Scanning probe microscopy of AlGaAs/GaAs diode after partial electrical breakdown

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Abstract. Scanning probe microscopy allows to study surface processes in semiconductor heterostructures. This work shows the investigation of topography and surface potential distribution in AlGaAs/GaAs p-n diode after applied reverse voltage. Formation of oxide on the surface in the area of p-n junction was found due to increasing of the applied reverse voltage. Formed oxide increases a breakdown voltage by 20%.

1. Introduction.
GaAs semiconductor heterostructures are used to create electronic devices such as diodes, transistors, laser diodes, HEMT[1]. Main drawback of GaAs heterostructures is high surface state density, which leads to a pinning of the Fermi level on the surface and increasing of surface leakage current[2]. Usually, increasing of surface leakage current relate to formation of natural oxide on the surface of GaAs. Conventionally, a surface passivation is used to prevent these negative effects[3].

Recently we have found an increasing of break-down voltage effect of GaAs/AlGaAs diodes with unpassivated surface. This effect was realized by cycle increasing of break-down voltage. In this work the process of increasing the break-down voltage of GaAs/AlGaAs heterostructures with appearance of surface leakage current will be studied by using a Scanning Probe Microscope (SPM).

2. Samples and methods.
Heterostructure was created on n-GaAs substrate by MOCVD methods. The following layers were grown on the substrate: Al0.35Ga0.65As (n = 1.5 * 10¹⁸ cm⁻³, with thickness of 1.47 um); GaAs (p = 3-3.5 * 10¹⁶ cm⁻³, with thickness of 2 um); GaAs (p = 6*10¹⁹ cm⁻³, with thickness of 0.4 um). Ohmic contacts were formed on the compositions of AuGe/Ni/Au for n type and AuZn/Au for p type. The structure was cleaved on the elements with size: 400x400 um. The elements were installed on the cuprum base, using an indium solder. Figure 1. a) shows the topography of a surface of the cleavage in location of p-n junction. The difference between AlGaAs and GaAs layers on the topography is explained by the greater layer’s thickness of surface oxide of AlGaAs[4]. Height difference in this location is about 1 nm.

SPM methods allows to investigate physical processes on the surface of structure. In addition to standard topography measuring, a surface potential distribution was measured. The surface potential was obtained by Gradient Kelvin-probe microscopy (GKPM)[5]. The study was carried out on the scanning probe microscope Ntegra AURA (NT – MDT company, Zelenograd, Russia). In this experiment we use silicon probes with conductive Pt/Ir coating. One part of experiment was carried out in the vacuum (P= 10⁻² mbar), other part in the atmospheric conditions (P=1 bar, humidity 24%).
Figure 1. GaAs/AlGaAs diode structure. a) Topography of the chip’s surface in location of p-n junction. b) Average profile of the surface potential distribution in the dark and in the light.

The figure 1. b shows the profiles of the surface potential distribution. In this case the surface potential is the difference between a work function of the SPM probe and the surface in the measurement point. Without light illumination the maximum contrast of the surface potential distribution is of 0.2 eV. This is explained by a pinning of the Fermi level on the surface in the middle of bandgap. Indeed, difference between the Fermi level pinning on the surface in p+ and n+ layers is about 0.2 eV in the AlxGa1-xAs alloys[6,7].

Under the light illumination, nonquilibrium charge carriers under the effect of near-surface field move to the surface and reduce the near-surface band bending. This leads to increasing the difference between Fermi level pinning of p and n layers. As the near-surface field has opposite directions in the p and n layers, the illumination increases the surface potential in n layer, and reduces in p layer[8]. From the Figure 1.a, b it follows that location of p-n junction coincides with GaAs/AlGaAs heterointerface with accuracy of 100 nm.

3. Results and discussion.

For the study of the effect of a break-down voltage increasing, it was used a ‘training’ procedure. The training is a process of increasing of a break-down voltage of the structure, using cyclic increasing of external reverse voltage during the measurement of an I-V curve. Figure 2 shows topography (a), surface’s profiles (b) and I-V curves (c), which are corresponding to the three stages of training.

