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THE ANALYSIS OF HIGH TEMPERATURE IMPACT ON EPITAXIC STRUCTURES AND CONTACT SYSTEMS FOR PHOTOELECTRIC TRANSDUCERS

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Purpose. One of the major aims in the engineering of solar elements is increasing their efficiency. For effective transformation of solar radiation into electric energy due to the division of electron-hole pairs by internal electric field, the depth of stratification of the field, that separates them, should be sufficient for penetration of the main stream of photons. The analysis demonstrates, that the displacement to the short-waves spectrum increases the efficiency of energy transduction. However, in the conditions of reality, it is necessary to work in the spectrum close to infrared, i.e. of short waves. It can be explained by the fact, that the atmosphere is more transparent for them. To achieve that, the depth of the internal field stratification should be enlarged. In case the wavelength is less than 1,1 μm, photoelectric transducers are not sensitive to the photons stream, as far as their energy is not sufficient for generation of charge carriers. The problem of increasing of PET sensitivity can be solved by means of choosing of heterostructure SNS (semiconductor – nonconductor – semiconductor), that constitutes its fundamentals, and by means of application of high-quality contact systems. **Methodology.** The authors elaborated the contact system Al-Cu-Si, which is marked by increased stability to electro-migration and which prevents silicon erosion in contact windows simultaneously. The function of the backing was done by silicon plates of nn+ – type with resistivity 0,5-5 Ohm·sm. The plates' diameter was 76 mm, their width - 500 μm. On corresponding batches of plates the layers of Al, Al-Cu (2%) Al-Cu (2%) –Si (1%) 0,8 μm thick were pulverized. Immediately before the sedimentation the plates were polished in the solution of HF (concentrated) for 30 seconds, after the etching they were washed in a hot and the in a cold distilled water, in alcohol and dried up in the thermostat. After that the plates were put into the camera of the vacuum pulverization device. The interval between the processings and loadings of the camera was 30 minutes. After the formation of the adjusted topology of metallization, the plates were exposed to nitrogen burning with the temperature of 450ºC during 15 minutes and the protective coat of SiO_2 of 0,9 μm thick was applied. It was followed by the oxide removal from the excretive grounds and the splitting into separate crystals was completed. The quality test of instrument structures was held by means of measuring of contact resistance of contact systems. The amount of resistivity ρ for contacts Al-Cu-Si was (0,76-1.52) 10^{-6} Ohm·sm^2. **Results.** The analysis of the stability of contact systems before electro-migration demonstrated, that the Al-Cu-Si systems did not prove any refusal either in the process of exposure to the temperature of 150ºC, or in the course of electro-migration tests, whereas for the structures Al and Al-Cu a significant quantity of refuses was observed. Thus, after 1000 hours of exposure to the temperature of 150ºC 2 of 15 Al structures and 2 of 15 Al-Cu structures demonstrated refuses. As a result of electro-migration tests during 256 hours with the temperature of 215^{o}C there were 14 refusals (with 20 tested structures) for Al and 7 refusals for Al-Cu. In the course of the analysis of Al-Cu-Si structures neither in the process of exposure to the temperature of 150ºC, nor in the course of electro-migration tests, there were no refusals observed, only insignificant amount of silicon precipitate was noticed. For Al and Al-Cu structures a significant amount of refusals and silicon erosion are characteristic. **Originality.** The variation of the contact resistance points out the necessity of thorough preparation of contact windows before the contact. It was also proved, that cleaning of the backings surface in the processing camera of the vacuum device immediately before the metal coating significantly diminishes the variation of the contact resistance. **Practical value.** All in all, it is advisable to apply Al-Cu-Si contact systems for a series of photoelectric appliances. Technological processes of the systems obtained do not demand any complicated equipment, the applying of precious metals and require a small amount of operations. The optimal width of the layers in the contact system recommended was approximately 500 ^{0}A.

Key words: defect, the substrate, the contact system, plate, photovoltaic inverters.

