Study of Interface of Ohmic Contacts to AlGaN/GaN Heterostructure

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Abstract. *The paper embraces studies of the interface of ohmic contacts and AIIIBV-N heterostructure. The TiAl based metallization stack was investigated. The Ti/Al/Ni/Au contact to AlGaN/GaN heterostructures fabricated by metal-organic vapour phase epitaxy was examined using three methods i.e. etching of annealed contact metallization, fractures (prepared at room temperature and after a bath in liquid nitrogen) and microsections imaging. The main focus was on the estimation of reaction range on the metal-semiconductor interface of samples. In the first method, the surface of AlGaN/GaN heterostructure after etching of metallization was studied by an optical microscope, scanning electron microscope and atomic force microscope. The changes of surface morphology of heterostructure directly reflect solid state reactions range between metallization and semiconductor. The range of reactions was also observed using the small-angle microsections method while the fractures analysis did not bring valuable information.*

Keywords

AIIIBV-N heterostructures, metal-semiconductor interface, Ti/Al/Ni/Au metallization.

1. Introduction

AlGaN/GaN heterostructure based High Electron Mobility Transistors (HEMTs) are good candidates for high-power and high-temperature application. This area of applications enforces thermal stability of applied materials, thus also ohmic/Schottky contacts have to be of good quality, appropriate morphology, low-resistance and thermal stability [1], [2]. Parameters of ohmic contacts depend on various factors as e.g.: used metal stack, thicknesses of metal layers, heterostructure properties, and thermal annealing process parameters [3]. The standard scheme of metallization consists of Ti/Al/metal/Au, where metal could be one of Ni, Pd, Pt, Mo [4]. The metallization is processed in thermal annealing system after deposition. Depending on applied temperature of annealing, improvement or deterioration of electrical parameters of metal-semiconductor system occurs.

While the mechanism of contact formation to GaN is already understood, the ohmic contact formation to AlGaN/GaN needs further studies [5]. The most common method of investigation of metal-semiconductor (m-s) interface phenomena is TEM (transmission electron microscope) analysis [4], [5], [6] and [7]. In the paper, the m-s interface of Ti/Al/Ni/Au and AlGaN/GaN was studied using three methods. First technique included deposition of metallization on the surface of AlGaN/GaN, thermal annealing, etching of annealed ohmic contact and further observation of the etched surface of semiconductor using microscope methods as Scanning Electron Microscope (SEM) and Atomic Force Microscope (AFM). That gave an information on the m-s interface and permitted for estimation of the reaction range. Second one relied on fractures preparation and observation of the interface by application of SEM (Scanning Electron Microscope). The third method required polishing of the metallization near the edge of the sample. Obtained small-angle microsection permitted for observation of semiconductor surface.

2. Technology

The investigated samples contained metallization stacks deposited on AlGaN/GaN heterostructures fabricated using metalorganic vapour phase epitaxy method on Al_2O_3 substrates. Mesa structures were formed in chloride plasma of Reactive Ion Etching (RIE). The etching process was carried out through the oxide mask (SiO_2) deposited in Plasma-Enhanced Chemical Vapour Deposition (PECVD) system. The pattern was achieved in standard lithography process. The mask layer thickness was of about 300 nm.

Samples with Ti/Al/Ni/Au (20/100/40/150 nm) layers deposited in UHV system by electron beam (Ti, Ni) and resistance heater (Al, Au) evaporation were investigated. The test structures were fabricated using photolithography process in lift-off technique by application of LOR and SPR 700 bi-layer. The samples were coated by the layers using spin-coating method. Samples with Ti/Al/Ni/Au multilayer metallization were annealed in Rapid Thermal Annealing (RTA) system at a temperature of 820 °C.

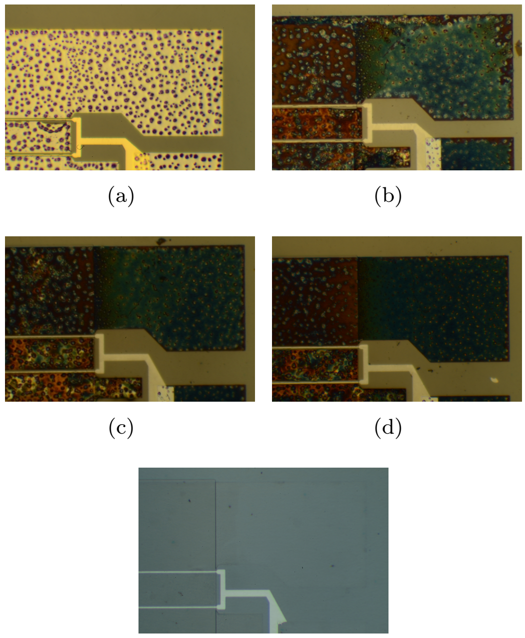
To study the influence of annealing process on the properties of heterostructure the metallization layers after annealing were selectively etched layer by layer. The etching process was carried out in:

- iodine-potassium iodide (Au),
- H_3PO_4:H_2O (1:3) at 70 °C (Ni),
- H_3PO_4:HNO_3:CH_3COOH:H_2O (85:5:5:5) at 45 °C (Al),
- hydrogen peroxide at 65 °C (Ti).