The first training was performed in vacuum conditions (Fig. 2.a, 2 picture; Fig. 2.b, c, blue lines). Using the measured I-V curves (Fig. 2.c, blue line), it’s possible to find the break-down voltage, which was of 20 V. Profiles and topographies which are corresponding to first training are different from profiles and topographies of not trained structure (Fig. 2.a, 1 picture; Fig. 2.b, red line). The changes of structure topography are explained by the process of oxide formation in location of p-n junction. After the first training the height of oxide was 4 nm (Fig. 2.a, 2 picture; Fig. 2.b, blue line). The process of oxide formation will be explained below. After the second training the height of oxide was increased by 1 nm (Fig. 2.a, 3 picture; Fig. 2.b, green line). I-V curve (Fig. 2.c, green line) has changed compared to the first training (Fig. 2.c, blue line). Indeed, the break-down voltage was increased.
Figure 2. a) Surface topography: 1. Before training. 2. After the first training (vacuum). 3. After the second training (vacuum). 4. After third training (atmospheric conditions). b) Surface profiles which is corresponding to topography. c) I-V curves, which is corresponding each training process.

Training in the atmospheric conditions leads to the most increasing of oxide height in location of p-n junction (Fig. 2.a, 4 picture; Fig 2.b, black line). The height of the oxide was 15-20 nm. The break-down voltage was also increased (Fig. 2.c, black line).

From the figure 2 it is follows that oxide formation depends on the conditions of training and the applied reverse voltage. Break-down voltage depends on the height of oxide. For the explanation, one can assume that the formation of the oxide blocks the channel of surface leakage current.

Figure 3 schematically shows the oxidation process. This process is similar to a process of local anodic oxidation [9]. Oxide formation in location of p-n junction depends on several factors: presence of a surface absorbed water film, high electric field strength for water dissociation, and conditions for current flowing.

Conventionally, the water film presence on the surface of the semiconductors in the atmospheric ambient conditions. However, the formation of the oxide was observed also during the training in vacuum conditions. This oxidation was due to a moderate vacuum pressure (10-2 mbar). It was shown that the water film remains on the surface in these conditions [10]. The oxide formation processes are described by the following reactions:
For n layer:

\[ 2\text{AlGaAs} + 6\text{H}_2\text{O} \rightarrow \text{Al}_2\text{O}_3 + \text{Ga}_2\text{O}_3 + 2\text{As}_2\text{O}_3 + 6\text{H}_2 \]  

For p layer:

\[ 2\text{GaAs} + 3\text{H}_2\text{O} \rightarrow \text{Ga}_2\text{O}_3 + 2\text{As}_2\text{O}_3 + 6\text{H}_2 \]

In this case, the presence of strong electric field is necessary for oxide formation. Molecule of water dissociates on the hydroxyl group and hydrogen under the influence of this field. Under the reverse voltage of 20 V, the electric field in the area of p-n junction increases to the level of 10^5 V/cm which is leads to water dissociation[9].

![Figure 3. Model of the surface anodic oxidation in the area of p-GaAs/n-AlGaAs junction.](image)

Increasing of the water thickness on the surface in the atmospheric conditions increases the surface leakage current. Indeed, in a voltage range of 10-18 V (Fig. 2) the current in the atmospheric conditions (black line) is bigger than current in the vacuum conditions. From the other hand, a thicker water film leads to thicker oxide formation during the training in the atmospheric conditions.

4. Conclusion.

Thus, the surface of the cleavage of the p-GaAs/n-AlGaAs diode was studied by scanning probe microscopy methods. From the topography and surface potential distributions, a location of the p-n junction was find. Applying of the reverse voltage exceeding a breakdown leads to a formation of surface oxide in the area of the junction. This oxidation is followed by an increasing of the breakdown voltage by 20%. Local anodic oxidation mechanism was proposed for the oxide formation. Due to this mechanism a surface water film dissociates in the p-n junction electric field. Products pf the dissociation oxidizes GaAs and AlGaAs. Formation of the oxide blocks a surface leakage current.

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