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OPTIMIZATION MANUFACTURING TECHNOLOGY OF ULTRAHIGH-FREQUENCY DIODE

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A microwave semiconductor diode (microwave diode) is a semiconductor diode designed for converting and processing a microwave signal. Semiconductor microwave diodes are used in various radio electronic equipment and measuring equipment in the microwave range, i.e. at frequencies above 300 MHz. Initially, microwave diodes were used for detecting and mixing signals. For these purposes, point diodes were used, in which the rectifying electrical transition occurred between the semiconductor crystal and a clamping metal electrode in the form of a pointed spring. Recently, new types of microwave diodes have almost completely replaced point detector and mixing diodes. They make it possible to solve the problems of generating and amplifying electromagnetic oscillations in the microwave range, frequency multiplication, modulation, regulation, signal limitation, etc. However, despite their widespread use, the cost of microwave diodes remains relatively high due to the low yield of usable diodes, which is explained by the high level of reverse current of the devices. The article discusses the causes and mechanisms of degradation of the reverse characteristics of microwave diodes. It is shown that the reason for the low yield of diodes is the significant influence on their reverse characteristics of structural defects and impurities and the quality of the surface of varicap structures. It is established that the main reason for the low percentage of yield of suitable investigated varicaps are epitaxial packing defects in the original epitaxial structures and oxidative packing defects formed in the active regions of varicap structures in the processes of high-temperature operations. The conducted studies have shown that the most effective method of preventing the formation of structural defects in epitaxial layers is the creation of a gettering region on the reverse side of the substrates by means of its processing with an Nd – laser. The proposed technology for manufacturing diode structures using gettering with a getter region created on the reverse side of a silicon substrate by laser processing it before deposition of an epitaxial layer is considered in detail. Experimental results of the study of the influence of gettering on the reverse characteristic of a microwave diode are presented, and possible mechanisms of this influence are analyzed. The effectiveness of the proposed technology using gettering in reducing the level of reverse currents and increasing the percentage of yield of suitable devices is shown.

***Key words:** ultra-high-frequency diode, epitaxial packing defects, oxidative packing defects, reverse current, getter, diode structures.*

Литвиненко В. М., Зубенко В. О. Оптимізація технології виготовлення надвисокочастотного діода
Надвисокочастотний напівпровідниковий діод (НВЧ-діод) – це напівпровідниковий діод, призначений для перетворення і обробки надвисокочастотного сигналу. Напівпровідникові НВЧ-діоди застосовують в різній радіоелектронній апаратурі і вимірювальній техніці НВЧ-діапазону, тобто на частотах більше 300 МГц. Спочатку НВЧ-діоди використовували для детектування і змішування сигналів. Для цих цілей застосовували точкові діоди, випрямляючий електричний перехід в яких виникав між кристалом напівпровідника і притискним металевим електродом у вигляді загостреної пружинки. Створені останнім часом нові типи НВЧ-діодів практично цілком замінили точкові детекторні і змішувальні діоди. Вони дають можливість вирішувати завдання генерації і посилення

електромагнітних коливань НВЧ-діапазону, множення частоти, модуляції, регулювання, обмеження сигналів тощо. Однак незважаючи на широке застосування, вартість НВЧ-діодів залишається порівняно високою із-за низького виходу придатних діодів, що пояснюється високим рівнем зворотного струму приладів. В статті розглянуті причини та механізми деградації зворотних характеристик надвисокочастотних діодів. Показано, що причиною низького виходу діодів являється суттєвий вплив на їх зворотні характеристики структурних дефектів і посторонніх домішок та якості поверхні варикапних структур. Встановлено, що головною причиною низького відсотка виходу придатних досліджуваних варикапів є епітаксіальні дефекти упакування у вихідних епітаксіальних структурах та окислювальні дефекти упакування, що утворюються в активних областях варикапних структур в процесах проведення високотемпературних операцій. Проведені дослідження показали, що найбільш ефективним методом запобігання утворенню структурних дефектів в епітаксіальних шарах є створення гетеруючої області на зворотному боці підкладок за допомогою її обробки Nd – лазером.

Детально розглянута запропонована технологія виготовлення структур діодів з використанням гетерування областю гетера, створеною на зворотній стороні кремнієвої підкладки за допомогою обробки її лазером перед осадженням епітаксіального шару. Наведено експериментальні результати дослідження впливу гетерування на зворотну характеристику НВЧ-діода, а також проаналізовано можливі механізми цього впливу. Показана ефективність запропонованої технології з використанням гетерування щодо зниження рівня зворотних струмів і підвищення відсотка виходу придатних приладів.

