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STUDY OF ANTI-REFLECTIVE COATINGS Ta_2O_5 / SiO_2 FOR IMPROVING THE EFFICIENCY OF MODERN SOLAR CELLS FOR SPACE APPLICATIONS

M. A. Genali[1*], S. K. Sharov[1], A. A. Lebedev[1, 2], N. T. Vagapova[1], B. V. Zhalnin[1]

[1]JSC "Research and Production Enterprise "Kvant"
16, 3rd Mytischinskaya Str., Moscow, 129626, Russian Federation
[2]The National University of Science and Technology "MISiS"
4, Leninsky Av., Moscow, 119049, Russian Federation
[*]E-mail: otdel_17@npp-kvant.ru

Solar cells based on AIIIBV materials in solar arrays are the main energy sources for most modern spacecraft. In spite of the fact that high characteristics have already been achieved, the work for improving solar cells is being continued due to the growth of energy consumption by spacecraft.

One of the directions is decreasing solar radiation reflection by solar cell surface due to the deposition of antireflection coating (ARC). In the article we show the results of the study of ARC (Ta_2O_5 / SiO_2).

We have presented the results of spectral and thickness calculations by special software of ARC on the triple junction (InGaP / InGaAs / Ge) solar cell taking into account cell structure as well.

We have performed the experiment of ARC on the glass-substrate to confirm the manufacturability of the process. ARC deposition has been made by electron-beam evaporation in vacuum. The results of investigation of spectral characteristics of samples obtained by a spectrophotometer confirm the uniformity of covering without relation to the sample position in a machine. Spectral characteristic calculations for glass-substrate coincide with experimental data.

The results of studying spectral characteristics of ARC on a solar cell demonstrate good correspondence with experimental data. The electric characteristics measured by the solar simulator (AM0) before and after the ARC covering on the experimental samples show the increase of short-circuit current up to 122 mA and the rise of efficiency up to 7.5 %. We have demonstrated the results of scanning electron microscopic investigation of ARC on the different positions of solar cells.

Keywords: antireflection coating (ARC), triple junction (TJ) solar cells, current-voltage characteristic, tantalum oxide (V), silicon oxide (IV).

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ИССЛЕДОВАНИЕ ПРОСВЕТЛЯЮЩЕГО ПОКРЫТИЯ Ta_2O_5 / SiO_2 СОВРЕМЕННЫХ СОЛНЕЧНЫХ ЭЛЕМЕНТОВ КОСМИЧЕСКОГО НАЗНАЧЕНИЯ

М. А. Генали[1*], С. К. Шаров[1], А. А. Лебедев[1, 2], Н. Т. Вагапова[1], Б. В. Жалнин[1]

[1]АО «Научно-производственное предприятие «Квант»
Российская Федерация, 129626, г. Москва, ул. 3-я Мытищинская, 16
[2]Национальный исследовательский технологический университет «МИСиС»
Российская Федерация, 119049, г. Москва, Ленинский просп., 4
[*]E-mail: otdel_17@npp-kvant.ru

Солнечные элементы (СЭ) на основе материалов AIIIBV в составе солнечных батарей являются основными первичными источниками энергии для большинства современных космических аппаратов (КА). В связи с продолжающимся ростом энергопотребления КА, несмотря на уже достигнутые высокие характеристики, продолжаются работы по совершенствованию СЭ.

Одним из направлений является уменьшение отражения солнечного излучения с фотоактивной поверхности СЭ за счет применения антиотражающего (просветляющего) покрытия (АОП). Приведены результаты исследований АОП на основе слоев оксидов тантала (V) и кремния (IV) (Ta_2O_5 / SiO_2).

Представлены результаты расчета толщин и спектральной характеристики данного покрытия на поверхности трехкаскадного СЭ (InGaP / InGaAs / Ge) с учетом особенностей структуры СЭ, проведенного в специальном программном обеспечении.

