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Influence of strip mesastructure topology on a low-voltage GaAs thyristor main parameters

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A GaAs thyristor with mesa-strip has been fabricated and experimentally studied. It is shown that changing topology of the heavily doped *p*-emitter and the anode ohmic contact leads to an increase in magnitude and decrease in variation of breakover voltage of the samples, as well as to a decrease in off-state current.

Keywords: Thyristors, Mesastructure, Gallium arsenide, Breakover voltage, Off-state current.

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1. Introduction

A negative effect on the characteristics of surface states having a high density both on the surface of plates and on the side surfaces of mesastructures is a well-known problem of all semiconductor devices based on gallium arsenide, including thyristors [1]. The technology of fabrication of small-sized low-voltage thyristors grown by MOCVD includes the formation of mesas of different topologies by etching of epitaxial layers [2–6]. It should be noted that the blocking capability of such devices can be significantly reduced because of the presence of a charge of surface states along the perimeter of $p-n$-junctions extending to the lateral surface of the mesa. This charge can result in the formation of an inverse layer on the surface of a high-resistance region or in the occurrence of an electric field on the surface exceeding the field in volume which results in a surface breakdown at a lower voltage [1,7,8].

We noted when studying of GaAs thyristor mesastructures of round and stripe geometry [6,9] that a significant variation of the breakover voltage of different samples in the batch is observed without additional treatment of mesas, as well as a gradual degradation of characteristics during multiple switching. We proposed various methods in Ref. [9] (chemical sulfidation and profiling of mesas) for treatment the lateral surface of GaAs mesas of round geometry with a diameter of up to 4 mm which contributed to the increase of the magnitude and stability of the breakover voltage of the samples. This work is a continuation of these studies and is devoted to the study of GaAs thyristor mesastructures of stripe geometry. The impact of the topology of a strongly doped *p*-emitter and an anode ohmic contact on the value of the breakover voltage and the off-state current is considered.

2. Test samples and experimental procedure

The thyristor $p-n-p-n$-structure was grown on a n^+-GaAs(100) substrate by MOCVD. The concentration of dopant was $\sim 10^{18}\,\mathrm{cm}^{-3}$ in the emitter regions of *n*- and *p*-type with a thickness of 0.55 and $0.30\,\mu$m, respectively. The base regions of n^0-type ($1.9\,\mu$m) and p^0-type ($2.2\,\mu$m) were doped to the level of $\sim 10^{16}\,\mathrm{cm}^{-3}$. Thyristor designs were formed based on the grown structure by etching mesas of a stripe geometry with a depth of $\sim 0.5\,\mu$m and a width of $360\,\mu$m. The anode and control ohmic contacts to the *p*-emitter and n^0-base were formed on the basis of AuGe in the form of $300\,\mu$m wide stripes. The cathode contact was also made on the basis of AuGe and was applied to the n^+-GaAs substrate in a solid layer. The plate with the fabricated structure was split into strips with a length of mesastripes of ~ 1 mm.

It should be noted that all layers of the epitaxial structure t in the described topology of thyristors (type 1), including metal stripes of ohmic contacts, faced the chipped edges of the thyristor strips (Figure 1, *a*). The ohmic contact stripes were shortened on some strips by removing the areas adjacent to the chipped edges in the iodide etcher ($\sim 200\,\mu$m on each side). The topology of the obtained thyristors (type 2) is shown in Figure 1, *b*. The parts of *p*-emitter layer adjacent to the chipped edges of the strips ($\sim 150\,\mu$m on each side) were etched on other strips, in addition to the ohmic contact. The etching of the *p*-emitter was performed to a depth of $\sim 0.5\,\mu$m, thus removing part of the n^0-base layer with a depth of $\sim 0.2\,\mu$m. The topology of these thyristors (type 3) is shown in Figure 1, *c*.

Sample linear arrays of thyristors with the initial topology of types 1, 2 and 3 were studied in this paper, as well as array of type 1, which were successively subjected to additional treatment to obtain a topology of types 2 and 3 on them. The current-voltage ($I-U$) characteristics of thyristors without a control signal were measured in the