Etching stages duration was 10 minutes each. After etching of metal layers optical microscope and SEM images of surface morphology of chosen area were recorded. This permitted to estimate the range of metal-semiconductor solid state reactions, follow the morphology changes and its correlation with m-s interface topography.

The study of application of fractures technique for the solid state reaction range on the interface of annealed metallization and AlGaN/GaN was carried out. The fractures technique was adopted from AIIIBV technology [8]. The mechanical incision of samples for this investigation was made using diamond blade. Samples were incised from the Al_2O_3 side for the depth of about 180 μm. Then samples were fractured at room temperature or immediately after bath in liquid nitrogen. Also samples fractured during the technological process because of the large stress were examined.

The last group were samples grinded and polished under small-angle near the edge of the sample. This method permitted for observation of the reactions range occurring on the interface in only little invasive way. In contrary to two above-mentioned methods, the sample after microsection preparation and observation can be used for further processing.



(a) (b) (c) (d) (e)

Fig. 1: Optical images of metallization surface (a) before etching and after etching of (b) Au, (c) Ni, (d) Al and (e) Ti.

3. Results

The rapid thermal annealing process of ohmic contacts to AlGaN/GaN heterostructure based devices affects parameters of the contact. The selection of appropriate temperature value of annealing temperature was made based on presented and discussed earlier paper [9]. Application of annealing at temperature above 835 °C led to the degradation of AlGaN/GaN heterostructure surface beneath the contact. Temperature equal to 805 °C started reactions at the level of 2DEG position i.e. of about 25 nm from the surface. Therefore, the intermediate value of 820 °C was chosen for annealing of investigated samples. During thermal annealing of the Ni-based metallization the agglomerates appear on the surface (black spots in Fig 1(a) and Fig 3(a)). They are a consequence of migration and coalescence of melted Ni. The mechanism of agglomeration formation was already studied and described [10]. Figure 1 presents optical images of metallization surface Fig. 1(a) before etching, and remained metallizations layers after etching of Fig. 1(b) Au, Fig. 1(c) Ni, Fig. 1(d) Al and Fig. 1(e) Ti.

Each step of etching changed the surface of ohmic contact. The remained metal films (Fig. 1(b), Fig. 1(c), Fig. 1(d) and Fig. 1(e)) had slightly different topography. After first etching mostly the largest agglomerates of the contact (remarkable as black spots in Fig. 1(a)) were still observed. That could indicate lack of gold in the agglomerates volume, which corresponded to

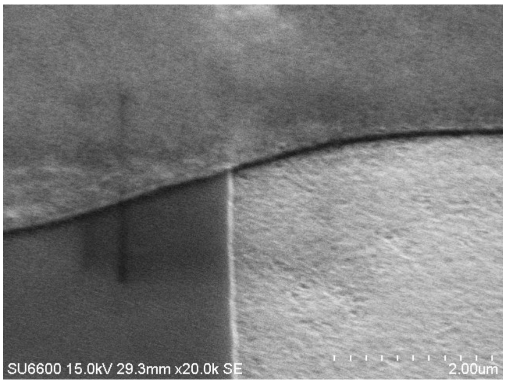


Fig. 2: SEM image embracing three types of areas: metallization on etched GaN (A) and mesa (A'), mesa surface (B), etched GaN (C).

[11]. It was observed that the remained metallization (Fig. 1(b), Fig. 1(c) and Fig. 1(d)) topographies did not reflect the m-s interface topography (Fig. 1(e)). Nevertheless, there were significant differences in topographies of surfaces beyond the ohmic contact on the mesa (Fig. 2, A) and outside of it (Fig. 2, A'). That may be explained by various topographies before metallization deposition (Fig. 2, B and C) and various materials (i.e. AlGaN and GaN).

Figure 3 presents SEM images of metallizations layers, Fig. 3(a) before etching and remained after etching of Fig. 3(b) Au, Fig. 3(c) Ni, Fig. 3(d) Al and Fig. 3(e), Fig. 3(f) Ti.

SEM images confirmed graduate removal of the metallization layers in subsequent stages except of etching the Al layer. It could be explained by occurring of a metal compound that could not be etched in used solution in contrary to H_2O_2.