Для подтверждения технологичности процесса нанесения АОП проведен эксперимент по нанесению покрытия на стеклянную подложку. Нанесение АОП проводилось методом электронно-лучевого испарения в вакууме. Результаты исследования спектральных характеристик на группе образцов, полученные с помощью спектрофотометра, подтвердили равномерность покрытий вне зависимости от положения образцов в камере *установки. Предварительный расчет спектральной характеристики для АОП на стеклянной подложке показал удовлетворительное совпадение с экспериментальными данными.*

Результаты исследований спектральных характеристик АОП, нанесенного на поверхность СЭ, показали хорошее совпадение с расчетными данными. Измерение электрических характеристик с помощью импульсного имитатора солнечного излучения (АМ0) до и после нанесения АОП на всех экспериментальных образцах СЭ показало прирост тока короткого замыкания в среднем на 122 мА, а КПД – на 7,5 %. Приводятся результаты электронно-микроскопических исследований АОП в различных частях СЭ.

Ключевые слова: просветляющее покрытие, антиотражающее покрытие (АОП), трехкаскадный солнечный элемент, фотоэлектрический преобразователь, вольт-амперная характеристика, оксид тантала (V), оксид кремния (IV).

Introduction. Currently primary energy sources for most spacecraft are solar arrays; their generating part consists of semiconductor devices that perform direct conversion of solar energy into electrical energy. Such devices are called photovoltaic converters or solar cells [1; 2].

Modern triple junction (TJ) solar cells based on AIIIBV semiconducting compounds have high values of output characteristics and resistance to radiation greater than single junction solar cells based on AIIIBV, as well as solar cells based on monocrystalline silicon [3].

However, power requirements to spacecraft are permanently increasing, consequently, requirements to technical characteristics of solar panels are increasing as well, primarily requirements to the efficiency of converting solar radiation flux into electrical energy or efficiency factor.

One of the directions to improve the output characteristics is decreasing the reflection of sunlight from the solar cell surface and thus increasing the penetration of radiation into generating parts of solar cells. The most common reflectivity decreasing method is cell surface antireflection coating (ARC), which represents thin dialectric film with certain reflectivity decreasing characteristics [4].

Single-layer ARC are simple to manufacture and can significantly increase the solar cell conversion efficiency of solar radiation. If some single-layer coating is applied to a semiconductor with a large refractive index, it is possible to achieve near-zero reflection at a certain wavelength, but in this case, changing the wavelength significantly increases the reflection coefficient, and it is a significant drawback [4]. To reduce the reflection over a wider range of wavelengths, we need to use more layers. To obtain low reflection in almost the entire spectral sensitivity region of the solar cell and to maximize their efficiency, one can use two- and three-layer ARC. The further increase in the number of layers theoretically reduces the reflected part of light, but the synthesis of complex coatings (more than 4 layers) is complicated by the difficulty of achieving the required quality in terms of homogeneity and uniformity of application.

When designing ARC, the materials (depending on their refractive indices and required thickness of the layers), are chosen so that the light wave reflected from the front surface of the coating due to interference is extinguished by a wave reflected from the boundary between the dielectric film and the semiconductor material [5]. As a rule, transparent amorphous films of nanometric thickness of the following compositions: ZnS, Ta_2O_5, TiO_2, MgF_2, Al_2O_3 and SiO_2 find use as materials for solar cell ARC [6].

Experimental part. Based on previous studies [7] and analysis of the structures of modern solar cells [8] we planned a comprehensive ARC study based on the materials of tantalum oxide (V) (Ta_2O_5) and silicon (IV) oxide (SiO_2). The study includes the following steps:

– calculation of ARC design by studying the features of the structure of TJ solar cell (InGaP / InGaAs / Ge) obtained by gas phase epitaxy from metalloorganic and hydride compounds;

– pilot-tests of manufacturing methods of ARC on more accessible substrates;

– application of optimized ARC directly to the surface of TJ solar cells (InGaP / InGaAs / Ge), measurement of critical parameters;

– experimental estimation of ARC influence on the solar cell characteristics.