АНАЛІЗ ВПЛИВУ ВИСОКИХ ТЕМПЕРАТУР НА ЕПІТАКСІЙНІ СТРУКТУРИ ТА КОНТАКТНІ СИСТЕМИ ДЛЯ ФОТОЕЛЕКТРИЧНИХ ПЕРЕТВОРЮВАЧІВ

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Сонячна енергетика в даний час є одним з перспективних напрямків розвитку екологічно чистих джерел електроенергії. Головне завдання використання сонячної енергії - це знизити її вартість до мінімуму або взагалі звести до нуля. Як відомо фотоелектричний метод перетворення сонячної енергії становить найбільший інтерес серед методів, використовуваних в нетрадиційній енергетиці. Технологія створення фотоелектричних перетворювачів включає підготовку підкладок і вихідних компонентів, контактних систем і струмознімальних сіток до них, поділ отриманих зразків на окремі елементи і інші. Поліпшення якості традиційних, а також освоєння нових напівпровідникових матеріалів і різних типів металізації дозволило розробити ряд класів оптоелектронних приладів. Особливо великі перспективи обіцяє застосування епітаксійних композицій для виготовлення фотоелектричних перетворювачів. Чітко виявляються тенденції створення найскладніших електронних пристроїв на основі багатошарових епітаксійних структур. При цьому формулюються дуже високі вимоги до електрофізичних властивостей і досконалості структури кожного шару, ставляться завдання створення досконалих і різких p-n переходів і гетерограниць на великих площах епітаксійних композицій. У статті запропоновано оптимальний режим виготовлення контактних систем для фотоелектричних перетворювачів на кремнієвих епітаксійних структурах і проведено порівняльні дослідження контактного опору і стабільності Al, Al-Cu і Al-Cu-Si контактів. Досліджено поведінку виявлених дефектів механічної обробки при впливі на пластину високих температур. Розроблено контактна система Al-Cu-Si, яка має підвищену стійкість до електроміграції і одночасно запобігає ерозії кремнію в контактних вікнах.

Ключові слова: дефект, підкладка, контактні системи, пластина, фотоелектричні перетворювачі.

PROBLEM STATEMENT. The improvement of the quality of traditional materials as well as mastering new semi-conducting ones and various types of metallization lead to the elaboration of a series of classes of optoelectronic devices [1–5].

WORK GOAL. Especially great perspectives are promised by application of epitaxic structures for the production of phoroelectric tranducers (PhT). The tendencies of creating the most complicated electronic appliances based on them are clearly articulated. Herewith very high demands are formulated for electro-physical qualities and perfection of every layer, the tasks are set for creating of perfect and abrupt n-transitions and heterointerface on large areas of epitaxic compositions. The task of current interest is a profound analysis of these structures imperfections, the origins of their formation, evolution of imperfections on different technological stages of the process of PhT formation.

MATERIAL AND RESULTS. The analysis demonstrates [6-10], that the most significant origin of defects in epitaxic structures is the tension in the course of crystallization or further cooling. In very thin membranes the force of surface tension serves as additional source of impact, which depending on surface tension, can lead to compression or distension of additional layers.

This research aims at the study of correlation between the density of structural defects in underlay and EC layer grown and the method of mechanical surface processing. For the research the underlays of 260 mcm wide with crystallographic oriented surface {111}, made of dislocation-free silicon mono-crystals with 10-50 Ohm*m resistivity. Structure defects were revealed by means of selective etching and were examined with the help of metallographic and raster electronic microscopes.

Underlays underwent various methods of operator side surface (on which the growth took place) processing: chemical mechanical polishing (CMP) with 1-2 mcm and 20 mcm of removed layer, mechanical polishing (MP) with diamond paste with abrasive grit of 1,0 mcm and 0,5 mcm. Methods of processing of rear underlay sides were also different: chemical mechanical polishing, grinding, gettering – grinding with loose abrasive followed by shallow mechanical polishing. After growing the ISS were ground and polished both sides with CMP method to get 80 mcm of operator side of underlay and 170-180 mcm of grown layer side. The results of research of the density of dislocations in both ISSs are mentioned in Table 1.

