Fig. 2. The temperature dependence of the electrical parameters.

When the heat–treatment temperature was increased up to 500 °C, the contact morphology became rough. XTEM analysis showed that large grains grew into GaAs as pyramidal pits (marked with white arrow in Fig. 1d). The pits are of size 0.25 μm. EDS investigation showed that the grains contained Al–Ni mixture with some Ga. Between the metal grains and GaAs, an interface layer was found. In this interface layer Moiré-fringes could be seen that are marked with a black arrow in Fig. 1d. The EDS results showed that this layer contains Ga, As and Al. It is worth mentioning that thickness of interfacial region was very inhomogeneous.

When studying the electrical properties, rectifying character was experienced in all cases of the studied samples. The obtained diode parameters improved increasing the heat–treatment temperature from 400 °C to 500 °C (Fig. 2).

4. *Discussion*

The XTEM and EDS results proved that even during the evaporation, or at least during the 180 °C heat–treatment, the evaporated Ge end Ni layers mixed. This layer was found to be Ni_5Ge_3 by Graham et al. [11]. Applying annealing at 400 °C for 20 minutes, the basic structure of the contact did not change. Florets appeared on the contact surface that are very similar to one experienced in Ref. 11. Our results showed that even below eutectic temperature these florets could be formed. That indicates a solid–phase process. At the metal/semiconductor interface, randomly distributed protrusions grew into the semiconductor due to the rather long annealing time.

Applying 450 °C annealing resulted in a very rough surface. The florets disappeared since almost all aluminium diffused to the metal/semiconductor interface. At the metal/semiconductor interface, a thick Al–Ni layer was formed; a similar layer was identified as Al_3Ni in Refs. 9 and 11. Although the Al–Ni layer contains a detectable amount of Ge, the larger amount of Ge forms a covering layer on the contact surface.

The sample annealed at 500 °C for 20 minutes consists of large grains. These grains grew into GaAs as pyramidal pits. Similar pits were observed in the Au/GaAs structure due to the gold–GaAs interaction [1]. Since Ni is able to dissociate GaAs [13,14], it is very likely that the reason of pit formation is the presence of Ni at the interface. Between the grains and GaAs, an interfacial region was found with Ge, As and Al components. This region showed Moiré-fringes that indicated overlapping of two different phases. The detected components and the presence of a second crystalline phase suggest the formation of an AlGaAs layer. Since the grains consist of Al–Ni with some Ga, the Ga substitution for Al seems to be plausible.

All of the investigated samples showed rectifying character. Comparing this result to that obtained in Refs. 7–11 we have to assume that the Ge in–diffusion into the GaAs did not take place in a proper degree during the annealing, in spite of the fact that rather long–time heat–treatment processes were applied. Only one group used similar or even longer heat–treatments, but the process used by Lampert et al. [12] was a repeated short–time annealing cycle. Taking into consideration that Ni diffusing into GaAs promotes Ge diffusion [13,14], it is reasonable to assume that in the investigated cases even Ni did not diffuse into GaAs. Al forming a compound with Ni hindered Ni diffusion and in this way prevented the proper extent of Ge diffusion, too. Although this hypothesis seems to be acceptable, the exact reason of the assumed improper doping of GaAs by Ge is not yet clear.

Zuleeg et al. [8] stated the field emission as the form of conduction in the case of an ohmic AlGe–based contact metallization, where the doping of GaAs by Ge was assumed. Our electrical measurements and temperature dependence showed that the possible form of conduction is an anomalous thermionic–field emission according to the calculations and explanations given in Refs. 16–20. The reason of an anomalous thermionic–field emission could be the "doping concentration enhancements in the near–interface region," or "transitional (alloyed or heteroepitaxial) surface layers with parameters different from those of the bulk semiconductor" (citations of Ref. 17). This explanation supports the assumption that even at 400 °C annealing a small extent of Ge doping took place.

Taking into account that the so–called diode parameters improved when increasing the heat–treatment temperature up to 500 °C, and recalling that Al content was found in the interfacial region in the samples annealed at 500 °C, it makes the formation of an heteroepitaxial AlGaAs layer to be likely.

5. *Conclusions*

Studying the effect of an open–tube furnace annealing on Al/Ni/Ge–nGaAs contact structure, the electrical parameters showed that the form of conduction is the anomalous thermionic–field emission. Although this is also the general conduction form of the so–called narrow barrier ohmic contacts, the investigated samples showed rectifying character. The direct cause of the rectifying character is assumed to be the improper extent of Ge doping at the metal/GaAs interface.

XTEM investigation of the contacts showed more emphasized interface roughening than reported in the literature [7,10,11]. The reason of this can be the different sample–preparation technique applied in our experiments.

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AlNiGe KAO NOV NAMJENSKI MATERIJAL ZA KONTAKTE NA n–GaAs

Slojevi Al(150 nm)/Ni(30 nm)/Ge(40 nm) termički su napareni na GaAs n–tipa. Uzorci su otpuštani u plinskoj smjesi H_2(30%)+N_2(70%) na 400 °C, 450 °C i 500 °C i njihovo legiranje je ispitivano elektronskom mikroskopijom. Suprotno objavljenim rezultatima, $I - V$ krivulje pokazuju da spojevi zadržavaju ispravljačko svojstvo nakon otpuštanja na svim primijenjenim temperaturama. Temperaturna ovisnost parametara koji su bili određeni na osnovi ovisnosti struje o naponu ili kapaciteta o naponu potvrđuju da je vođenje struje posljedica anomalne termionske emisije polja.