Calculation of ARC based on Ta_2O_5 and SiO_2 materials. For TJ solar cells (InGaP / InGaAs / Ge) obtained by gas phase epitaxy from metalloorganic and hydride compounds, we have carried out a series of ARC calculations based on (Ta_2O_5 / SiO_2), taking into account the features of the solar cell structure. Calculations have been performed in the program OptiLayer Thin Film Software [9].

The maximum sensitivity of TJ solar cells based on AIIIBV is in the range 400–1500 nm, as it is shown in fig. 1 [10]. The long-wave part of the spectrum (from more than 900 nm) is absorbed and transformed by germanium subcell. When the subcells are connected in series, the current contribution of the germanium subcell is not limiting, so the lower stage has a significant current reserve, which allows us to narrow the spectral optimization range to 400–900 nm. Thus, the calculation of the optimization have been carried out taking into account the minimization of reflection in the wavelength range 400–900 nm of the solar radiation spectrum AM0.

It should be noted that there are not sufficient data in the literature to perform the calculations, therefore, we have performed experimental work to obtain dispersion dependencies: each of the layers (Ta_2O_5 and SiO_2) has been deposited on germanium substrates by electron-beam evaporation in vacuum. Dispersion dependences of the deposited layers have been obtained on a spectrometric ellipsometer SENTECH's SENpro in the wavelength range 400–900 nm.

Dispersion dependences of refractive indices Ta_2O_5, SiO_2, InAlP и InGaP [11–14] used in the calculations are shown in fig. 2.

In calculations we have used characteristics of TJ structures (InGaP / InGaAs / Ge): the upper subcell is the layer of composition $In_{0.49}Ga_{0.51}P$ with the thickness ≥ 0.5 μm and above it the wide-gap “window” of the upper subcell is the layer of composition $In_{0.5}Al_{0.5}P$ with the thickness varying from 35 to 100 nm. The thickness of the “window” layer of the upper is comparable to the thicknesses of the ARC layers and the spectral reflection coefficients have large values in comparison with the selected oxides, therefore, the epitaxial layers will have a significant effect on the results of calculations ARC (Ta_2O_5 / SiO_2). It should be noted that we have carried out all the calculations for the light incidence angle 0^o, i. e. along the normal to the surface of a solar cell.

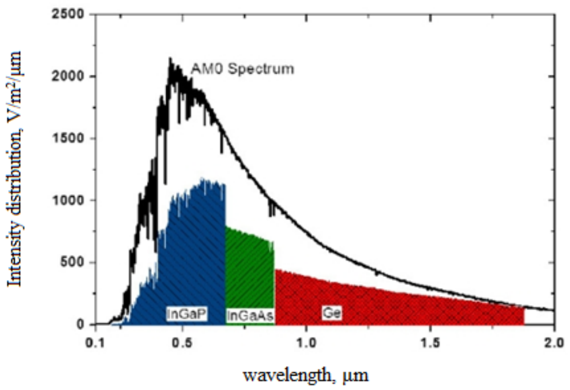

Fig. 1. Spectral distribution of absorption intensity of solar radiation for TJ solar cells

Рис. 1 Спектральное распределение интенсивности поглощения солнечного излучения для трехкаскадных СЭ

