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INFLUENCE OF GETTERING ON ALUMINUM OHMIC CONTACT FORMATION

The study considers the reasons and mechanisms of degradation of reverse characteristics of varicaps with aluminum-based ohmic contacts. The authors present and analyze the experimental results on how gettering affects the reverse current of varicaps, as well as possible mechanisms of such effect. Gettering was performed with a getter site created on the back side of the substrate before the epitaxial layer is deposited on the working side of the substrate. The article demonstrates that the proposed technology using gettering is rather effective in reducing the level of reverse currents and in increasing the yield of devices.

Keywords: aluminum, ohmic contact, gettering, varicap, defects, reverse current.

Varicaps are widely used in radio electronics as a variable capacitance, the value of which is controlled by voltage [1—4]. The weak point in the production process of varicaps is formation of ohmic contacts, which are usually made of nickel or aluminum. The diffusion coefficient of nickel atoms in silicon is several orders higher than that of dopant atoms, such as boron and phosphorus. That is why if structural defects are contained in silicon then nickel easily penetrates the space charge area of the *p–n* junction during annealing of a nickel film after its deposition on the surface of a varicap structure during the ohmic contact formation. This results in increasing of the level of reverse varicap current [5]. Aluminum has high electrical conductivity, it is cheap and plastic (i.e. it tolerates thermal cycling well). This metal is easily sputtered, well etched and provides high resolution at photolithography. Moreover, aluminum is suitable for use in radiation-resistant devices. However, as practice has shown, when an aluminum-based ohmic contact is used, the reverse branch of the current-voltage characteristic (**CVC**) of the varicap may degrade. It was found [6, 7] that the cause of frequent failures of semiconductor devices with aluminum metallization is the aluminum spikes, which shunt *p–n* junctions. These spikes appear during heat treatment stage after deposition of the aluminum film. Selective removal of the aluminum film from the substrate surface in the contact window area after heat treatment at 470°C for 30 minutes reveals that the morphological perfection of the Al–Si interface boundary deteriorates catastrophically due to the appearance of deep voids in silicon. The authors of [7] assert that the appearance of spikes in *p-n* junctions is connected with these voids, which are formed as a result of inhomogeneous dissolution of silicon in aluminum (**Fig. 1**). The voids are filled up by aluminum with dissolved silicon and can short-circuit *p–n* junctions.

The penetration depth of aluminum spikes into the silicon, which is estimated by the depth of the voids in the local places of the contact area, practically does not change in the range of 300—500°C and is about 40—90 nm [6]. In the temperature range of 500—577°C there is a sharp increase in the penetration depth up to 1.25—1.45 μm.

In [6] an assumption was made that the inhomogeneous dissolution of silicon and the filling of the voids by aluminum, as well as the drastic increase in the depth of penetration of aluminum into the silicon in the temperature range of 500—577°C were caused by the appearance of a liquid phase, which «melts» silicon, although the heat treatment temperature was lower than the melting point of the eutectic. The authors of [6] proposed to prevent the active interaction of aluminum with silicon

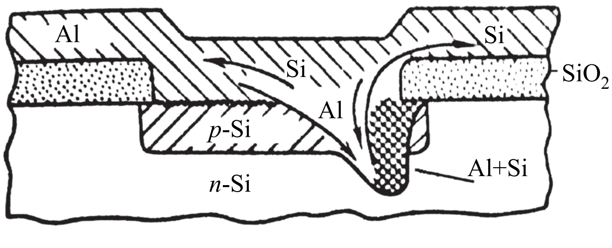

Fig. 1. Schematic drawing of aluminum film dissolving silicon [7]

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in the process of heat treatment by rapid annealing of the aluminum film after its deposition on the surface of the varicap structure. At such annealing, the temperature is high enough to form a liquid phase, but the duration is too small to cause intensive dissolution of silicon in aluminum and void formation. The disadvantage of such approach is pointed out by the authors [6] themselves. It is caused by the heat treatments required at subsequent process operations, which are not connected with metallization and can result in melting. For example, some operations of assembling crystals into housings can be performed at the temperatures over 510°C.