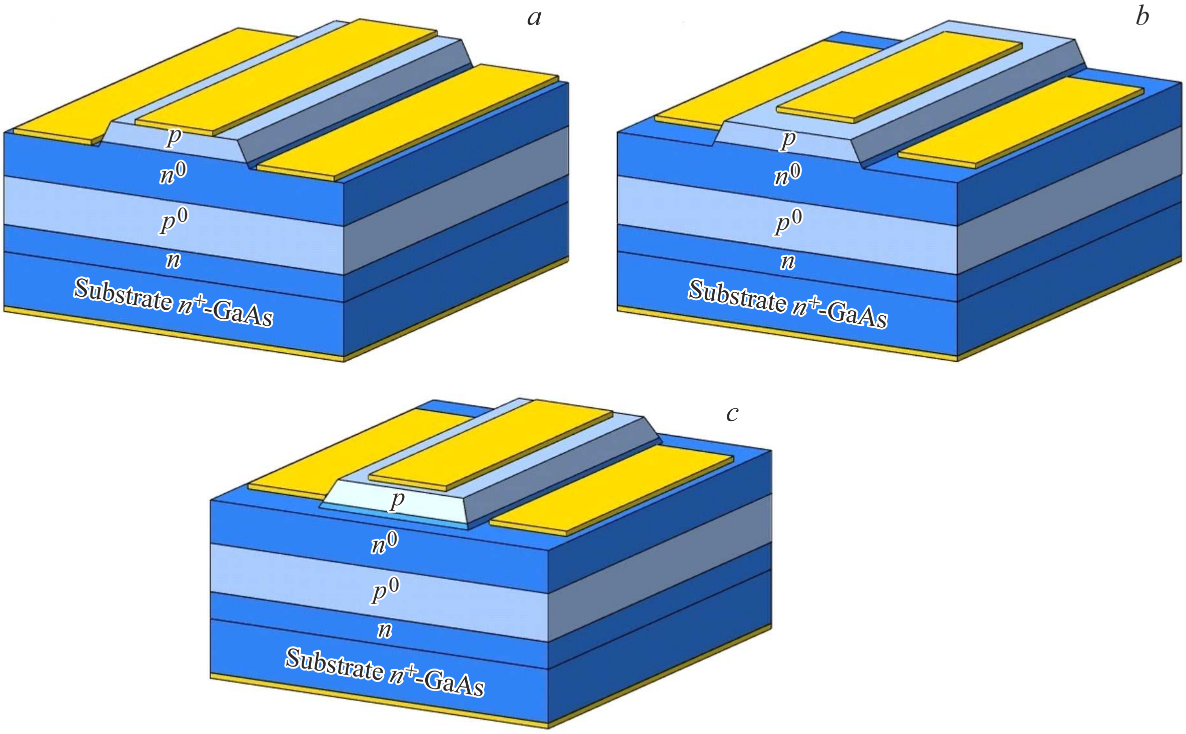

Figure 1. Schematic topology of thyristor GaAs mesastructures: *a* — type 1, *b* — type 2, *c* — type 3.

voltage source and a current source modes. The breakover voltage (U_{bo}) and the off-state current of the thyristor (I_o) were determined from the obtained dependencies.

3. Results and discussion

Initially, the linear arrays of thyristor mesastructures with topology of all three types were fabricated and studied and their typical $I-U$ characteristics in the current source mode are shown in Figure 2. All types of structures have S-shaped current-voltage curves which is attributable to the switching of thyristors from a off-state (high-resistance) to an on-state (low-resistance).

All further $I-U$ characteristics measurements were performed in the voltage source mode for a more accurate determination of the breakover voltage of the samples. The experimental values of U_{bo} and I_o thyristors with different topology types are given in Table 1. It can be seen that the value of U_{bo} differs by 3 times for samples in the same array of thyristors with a topology of type 1. A reduction of the area of the metal contact and the p-emitter of thyristor (type 3) resulted in the increase of the maximum breakover voltage by 30%, and the increase of the minimum breakover voltage by almost ~ 4 times compared with samples of type 1. At the same time, the variation of values of U_{bo} for thyristors with a topology of type 3 was reduced by 16 times, which is important in mass production, where strict requirements are imposed on the variation of parameters of fabricated products. Moreover, the average value and the variation of the thyristor off-state current of the samples with topology of types 2 and 3 decreased with the main voltage of 5 V.

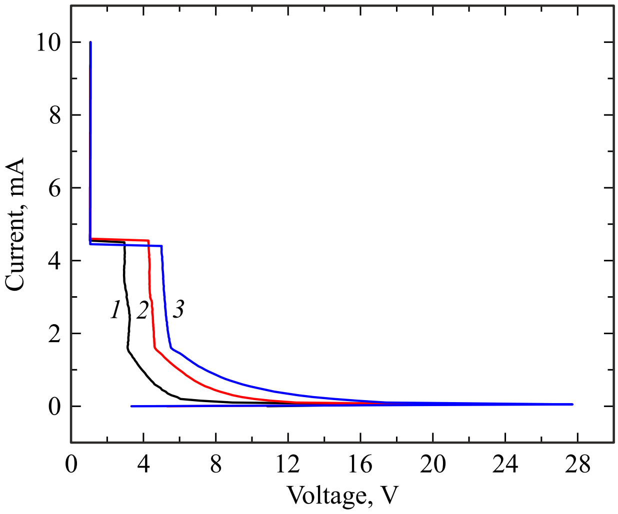

Figure 2. Typical $I-U$ characteristics (in current source mode) of thyristor mesastructures with different topologies: *1* — type 1, *2* — type 2, *3* — type 3.