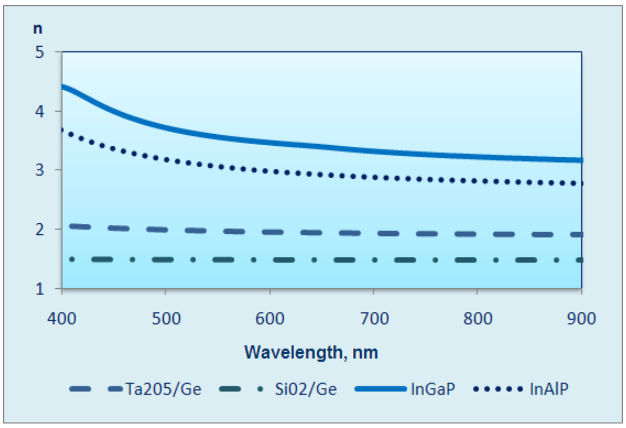

Fig. 2. Dispersion dependences of refractive indices: the dashed line is Ta_2O_5 / Ge; the dot-dashed line is SiO_2 / Ge; the solid line is InGaP, dotted line – InAlP

Рис. 2. Дисперсионные зависимости показателей преломления: пунктирная линия – Ta_2O_5 / Ge; штрих-пунктирная линия – SiO_2 / Ge; сплошная линия – InGaP; точечная линия – InAlP

Fig. 3 shows the calculated spectral characteristic (R (λ)) for ARC consisting of tantalum oxide Ta_2O_5 and silicon oxide SiO_2, taking into account the layer $In_{0.5}Al_{0.5}P$, on the layer $In_{0.49}Ga_{0.51}P$. The calculated thickness of ARC layers is 45 nm for Ta_2O_5 and 60 nm for SiO_2. The root-mean-square deviation of the calculation results from the target values is 3.9 %.

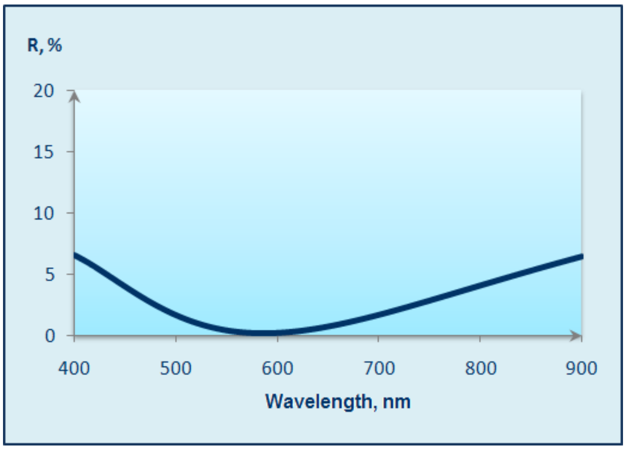

Fig. 3. The calculated spectral characteristic (R (λ)) for ARC (Ta_2O_5 / SiO_2) on the surface of the solar cell

Рис. 3. Рассчитанная спектральная характеристика (R(λ)) для АОП (Ta_2O_5 / SiO_2) на поверхности СЭ

Confirmation of the correspondence between the calculated and experimental values as well as the pilot-tests of manufacturing methods have carried out in another experiment that has included calculation part and physical deposition of ARC layers on the glass substrate.

ARC test (Ta_2O_5 / SiO_2) on a glass substrate. To confirm experimentally the calculated data, we have chosen glass substrates with geometric dimensions corresponding to the overall dimensions of the solar cell and the thickness of approximately 150 μm, the number of substrates is 4 pieces. The deposition of ARC on selected samples has been carried out by the electron beam method of sputtering the target in a high-vacuum industrial equipment, followed by the ARC thermal stabilization process.

The results of measuring the spectral dependence of the reflection obtained with the help of Shimadzu UV-3600 spectrophotometer for all four samples showed good agreement with the calculated dependences. To confirm the uniformity of the coating, as well as the reliability of the results for each sample, we have carried out a series of measurements on different parts of the surface.

The data obtained during the measurement of the spectral characteristics of the layers on a glass substrate, practically coincide with the calculated values in the greater part of the investigated range. It is shown in fig. 4. This fact confirms the reliability of calculations and allows us to expect such a matching of experimental and calculated data for ARC on the surface of a three-stage solar cell.