Another approach to the solution of the problem of Al–Si interaction was considered in [6, 7]. Its idea lies in the additional doping of the aluminum film with silicon to concentrations within the range of existence of the solid solution (0.5—1.0 mass %). This method can slightly reduce the intensity of the Al–Si interaction without eliminating the interaction itself. As a result, increasing the temperature at subsequent stages of technological process can cause nonequilibrium mass transfer and increase the depth of penetration of aluminum into silicon. Moreover, this method cannot provide equilibrium with local peculiarities of the crystal, such as defects, and thus cannot eliminate aluminum migration along them.

Thus, the cause of the inhomogeneous dissolution of silicon in aluminum is not completely identified. The ways to prevent deep penetration of aluminum into silicon during annealing of aluminum metallization proposed in [6, 7] are not optimal for solving this problem.

The aim of this work is to investigate the cause of local deep penetration of aluminum into the *p–n* junction area of the varicap during the annealing of aluminum metallization and to develop an effective technological method preventing this phenomenon, which, when used, will allow increasing the device yield.

Test samples

The structures of the investigated varicaps were produced using the standard planar-epitaxial technology [8, 9]. The epitaxial process was performed using the silicon substrates doped with antimony with specific resistance of 0.01 Ω·cm and oriented along the (111) plane. Epitaxial layers were grown by the chloride epitaxy. The temperature of the epitaxial process was 1150°C. Obtained epitaxial structures had a specific resistance of 1.3 Ω·cm and a thickness of 7 μm. The following operations with varicap structures were carried out in accordance with the standard technological process [8, 9]. The ohmic contacts on the working side of the varicap structures were formed thus: first, an aluminum film was deposited in vacuum, followed by photolithography on the aluminum layer and annealing of the contact in an inert medium at 560°C for 14 minutes.

Implementing the above operations resulted in obtaining the varicap structure shown in **Fig. 2**.

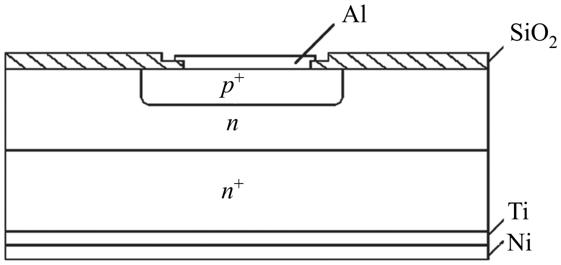


Fig. 2. Schematic drawing of varicap structure

Studying structural defects

In order to discover what causes the degradation of the reverse characteristics of varicaps during heat treatment of varicap structures with metallic film formed by photolithography, metallographic studies were conducted on the varicap structures rejected during the control of their reverse current level.

The Sirtl etch was used to detect structural defects. The duration of selective etching was in the range from 10 seconds to 20 minutes. The types of structural defects were determined and their density assessed using a METAM -1 metallographic microscope.

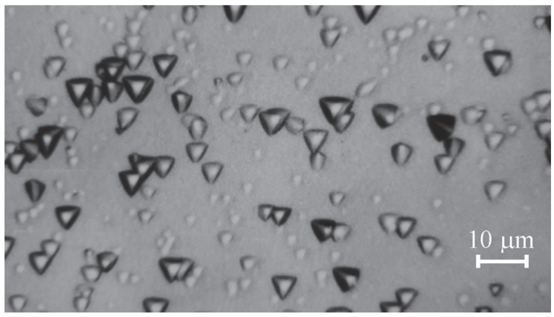
The density of defects was determined by the formula

$N = n/S$,

where N is the defect density;
n is the average value of the number of defects in five areas;
S is the area of the field of view in the eyepiece of the microscope.