Ключові слова: *надвисокочастотний діод, епітаксіальні дефекти упакування, окислювальні дефекти упакування, зворотний струм, гетер, діодні структури.*

Problem statement. In radio electronics, ultra-high-frequency diodes are used in microwave frequency multipliers, for the conversion and processing of ultra-high-frequency signals, etc. [1, 2]. However, it should be stated that the cost of diodes remains relatively high due to the low output of suitable devices for monitoring their reverse currents. Studies have shown that the main reason for the high level of reverse diodes currents are structural defects and impurities of heavy metals in the active areas of diodes [3-5]. In silicon-based diodes, heavy metal impurities, accelerating along structural defects, penetrate into the spatial charge region of the p-n junction, where deep levels are created in the forbidden zone of silicon, through which additional generation of charge carriers occurs, which leads to an increase in the level of the reverse diode currents [6]. Gettering is used to prevent the defects formation in the active areas of diode structures, or to eliminate already formed defects – the process of extracting impurities from the active areas of diodes into the gettering area, which is usually located in the inactive area of the diode, where they do not affect the device operation [7, 8], but, as practice has shown, many of them are ineffective in reducing the level of reverse diodes currents.

Formulation of the research objective. The object of this work is to study the effect of structural defects on the reverse current level of an ultra-high-frequency diode and to determine the effectiveness of the proposed technology for creating a gate junction area in the diode structure in terms of reducing its reverse current level and increasing the percentage of suitable devices.

Presentation of the main research material

Experimental samples. The studied diode structures were manufactured using standard mesa-planar technology [9] on phosphorus-doped silicon epitaxial structures of n-type conductivity with a resistivity of 30 Ω·cm and a thickness of 7 мm, grown on a silicon substrate oriented along the plane (111). I boron deposition by the open tube method from a solid source of B_2O_3 at T = 1050 °C for 25 minutes in a mixture of argon (120 l/h) and dry oxygen (7 l/h); removal of borosilicate glass in a hydrofluoric acid solution; boron expansion at T = 1150 °C in a mixture of dry oxygen (190 l/h) and argon (30 l/h) for 5.5 h; and photolithography to create a mask in the form of round silicon dioxide areas necessary for the manufacturing of mesa-structures; formation of mesa-structures by etching silicon in HF solution: HNO_3CH_3COOH=2:9:4; thermal oxidation of the wafers at T = 1050 °C with subsequent alternation of cycles: dry oxygen (30 min) – wet oxygen (140 min) – dry oxygen (30 min); the thickness of the resulting oxide is about 0.7 мм; pyrolytic deposition of a SiO_2 layer with a thickness of 0.35±0.05 мм; II photolithography to open windows in the silicon dioxide layer for boron deposition; II boron boring at T = 1050 °C for 20 minutes in a mixture of argon (110 l/h) and oxygen (8 l/h) from a solid source of B_2O_3; removal of the borosilicate glass layer using a hydrofluoric acid solution; deposition of an aluminum film in a vacuum on the working side of the plates; III photolithography on the aluminum layer; annealing of the aluminum contact in an inert environment at T = 560 °C for 20 minutes in an argon environment; grinding the back side of the plates to reduce its thickness to 180–190 мм; formation of an ohmic contact on the back side of the plates by forming a layer of nickel (by chemical deposition) and gold (by galvanic deposition).

As a result of performing the listed operations, the structure of the ultra-high-current diode shown in Fig. 1.

Investigation of structural defects. Metallographic studies have been conducted to determine the reasons for the low percentage of suitable diodes. Structural defects have been detected using a Sirtle's etching. The type of structural defects and their density have been evaluated using a metallographic microscope "Metam-R1".

The density of defects was determined by the formula [10]:

$$N = n / S,$$

where N – the density of defects; n – is the arithmetic mean of the number of defects in five sections; S – is the area of the field of view in the microscope eyepiece.