It was proved that in all examined ISSs operator layer contains dislocations, which density lies in the interval of $3*10^2$ - $4*10^3$ sm^{-2} , thus worked-out technology of growing will ensure relatively high level of structural perfection of ISS. Nevertheless there is still a potential for further improvement of ISS quality, one of them being, as it is obvious from the Table 1, the improvement of the way of mechanical processing of underlays surface. In the cases when operator side of an underlay underwent chemical mechanical polishing, the density of dislocations in underlay after growing was in average lower compared to one after mechanical polishing. The exception is underlays with ground rear side. The best results were obtained by the authors in the course of CMP method application with enlarged to 20 mcm width of removed layer of $3*10^2$ sm^{-2}.

Table 1 – Average density of dislocations in ISS, grown on dislocation-free swirl-free underlay

Method of underlay surface processing		Density of dislocations x 10^{-3}, sm^{-2}	
Operator side	Rear side	In the operator layer of ISS	In the supporting layer of ISS
Chemical-mechanical polishing with the depth of remote layer of 1-2 mcm	Chemical-mechanical polishing	1	4
	Mechanical polishing	1	8
	Gettering	0,4	6
	Grinding	4	20
Chemical-mechanical polishing with the depth of remote layer of 20 mcm	Mechanical polishing	0,3	5
Mechanical polishing with the size of abrasive grit of 1,0 mcm	-	2	7
Mechanical polishing with the size of abrasive grit of 0,5 mcm	-	1	20

The method of processing of rear underlay side also influences the quality of operator layer of ISS. Under the same processing of operator side of underlay grinding of its rear side leads to the growth of density of dislocations in operation layer of ISS in average by 4,5 times, while gettering – visa versa, leads to 2,5 times diminishing in comparison with mechanical polishing of rear side. At the same time application of rear side of ISS in comparison with mechanical polishing does not demonstrate bright improvement of ISS quality.

The degree of structural perfection of supporting (grown) layer of ISS also depends on the method of processing of both operator and rear underlay sides. One can see in Table 1 that mechanical polishing of operator underlay side, compared to CMP, stipulates noticeable increase of the density of dislocations in the supporting layer, while in the operator layer of ISS it is practically identical. The same result of increasing the density of dislocations in the supporting layer can be also achieved by means of grinding of the rear side of underlay in comparison with other methods of its processing. It is the density of wrapping defects in the grown layer that depends far more significantly on the methods of operator underlay side processing, that is increased from $5*10^3$ sm^{-2} (in average, according to the samples examined) with CMP and $2*10^4$ sm^{-2} with mechanical polishing.

Great impact on the development of structural defects in the course of inverted epitaxy is produced by swirl-defects in dislocation-free underlays. Regardless of the method of underlay surface processing, in all ISSs grown over underlays, containing swirl stripes of micro-defects of A-type, identical in form and distribution stripes with high density of dislocations and wrapping defects in a supporting layer (Fig. 1) and with increased density of dislocations in operator layer can be observed. The impact of swirl stripes on the development of dislocations in both operator and supporting layers of ISS are illustrated by experimental data, systematized in Table 2.

The authors assumed (Table 2), that swirl-defects produce the greatest effect on the development of dislocations in operator layer of ISS. The fact that in operator layer of ISS there are stripes of high-density dislocations increases several times the average value of dislocation density of this layer, i.e. they significantly decrease the quality of ISS.

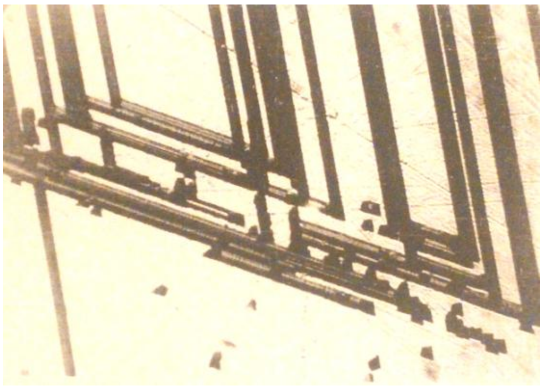

Figure 1 – Aggregation of wrapping defects and partial dislocations, revealed by means of selective etching, on the locus of epitaxial layer above the stripe of swirl-defect

The authors assumed (Table 2), that swirl-defects produce the greatest effect on the development of dislocations in operator layer of ISS. The fact that in operator layer of ISS there are stripes of high-density dislocations increases several times the average value of dislocation density of this layer, i.e. they significantly decrease the quality of ISS.