Initial epitaxial structures before the first high-temperature operation (thermal oxidation) were investigated for defects. Selective treatment with Sirtl etch showed (**Fig. 3**) the presence of epitaxial stacking faults with the

a)



b)

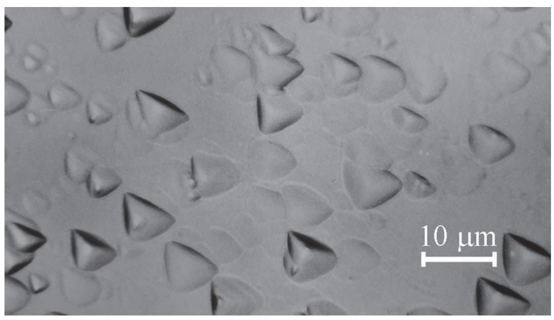


Fig. 3. Surface of silicon epitaxial structure with stacking faults (*a*) and dislocations (*b*) revealed after treatment in Sirtl etch

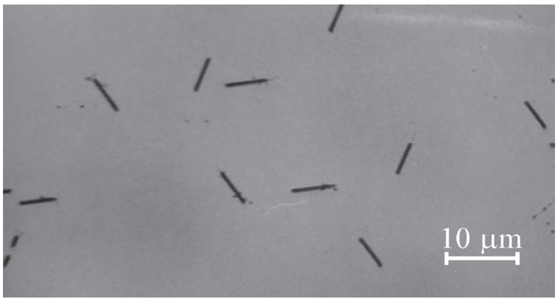


Fig. 4. A micrograph of the surface of the epitaxial structure after thermal oxidation and selective etching

density of 10^4—10^5 cm^{-2} (etching time 1.5 minutes) and dislocations with the density of 10^3—10^4 cm^{-2} (etching time 2 min).

After thermal oxidation and removal of the SiO_2 layer, the structures were treated with Sirtl etch for 20 seconds, which revealed oxidation stacking faults with the density of up to 10^5 cm^{-2} (**Fig. 4**).

The authors believe that the revealed structural defects cause an increase in the boundary solubility of aluminum at the temperature of aluminum film annealing (carried out after film deposition on the varicap structure surface followed by photolithography) and an increase in the aluminum diffusion coefficient in silicon along the defects. These two effects lead to a local penetration of aluminum into the *p–n* junction region of the varicap, which may cause degradation of the reverse characteristics of the varicap.

This assumption is confirmed by the authors of [10], who studied the processes of formation and directed migration of molten metal-semiconductor zones in single crystalline silicon at the presence of a dislocation density gradient field. It was ascertained that the molten zones in the matrix volume appear during annealing due to formation of alloys of impurities of a metal film (i.e. aluminum) with a single crystal at the metal-semiconductor interface boundary. According to the authors of [10], the impurity motion in the volume of a semiconductor was realized in the form of molten inclusions due to the difference of chemical potentials of atoms at the "back" and "frontal" boundaries of inclusion.

Gettering technology

In order to prevent the formation of structural defects, it was necessary to choose an effective method of gettering [11—17]. Since structural defects start to form from the epitaxy process, it is obvious that the getter site has to be created in the substrates before depositing the epitaxial layers. Studies have shown that the most effective way to prevent the formation of structural defects in the epitaxial layers is to create a getter site on the back side of the substrate by implanting it with phosphorus ions. The getter site was formed on the back side of the substrate by implantation of phosphorus ions with an energy of 100 keV and a dose of $8 \cdot 10^{15}$ cm^{-2} using an industrial ion doping system "Везувий-5" (Vesuvius-5). Next, the epitaxial layer was deposited on the working side of the substrate at T = 1150°C by the chloride method using a "УНЭС-2П-КА" (UNES-2P-KA) system. Epitaxial structures were produced according to the technological process given above.

Testing the effectiveness of the developed technology

For the research, two experimental batches of varicap structures were formed, each of them divided into two equal parts. One half of the structures in each batch were manufactured using basic technology (no. 1-b, no. 2-b), the other half had a gettering stage (no. 1-g, no. 2-g). The efficiency of the developed technology was evaluated by the yield of varicap structures. The quality of structures was defined based on the results of metallographic studies and by the value of the reverse current I_{rev}.

The validity criterion was set at $I_{rev} \leq 0.5$ μA for 30 V reverse voltage. Results of the control over the reverse current validity criterion of the varicap structures manufactured by the basic and developed technologies are given in **Table**. Comparison shows that the use of gettering increases the varicap structures yield by an average of 10.7%. The reverse current levels of the structures manufactured using gettering were 4 to 5 times lower than the ones manufactured by basic technology.