ARC (Ta_2O_5 / SiO_2) deposition on the TJ solar cell surface. Having carried out a number of necessary growth and build-up processes, we applied ARC (Ta_2O_5 / SiO_2) on the face of the solar cell in a similar way in a high-vacuum equipment with the use of electron-beam sputtering method and subsequent thermal stabilization. The study of the spectral characteristic (R(λ)) of the obtained ARC, similar to the experiment with glass substrates, has been carried out on a spectrophotometer.

The comparison of the experimental and calculated spectral characteristics (R(λ)) for ARC (Ta_2O_5 / SiO_2) on the surface of a TJ solar cell (you can see it in fig. 5) showed good agreement in the spectral range of the upper subcell, and deviations do not exceed 3 %. The variance in the region of more than 720 nm is explained by the presence of a distributed Bragg reflector in the structure of the solar cell between the second and the third subcell, which is not taken into account in the calculations. It should be taken into consideration that nanoscale ARC (Ta_2O_5 / SiO_2) can have composition deviations from stoichiometry in real layers, which can lead to additional measurement errors. Unfortunately, the computational algorithms also do not take into account the contribution of the reflection of the metal contact mesh on the facial area of real samples. Thus, according to estimates [15], the shading for the solar cell of the standard size used in the experiment is 1.82 %.

The dimensions of the contact grid and their contribution to the reflection can be estimated from the image obtained with the scanning electron microscope (SEM) in fig. 6, *a*. This image (fig. 6, *b*) also shows the features of real layers of ARC (Ta_2O_5 / SiO_2) on the solar cell. The studies carried out with the help of SEM confirmed the value of the given layer thicknesses taking into account the measurement inaccuracy on the microscope (fig. 6, *c*, *d*).

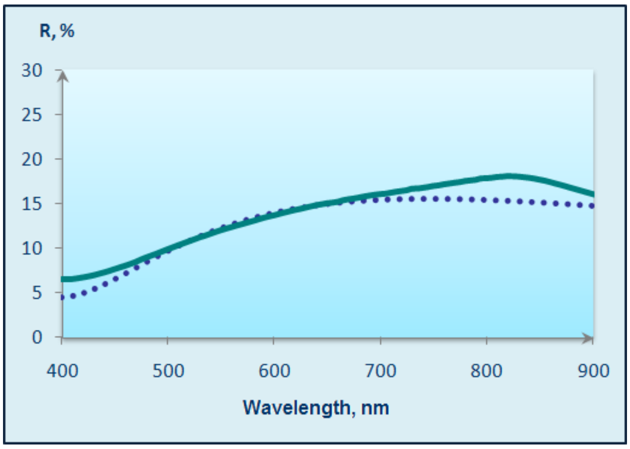

Fig. 4. Comparison of the experimental and calculated spectral characteristics (R(λ)) for (Ta_2O_5 / SiO_2) ARC on a glass substrate: solid line – experimental data, dotted line – calculated data

Рис. 4. Сравнение экспериментальных и расчетных спектральных характеристик (R(λ)) для АОП (Ta_2O_5 / SiO_2) на стеклянной подложке: сплошная линия – экспериментальные данные, точечная линия – расчетные данные

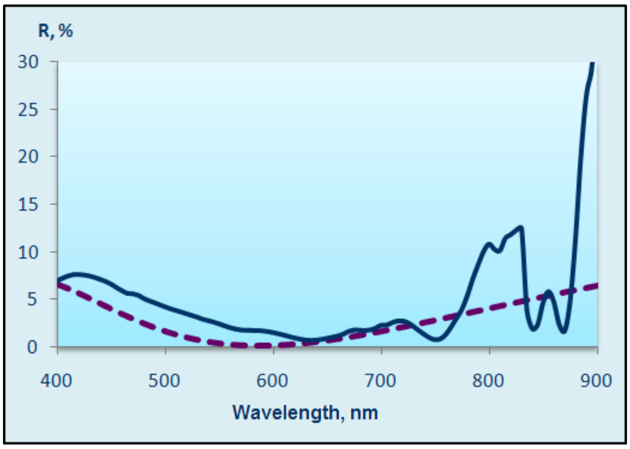

Fig. 5. Comparison of the experimental and calculated spectral characteristics (R(λ)) for ARC (Ta_2O_5 / SiO_2) on the surface of TJ solar cell: solid line – experimental data, dotted line – calculated data