An experiment was performed for confirming obtained results in which a metal contact layer of arrays of thyristors with a topology of type 1 was sequentially etched, and then a layer of the p-emitter was etched for obtaining samples with a topology of types 2 and 3 on the same arrays of thyristors. The $I-U$ characteristics of the obtained

Table 1. Breakover voltage and off-state current of GaAs thyristor mesastructures with different topologies

Topology of samples	U_{bo}, V	I_o, μA ($U = 5\,$V)
Type 1	8–24	0.1–0.6
Type 2	17–32	0.2–0.3
Type 3	31–32	0.1–0.2

Table 2. Characteristics of thyristor mesastructures with sequential change of topology from type 1 to type 3

Treatment stage	U_{bo}, V	I_o, μA ($U = 5\,$V)
Initial structure (type 1)	8–24	0.1–0.6
Partial removal of ohmic contact (type 2)	19–32	0.3–0.5
Partial removal of p-emitter (type 3)	26–34	0.1

thyristors was measured after each stage of treatment. The measurement results are provided in Table 2. They confirm that each additional stage of treatment of the thyristor mesastructure ensures an increase of the blocking ability of the samples compared to the previous stage. However, a significant variation of the values of U_{bo} should be noted for samples of all three types. For example, it decreased by only 2 times for samples with a topology of type 3 compared to the original samples of type 1. The absolute value of the variation (8 V) is much higher than the similar value from Table. 1, which may be attributable to the formation of current shunts in the volume of the structure during the measurement of the $I{-}U$ characteristics, which are preserved during subsequent treatments of mesastructure surface. In addition, a slight increase of the average value of the off-state current at the main voltage of 5 V was observed for the array of thyristors after partial removal of the stripe ohmic contacts.

Figure 3, *a* shows typical $I{-}U$ characteristics of thyristors with successive change of topology from type 1 to type 3, and Figure 3, *b* — sections of the same $I{-}U$ characteristics corresponding to the off-state on an enlarged scale. Figure 3, *a* clearly illustrates the conclusion that the removal of parts of the metal contact and the strongly doped layer of p-emitter facing the chipped edge of the thyristor mesastructure results in an increase of the breakover voltage of the samples. We observed a similar result in Ref. [9] when creating a stepped topology with a complex profile of the lateral surface of GaAs thyristir mesastructures of round geometry by liquid etching.

Attention is drawn in Figure 3, *b* to the faster nature of the current increase of the initial section of the curve *2* (from 0 to 2.5 V) compared to the curves *1* and *3*. This feature of type 2 thyristors is most likely caused by contamination of their surface with ions of foreign impurities from the iodide etchant used to remove the anode ohmic contact, washing water or the external atmosphere [8]. A surface shunt of the anode emitter $p{-}n^0$-junction may be formed as a result of such contamination, which contributes to the leakage of nonequilibrium electrons from the n^0-base region in case of low voltage values and results in a rapid increase of I_o. As a result, the accumulation of electrons in the n^0-base with the critical concentration necessary to switch the thyristor to the on-state takes place at a higher voltage value [10].

The increase of the current in the off-state in the initial sections of the curves *1* and *3* in Figure 3, *b* has a qualitatively similar character. The reduction of the slope of the $I{-}U$ characteristics curve *3* compared to the curve *1* may be caused by a number of reasons. Firstly, the contribution of surface contaminants to the value of I_o is reduced for samples with a topology of type 3, since GaAs etching removes contaminations from the surface.