The metallographic studies of the varicap structures manufactured with gettering were carried out after boron redistribution and showed the surfaces to be free of the structural defects that affect the interdiffusion of aluminum and silicon (**Fig. 5**).

Yield of varicap structures produced by the basic and the newly-developed technologies based on reverse current control

Manufacturing technology	Batch number	Structures yield, %
Basic	1-b	84.8
	2-b	82.9
Using gettering	1-g	93.8
	2-g	95.3

Fig. 5. Surface of the varicap structure manufactured using gettering after boron redistribution

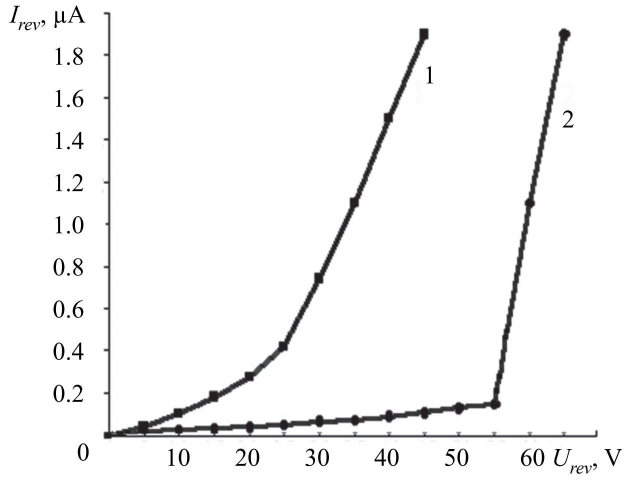


Fig. 6. Reverse CVC of varicap structures:
1 — varicap structure manufactured by the basic technology; *2* — varicap structure manufactured using gettering

Fig. 6 shows the averaged reverse branches of the CVC of varicap structures manufactured by basic technology and using gettering. As can be seen from Fig. 6, the varicap structure manufactured with gettering has a CVC (curve *2*), which is typical for a silicon diode at the absence of structural defects and undesirable impurities in its active regions. The varicap structure manufactured by basic technology, on the other hand, has a so-called "soft" CVC (curve *1*), which indicates the presence of structural defects (stacking faults, dislocations) and metal impurities in the active areas of the varicap or the presence of an aluminum spike, penetrating deeply into area of space charge of p^+–n junction.

Comparison of curves *1* and *2* shows that the varicap structure manufactured by the basic technology (curve *1*) has a much higher level of reverse currents compared to the varicap structure manufactured using gettering (curve *2*).

The influence of the getter site, which was created on the back side of the substrate before the epitaxial layer was deposited on its working side, on the varicap parameters can be explained as follows. During epitaxy, which is carried out at the temperature of 1150°C, dislocations of high density are formed on the back side of the substrate. These disruptions of crystal structure lead to diffusion of the defects nuclei, such as substitutional impurities, interstitial atoms, and vacancies in the field of elastic stresses to the broken layer, which absorbs them. This makes it possible to prevent the formation of stacking faults and dislocations in the epitaxial layer during its growth. Apart from that, at the high-temperature operations, such as thermal oxidation and boron injection and redistribution, the getter site created on the back side of the plate, absorbs both uncontrolled impurities and nucleation centers of stacking faults from the volume and surface region of the substrate, preventing formation of defects. Elimination of structural defects in active varicap regions excludes local penetration of aluminum into the *p–n* junction due to both increasing of the aluminum solubility in silicon at the temperature of aluminum film annealing and absence of structural defects, which accelerate a diffusion of aluminum into silicon.

Conclusion

Thus, the low yield of varicap structures, which is associated with the local penetration of aluminum into the *p–n* junction region, is connected with structural defects (epitaxial and oxidative stacking faults and dislocations), which are formed during high-temperature technology operations. Application of the developed technology for the manufacturing of varicap structures using gettering with a getter site created on the back side of the plate before depositing the epitaxial layer on its working side, allows removing the nucleation centers of defects and unwanted impurities from the active regions of the varicaps. It prevents the formation of structural defects in them and occurrence of the phenomenon of local aluminum penetration into the *p–n* junction region, which significantly decreases the reverse currents of the varicaps and increases yield of devices.