Step of Au etching caused a delamination near the agglomerates (Fig. 3(b)). The surface beneath the ohmic contact after etching of all layers of metallization changed significantly. Topography of this area is a reflection of the m-s interface. The topographies under agglomerates and outside of this area were nearly identical. The difference between surfaces of a sample before and after Al etching (Fig. 3(c) and Fig. 3(d) was nearly unnoticeable, which corresponded to optical microscope images (Fig. 1(c) and Fig. 1(d). It could be caused by etching of Al layer (or its compound) by solution of H_3PO_4:H_2O, used for Ni layer removal but it requires further analysis e.g. by EDX (Energy Dispersive X-ray Spectroscopy).

The consumption of the AlGaN layer was significant (Fig. 3(f)) – represented as dark spots on the picture. Figure 4(a) presented SEM image of two areas of mesa – bare surface (A) and surface with deposited and etched metallization (B). The AFM images were taken

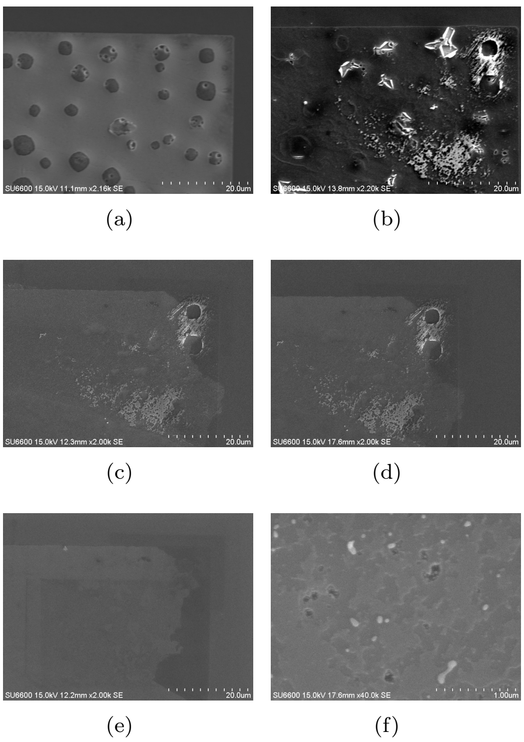


Fig. 3: SEM images of metallization surface before etching (a), and remained metallizations layers after etching of (b) Au, (c) Ni, (d) Al, (e) and (f) Ti.

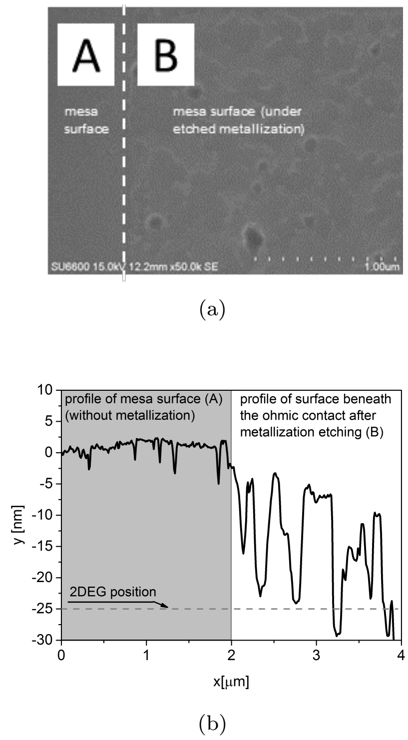


Fig. 4: (a) SEM image of semiconductor layer; mesa (A) and mesa surface after etching of ohmic contact (B), (b) profile of the surface after metallization etching (extracted from AFM image).

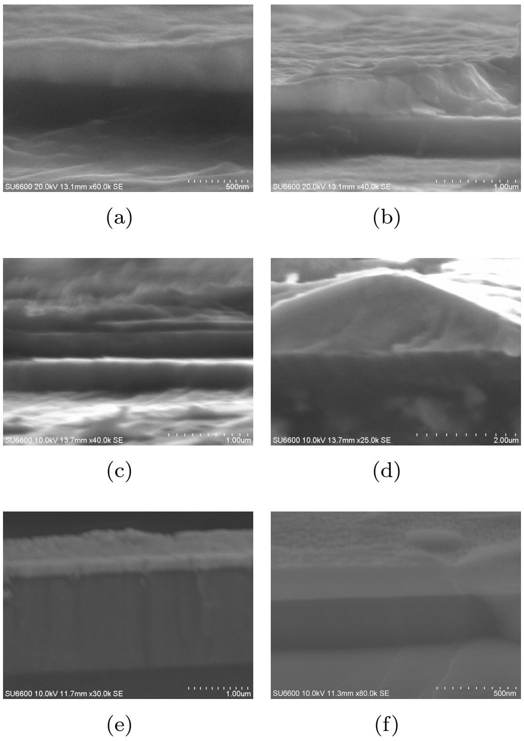


Fig. 5: Example SEM images of fractures of annealed Ti/Al/Ni/Au metallization and AlGaN/GaN heterostructure made at room temperature (a), (b), immediately after bath in LN_2 (c), (d) and fractured during technological process (e), (f).