Table 2 – Correlation of dislocation density in the locus of swirl-defect and in remaining scope of ISS (the method of processing of operator underlay side is CMP)

Method of rear side of underlay processing	Operator layer of ISS	Supporting layer of ISS
Chemical mechanical polishing	5	3
Mechanical polishing	170	8
Gettering	18	2

The research of the development of defects in EC (silicon structures with dielectric isolation (SSDI)) demonstrated that while using dislocation-free underlays, A-micro-defects, contained in them, generate dislocations, starting with technological operation of the production of isolating layer of silicon dioxide. As we can see from Fig. 2, dislocations are developed in places of intersection of micro-defects stripes with dividing grooves. In this case micro-defects serve as a source and concentration of tension in the grooves – as stimulus of the generation of dislocations in mono-crystalline well. In the proceeding operation of deposition of polycrystalline silicon layer thermo-high-resiliency tension incease generation processes, while dislocation density rises to 10^4 sm^{-2}.

The empirical results obtained leads to the conclusion that it is advisable to apply dislocation-free underlays without micro-defects stripes of A-type for the production of PhT on EC basis with low density of dislocations. Under all equal conditions the best quality of EC is achieved by means of thorough chemical-mechanical polishing of operational side of underlay and gettering of the rear side.

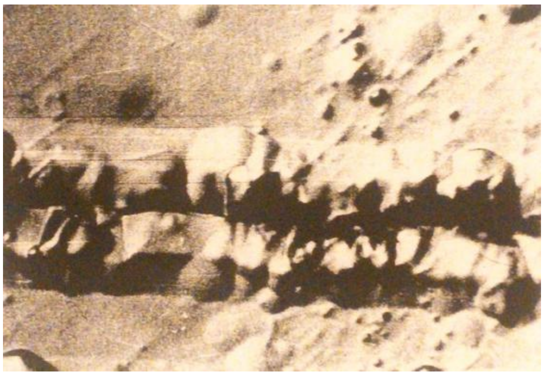

Figure 2 – Figures of dislocations etching on micro-relief grooves of SSDI.

In experimental studies established (Fig. 3), depending on the transition of the surface layers in the molten state silicon and impurity profiles vary.

At an energy density of 0.64 J/cm^2 profile atoms in virtually indistinguishable from the original, the residual defects as dislocation loop are stored and only 30% of the atoms are activated. When the energy of $\geq$ 1,1 J/cm^2 occurs plot constant concentration, concentration profile extends, and with a further increase in the beam energy is achieved almost complete electrical activation.

Our results agree well with the calculated values, allows for the diffusion of atoms B in the liquid silicon at a temperature above the melting point.

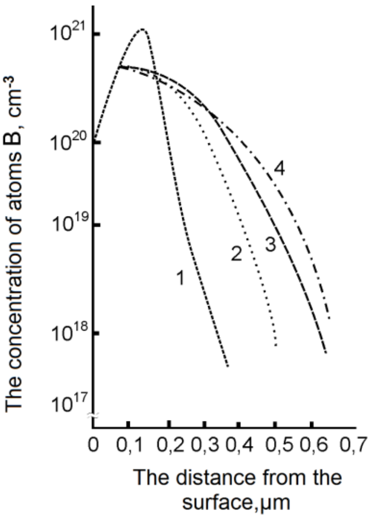

Figure 3 – Distribution of atoms in depending on the laser energy per pulse.

The high coefficient of diffusion of atoms As, about 10^{15} cm^2/s, from high layer is also characteristic of the annealing laser pulse Nd: YAG (λ = 1,06 μm). It was found that the impurity profile depends on the radiation power per unit area (Fig. 4). When power 38 mW/cm^2, there is some redistribution of impurities, however, while maintaining a sufficiently large number of structural defects. Defects is significantly reduced with the increase in power up to 76 mW/cm^2, and the As atoms penetrate to a depth of 500 nm at an initial value of the projection path of 50 nm.