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ВПЛИВ ГЕТЕРУВАННЯ НА ПРОЦЕС ФОРМУВАННЯ АЛЮМІНІЄВОГО ОМІЧНОГО КОНТАКТУ

Варикапи широко використовуються в радіоелектроніці як змінна ємність, величина якої керується напругою. Однак слід зазначити, що вартість варикапів залишається порівняно високою. Це викликано низьким виходом придатних приладів внаслідок високого рівня зворотних струмів і низьких пробивних напруг варикапів, що пов'язано з істотною залежністю їхніх зворотних характеристик від щільності структурних дефектів і сторонніх домішок у структурах варикапів.

Роботу присвячено з'ясуванню причин та механізмів деградації зворотних характеристик варикапів з омічним контактом на основі алюмінію в процесі відпалу плівки алюмінію під час формування омічного контакту, а також визначенню можливості застосування операцій гетерування для запобігання деградації зворотних характеристик варикапів і підвищення виходу придатних приладів.

Встановлено, що причиною деградації зворотних характеристик варикапів з омічним контактом на основі алюмінію є структурні дефекти, що утворюються в активних областях варикапів у процесі проведення високотемпературних технологічних операцій.

Докладно розглянуто запропоновану технологію виготовлення структур варикапів з омічним контактом на основі алюмінію із застосуванням гетерування областю гетера, створеною на зворотній стороні пластини перед осадженням на її робочу сторону епітаксійного шару. Розглянуто причини та механізми деградації зворотних характеристик варикапів з омічним контактом на основі алюмінію в процесі відпалу плівки алюмінію під час формування омічного контакту.

Показано, що розроблена технологія виготовлення структур варикапів із застосуванням гетерування дозволяє очистити активні області варикапів від зародків дефектів та небажаних домішок і запобігти утворенню в них структурних дефектів, що унеможливлює локальне проникнення алюмінію в область p–n-переходу та забезпечує суттєве зниження рівня зворотних струмів варикапів і підвищення виходу придатних приладів.

Ключові слова: алюміній, омічний контакт, гетерування, варикап, дефекти, зворотний струм.

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ВЛИЯНИЕ ГЕТТЕРИРОВАНИЯ НА ПРОЦЕСС ФОРМИРОВАНИЯ АЛЮМИНИЕВОГО ОМИЧЕСКОГО КОНТАКТА

Варикапы широко используются в радиоэлектронике в качестве переменной емкости, величина которой управляется напряжением. Однако следует отметить, что стоимость варикапов остается сравнительно высокой, что связано с низким выходом годных приборов. Это объясняется высоким уровнем обратных токов и низкими пробивными *напряжениями варикапов, что связано с существенной зависимостью их обратных характеристик от плотности структурных дефектов и посторонних примесей в структурах варикапов.*

Работа посвящена выяснению причин и механизмов деградации обратных характеристик варикапов с омическим контактом на основе алюминия в процессе отжига пленки алюминия при формировании омического контакта, а также определения возможности применения операций геттерирования для предотвращения деградации обратных характеристик и повышение выхода годных приборов.

Установлено, что причиной деградации обратных характеристик варикапов с омическим контактом на основе алюминия являются структурные дефекты, образующиеся в активных областях варикапов в процессе проведения высокотемпературных технологических операций.

Подробно рассмотрена предложенная технология изготовления структур варикапов с применением геттерирования с помощью области гетера, созданного на обратной стороне пластины перед осаждением на ее рабочую сторону эпитаксиального слоя. Рассмотрены причины и механизмы деградации обратных характеристик варикапов с омическим контактом на основе алюминия в процессе отжига пленки алюминия при формировании омического контакта.

Показано, что разработанная технология изготовления структур варикапов с применением геттерирования позволяет очистить активные области варикапов от зародышей дефектов и нежелательных примесей и предотвратить образование в них структурных дефектов, что делает невозможным явление локального проникновения алюминия в область p–n-перехода и обеспечивает существенное снижение уровня обратных токов варикапов и повышение выхода годных приборов.

Ключевые слова: алюминий, омический контакт, геттерирование, варикап, дефекты, обратный ток.

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