Рис. 5. Сравнение экспериментальных и расчетных спектральных характеристик (R(λ)) для АОП (Ta_2O_5 / SiO_2) на поверхности трехкаскадного СЭ: сплошная линия – экспериментальные данные, пунктирная линия – расчетные данные

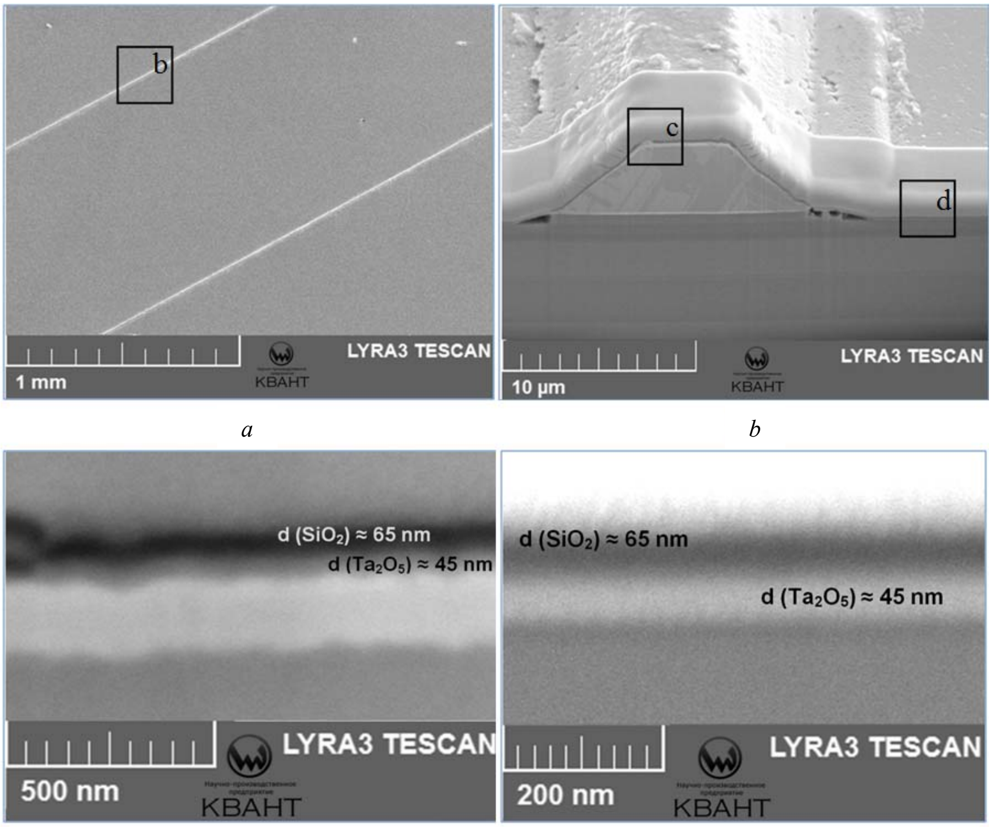

Fig. 6. Results of ARC (Ta_2O_5 / SiO_2) study by SEM

Рис. 6. Результаты исследования АОП (Ta_2O_5 / SiO_2) на СЭМ

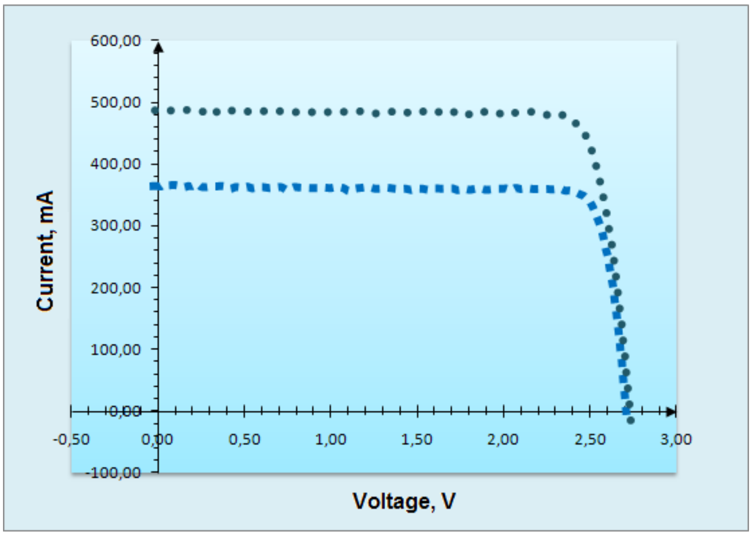

Fig. 7. Volt-ampere characteristic of a solar cell sample: the dotted line is a solar cell sample without ARC, the dashed line is a solar cell sample with ARC (Ta_2O_5 / SiO_2)

Рис. 7. Вольт-амперная характеристика образца СЭ: точечная линия – образец СЭ без АОП, пунктирная линия – образец СЭ с АОП (Ta_2O_5 / SiO_2)

To estimate the effect of ARC (Ta_2O_5 / SiO_2) on the output characteristics of solar cells, we have performed the measurements of the volt-ampere characteristics of solar cells using a pulsed radiation simulator in the AM0 spectrum before and after deposition of ARC on the surface of a TJ solar cell. The results of the experiment are shown in fig. 7. For processing the obtained data, we have used the program for analyzing volt-ampere characteristics of photoelectric converters, which is an element of technology support systems [16; 17].

According to the results of testing a batch of samples, the short-circuit current (I_{sc}) increased on average by 122 mA after applying ARC (Ta_2O_5 / SiO_2) on the solar cell, and the efficiency increased in average by 7.5 %.

Conclusion. We have made calculations of ARC (Ta_2O_5 / SiO_2), taking into account peculiarities of structure of TJ solar cell (InGaP / InGaAs / Ge). The calculations allow suppose that the deposition of this coating is rather promising.