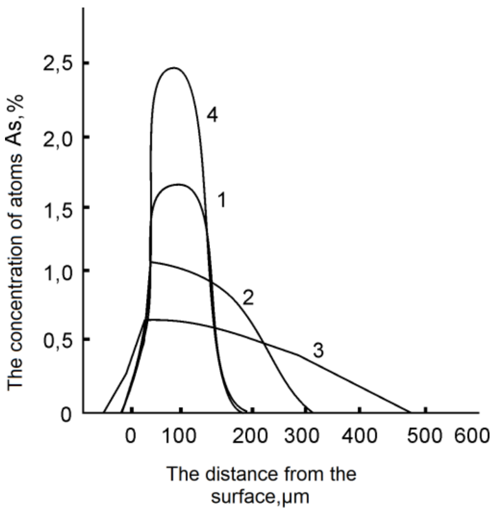

Figure 4 – Distribution of As atoms after annealing laser Nd: YAG as a function of pulse power**.**

LA results are sensitive to the conditions of implantation and the properties of the treated high-alloy layer.

For studies were taken LA layers formed by implantation of As ions with a dose of 10^{15}, 10^{16}, and $5 \cdot 10^{16}$ cm^{-2} in the Si (110) - orientation. The energy of 60 keV projection provided ion path length of 35 nm, and the ranges of doses occurred amorphization silicon.

With two large doses of LA observed incorporation into the lattice more than 95 atom% As. At a lower dose of the impurity profile is practically unchanged as a result LA, whereas said large doses lead to a significant increase in the area of high layers (Fig. 5, sections 2 and 3). In this case, a corresponding influence the structure of the implanted layer.

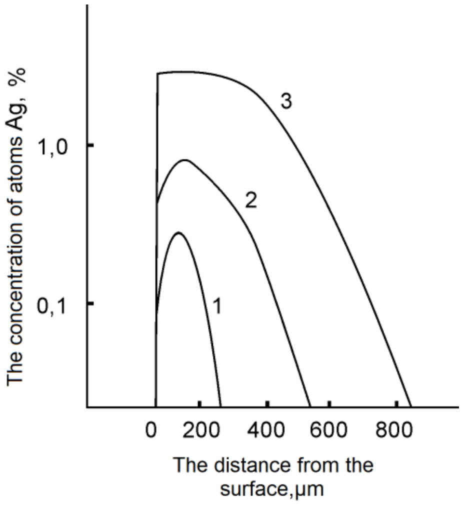

Figure 5 – Dose according to the distribution of as atoms in the layers after the LA mode: laser Nd: YAG.

It is found that the higher the dose of implantation, the greater the thickness of the amorphous layer produced and the greater the degree of amorphization and absorption. Therefore, the melting point of the layer occurs before and during the action of radiation pulses melt extends to a greater depth. The consequence of these processes is to expand high-alloyed layer.

In pulsed LA perfection resulting structure is determined by the depth of penetration relative to the original layer violation. It should be noted that in the case of the amorphous layer is strong absorption of ruby laser radiation at the surface. At an energy of 0.7 J/cm^2, the melt zone encompasses the entire damaged layer thickness, for example, 180 nm, obtained by introducing a dose of $5{\cdot}10^5$ J/cm^{-2} of ions of P, whereas the deeper or heavily disturbed amorphous layers are seeded to promote recrystallization and formation of the polycrystalline layer with a thickness of 150 nm to 100 nm grain diameter. When the energy of 1,5 J/cm^2 whole amorphised layer is melted, crystallization occurred but at cluster layer and thus formed dislocation and stacking faults.

Based on the foregoing, it can be concluded that the LA mode selection must be made taking into account at least the projected layer structure subjected to ion implantation.

The resultant tension, plasticity of epitaxic structure, the width of layers, thermal conditions of growth and extra tension stimulate plastic deformation of epitaxic structures.