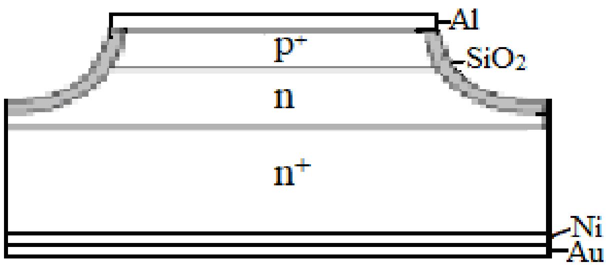

Fig. 1. Structure of an ultra-high-frequency diode made using the basic technology

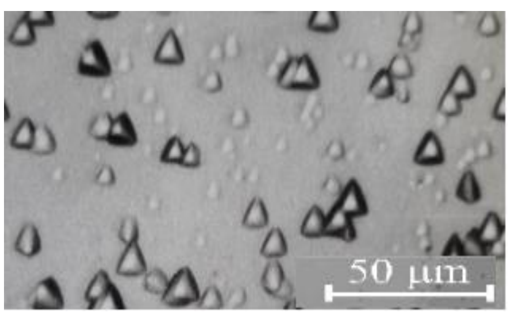

Fig. 2. The surface of a silicon epitaxial structure with detected epitaxial packaging defects

Epitaxial packing defects have been detected on the initial epitaxial structures even before the first high-temperature operation – the first boron billet (Fig. 2), the density of which was 10^3–10^4 cm^{-2} (the time of selective etching of the structures in the Sirtle reagent was 2 min).

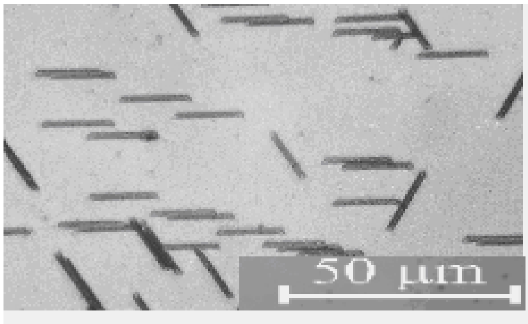

Fig. 3. The surface of a silicon epitaxial structure with detected oxidation defects in the packaging after thermal oxidation

After thermal oxidation and removal of the SiO_2 layer, oxidative packing defects (OSFs) have been found in the epitaxial structures (Fig. 3). The density of defects is up to 10^5 cm^{-2} (the time of selective etching of structures in the Sirtle reagent was 20 s).

Gettering technology. It was necessary to choose an effective getter method to prevent the formation of structural defects [7, 11]. Since structural defects are formed starting from the epitaxy process, it is obvious that the gettering area must be created in the substrates on which the epitaxial layers will be deposited. The studies have shown that the most effective method to prevent the formation of structural defects in the epitaxial layers is to create a gettering area on the back side of the substrates by treating it with an Nd laser of the LTN-102 type at a radiation density of 13 J/cm^2, followed by annealing the pallets a temperature of 1060 °C in an argon (120 l/h) and oxygen (7 l/h) environment for 40 minutes. The deposition of the epitaxial layer on the working side of the prepared substrates was carried out by the chloride method [9].

The conducted metallographic studies after thermal oxidation on epitaxial structures have made using gettering showed the absence of epitaxial and oxidative packaging defects (Fig. 4).

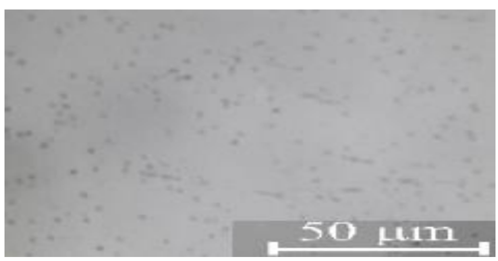

Fig. 4. The surface of diode structure made using gettering, after thermal oxidation

Research of the developed technology effectiveness. To test the proposed method of manufacturing ultra-high-frequency diode structures, experimental batches have been formed, each of which was divided into two parts: one part of the batch was made by the known method, the other by the proposed method using gettering. The effectiveness of the proposed method was evaluated by the percentage of output of suitable diode structures when they were controlled by the level of reverse currents (I_r). Suitability criterion: $I_r \leq 1$ мA at a reverse voltage of 45 V.

Table 1 shows the results of monitoring the reverse current of diode structures manufactured using the basic (batches 4–6) and developed (batches 1–3) technologies. It can be seen that the use of the proposed technology makes it possible to increase the output of suitable diode structures by an average of 8.7%. At the same time, the diode structures manufactured by the proposed method had a level of reverse currents 5 to 9 times lower compared to diode structures manufactured by the known method.