from the region embracing A and B. Figure 4(b) consisted of profile of the surface after metallization etching (extracted from AFM image). It confirmed phenomenon of AlGaN surface consumption. The depth of solid state reaction on the m-s interface reached even 30 nm within studied area. It seemed to penetrate the 2DEG region, but in this stage of research we are not able to estimate if heterostructure beneath metallization has to be preserved for obtaining the optimal parameters of m-s contact.

The applied fracture technique did not permit for observation of the penetration of ohmic contact into AlGaN/GaN heterostructure (Fig. 5). Despite obtained sharp fractures, the m-s interface on SEM images did not bring any valuable information. Bath in liquid nitrogen improved sharpness of the fractures, but it was still insufficient to investigate the changes occurring in the range of depth equal to 30 nm. This technique permitted only for distinguishing of ohmic contact and thickening metallization layer Fig. 5(d), Fig. 5(e) and Fig. 5(f).

The samples with annealed ohmic contacts were also examined using small-angle microsections. Figure 6(a) presents the microsection embracing two areas – metallization (upper part of the SEM image) and AlGaN/GaN heterostructure (bottom of the SEM image).

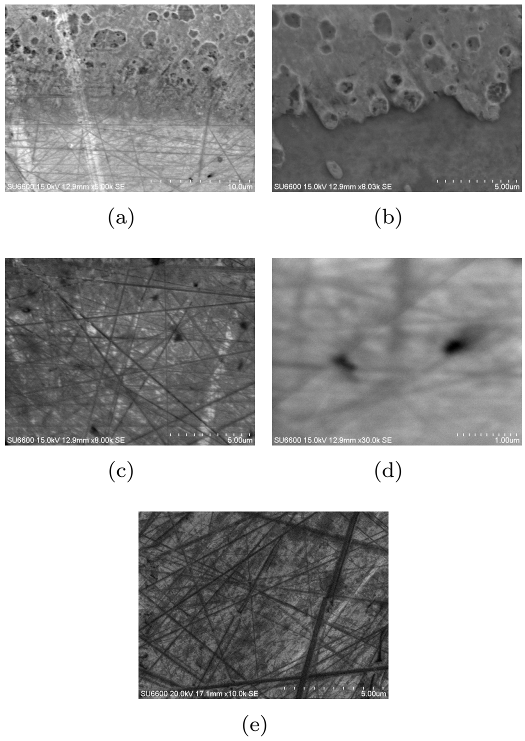


Fig. 6: Example SEM images of microsections of annealed Ti/Al/Ni/Au metallization and AlGaN/GaN heterostructure.

The spots on the surface of metallization could be agglomerates which are composed of materials in other propotions than metallization stack thus having other mechanical properties that led to more efficient polishing in those areas.

One of the disadvantages of this method is a tear off of the metallization in some areas of microsections. Nevertheless in the studies limited to the investigation of the AlGaN/GaN heterostructure surface morphology, the method does not require further optimization.

The study of the heterostructure surface beneath the ohmic contact (Fig. 6(c) and Fig. 6(d)) allows to observe the black spots among the polishing grooves that may indicate the interfacial reaction between the semiconductor and metallization. The size of the observed spots was of few tens of micron, similar as that for samples with etched ohmic metallization.

The spots were not observed on the microsection in the area outside the ohmic metallization Fig. 6(e).

4. Conclusion

The Ti/Al/Ni/Au metallizations to AlGaN/GaN heterostructures fabricated by metal-organic vapour phase epitaxy were studied. The range of reactions on the metal-semiconductor interface of samples was examined after etching of annealed ohmic contacts and using fractures.

At any stage of etching, topography of remained metallization did not reflect the topography of the m-s interface. Nevertheless, solid state reactions on the m-s interface were significant. The depth of reactions estimated on the bases of AFM images reached even 30 nm within studied area. SEM images of prepared fractures did not allow to estimate the depth of solid state reactions on the m-s interface. Application of LN_2 for fractures influenced slightly the sharpness of the fractures but did not enable analysis of solid state reactions on the m-s interface beneath annealed ohmic contact.

The applied method of small-angle microsections study permits for observation of range of reactions on the interface of Ti/Al/Ni/Au and AlGaN/GaN heterostructure. The reactions consequences are observable as black spots on the surface of semiconductor in the area beneath the ohmic contact.

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