The experiment in deposition of ARC (Ta_2O_5 / SiO_2) on the glass substrate allowed to draw conclusions about its technological effectiveness, as well as the necessity of performing a similar experiment on the surface of a TJ solar cell and to select the necessary modes for carrying out the process. The study of the spectral characterristic R(λ) of the obtained samples has showed the uniformity of coating application in all positions of the samples in a vacuum chamber.

Theoretically calculated and experimentally obtained on the solar cell surface of ARC (Ta_2O_5 / SiO_2) showed an increase in the output characteristics of the solar cells, namely, the I_{sc} increase was approximately 122 mA, and the efficiency increased by about 7.5 %. Electron microscopic study of the experimental samples of solar cells (InGaP / InGaAs / Ge) showed the uniformity of ARC (Ta_2O_5 / SiO_2), and, taking into account the inaccuracy, confirmed the specified thickness parameters of the layer thicknesses.

It should be noted that this coating is optimized for the structure of TJ solar cells (InGaP / InGaAs / Ge) and does not imply additional surface protection. However, for the application of solar cells in space, the front and back surfaces of the device are laminated with special protective glass. The design, which includes directly a solar cell with ARC applied, glue and protective glass is called a stack. The calculation does not take into account the design of the stack, which can have a significant effect on the final result. In the future, a full optical assembly (stack) of a TJ solar cell (InGaP / InGaAs / Ge) with ARC (Ta_2O_5 / SiO_2) should be calculated.

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