Table 1

Results of reverse current control of diode structures

Method for structures manufacturing of ultra-high-frequency diode	Experimental batch number	Output of suitable diode structures at level control of their reverse currents, %
The proposed method of diode manufacturing	1 2 3	94 95 93
The known method of manufacturing a diode	4 5 6	87 85 84

Therefore, the use of the proposed method of manufacturing ultra-high-frequency diode structures makes it possible to significantly increase the output of suitable diode structures on monitoring the level of their reverse currents, while significantly reducing the level of reverse currents of diodes.

Fig. 5 shows the reverse branches of current_voltage characteristics of diode structures manufactured according to the basic technology and technology using gettering.

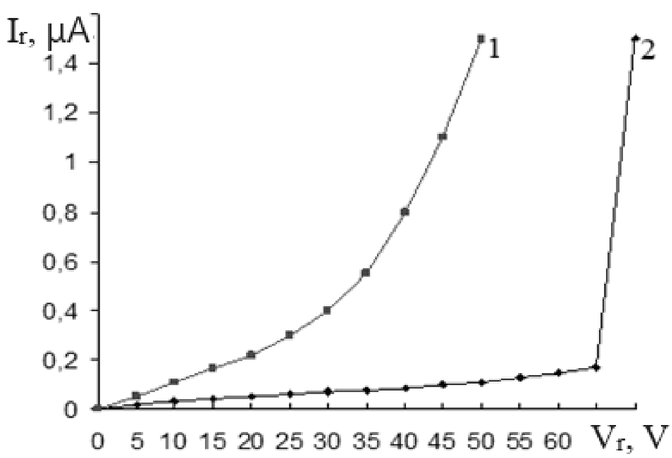

Fig. 5. Reverse I–V- characteristics of diode: 1 – diode structure manufactured by the basic technology; 2 – diode structure manufactured using gettering

From Figure 5 it can be seen that the diode structure made using gettering has a reverse I–V- characteristics (curve 2) typical of a silicon diode in the absence of structural defects and undesirable impurities in its active areas. Conversely, the diode structure manufactured according to the basic technology has a so-called “soft” reverse I–V- characteristics (curve 1), the appearance of which may indicate the presence of structural defects and impurities of metals in the active areas of the diode. From the comparison of curves 1 and 2, it can be seen that the diode structure manufactured by the basic technology (curve 1) has a much higher level of reverse currents at an inverse voltage of 45 V, at which the suitability of the diode structures is determined, compared with the diode structure manufactured using gettering (curve 2).

The effect of the getter region created on the back of the substrate before deposition on its working side of the epitaxial layer on the diode parameters can be explained as follows. In the process of epitaxy, which is carried out at 1150 °C temperature, a high dislocation density is formed on the back of the substrate. These disturbances lead to diffusion of substitution impurities, interstitial atoms and vacancies, which are embryos of defects, in the field of elastic stresses from the volume of the substrate and the increasing epitaxial layer to the disturbed layer and absorbed by it. Elimination of germ defects significantly reduces the likelihood of formation of packaging defects in the epitaxial layer during its expansion. Also, the getter area created on the back of the plate, in the processes of subsequent high-temperature operations (thermal oxidation, sublimation and acceleration of boron) absorbs uncontrolled impurities, germs of packaging defects from the volumetric and near-surface regions of the plate, thereby preventing the formation of new oxidative packaging defects and eliminating already formed OSFs silicon. In this case, the interstitial silicon atoms that make up the OSFs diffuse to the created getter area and are captured by it. As a result, previously formed OSFs decrease in size or completely disappear. Effective gettering of metal impurities and structural defects provides a significant reduction in the level of reverse diodes currents, the increase of which was associated with the influence of defects.

Conclusions. Based on the conducted experimental studies, it can be concluded that the reason for the low output of diode structures in the operations of controlling the level of their reverse current is structural defects (epitaxial and oxidation defects in the packaging) that are formed in the active areas of diodes in the processes of high-temperature technological operations. The application of the developed technology for manufacturing diode structures using the getter area created on the back side of the silicon substrate by laser processing before deposition of the epitaxial layer on its working side allows to clean the active regions of diodes from the germs of defects and undesirable impurities and prevent the formation of structural defects in them, which provides a significant reduction in the level of reverse diodes currents and increase the output of suitable devices.

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