As far as the tensions of unconformity arise immediately in the course of growth of epitaxic layer under the temperature of crystallization, i.e. the maximum temperature in the system, there is a great probability of their relaxation, accompanied by dislocations of unconformity and other defects.

It was found out that thermal tension in epitaxic structures can be triggered by both the difference of coefficients of thermal distention of compositions and uneven distribution of the temperature within the grown layer.

The research was carried out on structure pads, made of monocrystalline silicon without dislocation, alloyed with antimony up to specific resistance of 10^{-4} Ohm/sm, and on SWR-3 pads on non-alloyed monocrystalline without dislocation of hole-type of conductivity with the specific resistance of 60-100 Ohm/m.

The pads have undergone the standard cycle of mechanical processing, that includes cutting monocrystallines with diamond disk with inner cutting edge on the plate of 380 μm width with 28, 40 or 60 mm in diameter and of 500 μm width with 76 mm in diameter, polishing with diamond paste and chemo -mechanical polishing (CMP) with the suspension based on aluminosilicate. Structure defects in plates and ready-made composites were singled out with the help of chromic acid and investigated by means of metallographic methods, including 2-ray micro-interferometrics [11–14].

The research revealed, that the methodology of mechanical processing applied provides quite high quality of the plates' surface, except the peripheral parts of the plate of 0,5 mm width, which is not embraced as an operating area of the plate. On its remaining area no micro-roughness is observed. Nevertheless on the plates edges there are macro- and micro-cleavages, micro-cracks, micro-scratches of less than 100 μm width, as well as areas with residual deformations of lattice. Comparative analysis of the level of edges' defects after each stage of the processing leads to elaboration of correlation of the procedures of technological process and the exact type of defects caused. It turned out, that cleavages take place on the stage of cutting of monocrystallines into plates; the amount of cleavages, their area and depth change on other stages of mechanical processing. Micro-cracks arise on the stage of mechanical polishing, CMP which stands new mechanical defect neither on edges, nor on any other area of the plate. The impact of width and diameter of the plate as well as the presence of alloying additives in the initial monocrystalline in the interval of analysed values of proper parameters as for the character and level of edges imperfection and operating area of the plates were not observed. Further the behavior of the defects of mechanical processing during the impact of high temperature on the plate was analysed.

The plates on dislocation-free silicon of 60 mm in diameter 300, 500 and 1000 μm wide underwent annealing in the atmosphere of hydrogen under the temperature of 1450°C during 10 minutes.

With the help of selective digestion the dislocations in peripheral region of annealed plates were revealed. The authors concluded that as the active sources of dislocations generation serve the micro-cleavages on the plates edges, whereas micro-scratches and areas with remaining deformations – as additional sources of their generation on the plates edges. Micro-cracks on the edges of plates were caused during annealing of the line of gliding, which spread in crystallographic directions on the distance less than 1 mm. During epistaxis the length of lines of gliding, generated from micro-cracks, reaches 15 mm; in some cases micro-cracks initiate the development of slide, piercing all width of the pad and epitaxic layer and have the length up to 0,7 of the plate's diameter [15-19].

It is noteworthy, that on the operating area of the plate, where the defects of mechanical processing were absent, the development of dislocations in the course of annealing is observed only in the plates having the micro-defects of A-type; with other micro-defects the operating area of annealed plates is free of dislocations.

As it was demonstrated in the course of experimental analysis, that the level of structural perfection of the operating area of ready-made silicon composites is influenced by micro-cracks only, it is necessary to correct this very operation for the removal of such defects.

With this aim the authors of this article researched the quality of polishing on СДП-100 with separator and on machine tool M-201.

In another case the plates were glued to the faceplate and, unlike the first one, without producing any pressure on edges while polishing. It was demonstrated, that the polishing with loose abrasive on machine tool M-201 does not stimulate micro-cracks and areas with remaining deformations of crystal lattice. The application of pads, processed according to the described technology with the performance of operations of mechanical polishing on machine tools M-201, allowed to eradicate the spreading of gliding lines and the levels of slide during the epitaxic development of not only one-layer silicon structures (the time of sedimentation is 15 minutes), but oriented silicon structures as well (the time of development – 2/3 hours). However the productivity of machine tool M-201 is much lower than of СДП-100, therefore the application of the first one can be recommended only in the cases, when there are special demands as for the structural perfection of silicon epitaxic structures.