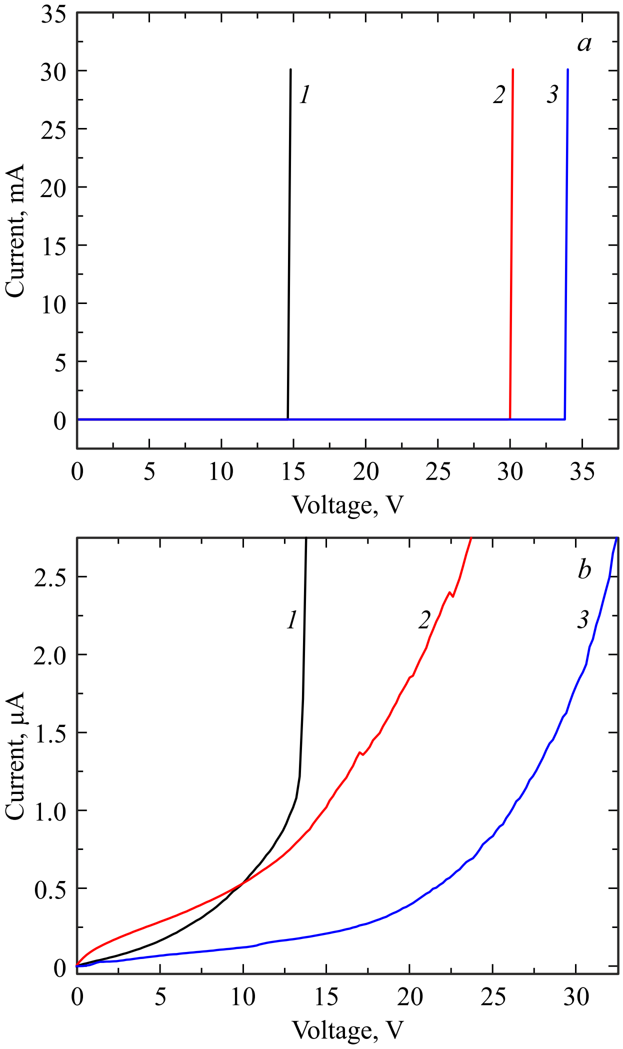

Figure 3. Typical $I{-}U$ characteristics (in voltage source mode) in the on-state (*a*) and off-state (*b*) of a thyristor with a topology of type 1 (curves *1*), as well as after partial removal of the metal contact (curves *2*) and p-emitters (curves *3*).

Secondly, the surface diffusion of holes injected into the n^0-base to the space charge region (SCR) of the collector p^0-n^0-junction is hampered due to the distancing of the surface of the emitter $p-n^0$-junction from it. And, thirdly, the volume component of the current through the emitter $p-n^0$-junction decreases due to a reduction of its area by ~ 1.5 times. All of the above factors contribute to a decrease of the accumulation rate of nonequilibrium charge carriers of critical concentration in the base regions, which results in an increase of U_{bo} (Figure 3, *a*).

It is interesting to note that the curves *2* and *3* in Figure 3, *b* have the same slope at high voltages, i. e., the main mechanism of current flow in these sections of the off-state for samples with topology of type 2 and 3 coincides. This is attributable to the fact that the emitter current in samples with a topology of the type 2 which varies exponentially, becomes significantly larger with the increase of the voltage than the shunt current, which varies linearly [10].

The collector p^0-n^0-junction in the studied samples which ensures the blocking properties of the thyristor, reaches the cleavage surface formed when the structure is divided into arrays of thyristors. The electric field on the surface of the mesa in mesastructural diodes with vertical walls is commensurate with the magnitude of the field in the volume according to Ref. [11], however, the surface breakdown prevails, as a rule (due to the presence of various kinds of structural inhomogeneities, surface charge, contamination, etc. on this surface). The width of the space charge region increases in the thyristor base regions with the increase of the main voltage of the thyristor. The calculated value of the SCR width in case of a breakdown of the $p-n$-junction is $1.6\,\mu$m for n^0-base layer with a dopant concentration of $1.8 \cdot 10^{16}\,\text{cm}^{-3}$ [12]. Therefore, the breakover voltage of the thyristor is unlikely to be limited by a puncture of n^0-base region with a thickness of $1.9\,\mu$m, at least in the volume of the structure. The switching of the thyristor to on-state requires an accumulation of nonequilibrium holes and electrons in p^0- and n^0-base regions, respectively, delivered from p- and n-emitters mainly through the drift-diffusion transport processes before the onset of the avalanche reproduction of carriers at high voltages. The changes in the topology of thyristor samples considered in this paper, on the one hand, contribute to reduction of the injection of holes from the p-emitter into the n^0-base in the near-surface region. On the other hand, they reduce the surface diffusion of injected holes to the space charge region of the p^0-n^0collector junction due to distancing of the surface of the emitter $p-n^0$-junction from it after the etching of the part of the p-emitter. All this results in an increase of the breakover voltage of the thyristors and a decrease of the off-state current.

In conclusion, it should be noted that the above results of studies of the modification of the topology of thyristor mesastructures indicate the surface nature of their breakdown. Therefore, it remains an important task to control the presence of leakage currents and marginal electric fields on the side surface of GaAs device structures of various designs.

4. Conclusion

Thus, this paper studies the influence of the topology of the strongly doped p-emitter and the anode ohmic contact of GaAs thyristor stripe mesastructures on their breakover voltage and the off-state current. It is shown that the change of the topology of the upper layers of mesastructures allows increasing the breakover voltage to 34 V, and reducing the off-state current to $0.1\,\mu$A (with a voltage of 5 V).

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Conflict of interest

The authors declare that they have no conflict of interest.

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