The increase of temperature influences the development of defects in epitaxic structures, the electric characteristics and parameters of PhT as well as the quality of their contact systems, which are to have high electro- and thermal conductivity, mechanical durability and reliability in exploiting.

Authors propose an optimal mode of producing contact systems for PhC on silicon epitaxic structures and comparative study of contact resistance and stability of Al, Al-Cu and Al-Cu-Si contacts was performed.

The research was carried out on special test structures with the size of 3,8 x 6,35 μm^2. The diameter of the plates was 76 mm, and their width was 500 μm. On the corresponding batch of plates Al, Al-Cu (2%) were put and Al-Cu (2%) - Si (1%) metallization of 0,8 μm width with magnetron pulverization on DC was performed.

Immediately before sedimentation the plates were polished in the solution of HF (concentrated) during 30 seconds, after the digestion were rinsed in hot and then in cold distilled water, washed in spirit and dried in the thermostat. After that the plates were placed into the cell of magnetron pulverization. The interval between the operations of the pads processing and loading them to the working cell was 30 minutes. After the formation of the stated topology of metallization the plates were annealed in nitrogen under the temperature of 450°C during 15 minutes, followed by putting the protective layer of SiO_2 with 0,9 μm of width. After that on field areas the oxide was removed and the basis was taken apart into separate crystals. The assembly of test crystals into the corpus was performed with the application of Au-Ge allegation. On the final stage the outputs were welded to the platforms by ultrasonic method and the test module was sealed with glass under the temperature of 450-500°C. The average values of contact resistance, received after 20 measurements for all types of metallization.

CONCLUSIONS.Authors propose an optimal mode of producing contact systems for PhC on silicon epitaxic structures and comparative study of contact resistance and stability of Al, Al-Cu and Al-Cu-Si contacts was performed.

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АНАЛИЗ ВЛИЯНИЯ ВЫСОКИХ ТЕМПЕРАТУР НА ЭПИТАКСИАЛЬНЫЕ СТРУКТУРЫ И КОНТАКТНЫЕ СИСТЕМЫ ДЛЯ ФОТОЭЛЕКТРИЧЕСКИХ ПРЕОБРАЗОВАТЕЛЕЙ

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Солнечная энергетика в настоящее время является одним из перспективных направлений развития экологически чистых источников электроэнергии. Главная задача использования солнечной энергии - это снизить ее стоимость до минимума или вообще свести к нулю. Как известно фотоэлектрический метод преобразования солнечной энергии представляет наибольший интерес среди методов, используемых в нетрадиционной энергетике. Технология создания фотоэлектрических преобразователей (ФЭП) включает подготовку подложек и исходных компонентов, контактных систем (КС) и токосъемных сеток к ним, разделение полученных образцов на отдельные элементы и другие. Улучшение качества традиционных, а также освоение новых полупроводниковых материалов и различных типов металлизации позволило разработать ряд классов оптоэлектронных приборов. Особенно большие перспективы сулит применение эпитаксиальных композиций для изготовления ФЭП. Четко проявляются тенденции создания сложнейших электронных устройств на основе многослойных эпитаксиальных структур. При этом формулируются очень высокие требования к электрофизическим свойствам и совершенству структуры каждого слоя, ставятся задачи создания совершенных и резких p-n переходов и гетерограниц на больших площадях эпитаксиальных композиций. В статье предложен оптимальный режим изготовления КС для ФЭП на кремниевых эпитаксиальных структурах и проведены сравнительные исследования контактного сопротивления и стабильности Al, Al-Cu и Al-Cu-Si контактов. Исследовано поведение обнаруженных дефектов механической обработки при воздействии на пластину высоких температур. Разработана контактная система Al-Cu-Si, которая обладает повышенной устойчивостью к электромиграции и одновременно предотвращает эрозию кремния в контактных окнах.

Ключевые слова: дефект, подложка, контактные системы, пластина, фотоэлектрические преобразователи.

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