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Encapsulation of solar cells in a transparent polymer composite material

© Ivan Yu. Dmitriev[a]✉, Artem V. Kochergin[a,c], Sergey A. Yakovlev[a,b], Vladimir S. Levitskii[a], Alexey S. Abramov[a], Eugenii I. Terukov[a,b,c]

[a] *R&D Center of Thin Film Technologies in Energetics,*
28, Politekhnicheskaya St., Saint Petersburg, 194064, Russian Federation,
[b] *Ioffe Physical-Technical Institute of the Russian Academy of Sciences,*
26, Politekhnicheskaya St., Saint Petersburg, 194021, Russian Federation,
[c] *Saint Petersburg Electrotechnical University "LETI",*
5, Professora Popova St., Saint Petersburg, 197022, Russian Federation

✉ I.Dmitriev@hevelsolar.com

Abstract: Lightweight photovoltaic modules are becoming increasingly popular in many technical applications. This study proposes an approach to the production of a glass-filled prepreg encapsulant for solar cells lamination. Lamination of solar cells strings can result in the creation of a transparent and mechanically strong protective composite material. Prototypes of composite photovoltaic modules with high-efficiency HJT solar cells connected using electroconductive adhesive technology were fabricated. The climatic resistance of the obtained samples was estimated. It was found that composite modules pass successfully thermal cycling, UV exposure and hail tests. Damp heat test has revealed increased degradation. Degradation caused by moisture penetration initiates corrosion processes in the layers of transparent conductive oxide ITO or contact metallization mesh. The use of composite polymer material makes it possible to reduce the weight of photovoltaic modules due to the use of sheet glass in their design while maintaining an acceptable level of their climatic resistance.

Keywords: photovoltaic cells; photovoltaic module; heterostructure silicon cells; silicon; solar cells; polymer composite materials; light transmission; thermal cycling; hail resistance.

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Инкапсуляция фотоэлектрических преобразователей в прозрачный полимерный композиционный материал

© И. Ю. Дмитриев[a]✉, А. В. Кочергин[a,c], С. А. Яковлев[a,b], В. С. Левицкий[a], А. С. Абрамов[a], Е. И. Теруков[a,b,c]

[a] *Научно-технический центр тонкопленочных технологий в энергетике,*
ул. Политехническая, 28, Санкт-Петербург, 194064, Российская Федерация,
[b] *Физико-технический институт им. А. Ф. Иоффе РАН,*
ул. Политехническая, 26, Санкт-Петербург, 194021, Российская Федерация,
[c] *Санкт-Петербургский государственный электротехнический университет «ЛЭТИ»,*
ул. Профессора Попова, 5, Санкт-Петербург, 197022, Российская Федерация

✉ I.Dmitriev@hevelsolar.com

Аннотация: Легковесные фотоэлектрические модули становятся все более востребованными во многих технических применениях. В работе предложен подход к изготовлению стеклонаполненного инкапсулянта-препрега для ламинирования фотоэлектрических преобразователей. В процессе ламинации матрицы скоммутированных фотоэлектрических преобразователей образуется прозрачный и ударопрочный защитный композиционный материал. Проведена характеристика структуры и свойств композиционного материала с применением спектрофотометрии, инфракрасной спектроскопии и термического анализа. Изготовлены прототипы композитных фотоэлектрических модулей с высокоэффективными кремниевыми ячейками гетероструктурного типа, скоммутированными с применением клеевой технологии. Проведена оценка климатической стойкости полученных образцов. Установлено, что прототипы композитных фотоэлектрических модулей хорошо проходят испытания на термоциклирование, УФ-воздействие и градостойкость. Испытания композитных модулей выявили относительно высокую деградацию во время воздействия высокой температуры при высокой влажности. Деградация, вызванная проникновением влаги через композиционное покрытие, запускает коррозионные процессы в слоях прозрачного проводящего оксида ITO или контактной металлизационной сетки. Применение композиционного полимерного материала позволяет существенно снизить вес фотоэлектрических модулей за счет ухода от применения листового стекла в их конструкции при сохранении приемлемого уровня их климатической стойкости.

Ключевые слова: фотоэлектрический преобразователь; фотоэлектрический модуль; гетероструктурная технология; кремний; солнечные элементы; полимерные композиционные материалы; светопропускание; термоциклирование; градостойкость.

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1. Introduction

Technical solutions in the development of lightweight photovoltaic modules (PVMs) are in demand in connection with the spread of solar energy in the areas of its integration into architecture, industrial and urban infrastructure, transport, mobile devices, communications equipment, and products for non-civilian use. The reliability of a typical PVM is ensured by the use of front and rear protective glass in its design, which makes a critical contribution to its weight. The specific weight of a glass-to-glass PVM structure is 15–16 kg·m^{-2}, while in a glass-free structure this value is 2–4 kg·m^{-2}. It is obvious that avoiding the use of sheet glass in the design of PVMs while maintaining an acceptable level of their climatic resistance and impact strength is an important practical task. At the scientific and technical center of the Hevel Group of Companies (*LLC Scientific and Technical Center of Thin-Film Technologies in Energy*), semi-flexible lightweight batteries have been developed that can be used to solve a wide range of similar problems. Some examples of implemented projects are shown in Fig. 1.

Fig. 1. Examples of completed projects for the integration of semi-flexible lightweight PVMs in sea, air, and mobile deployable applications

A common approach in the solar energy industry is to produce semi-flexible, lightweight PVMs by replacing the front glass with a protective transparent sheet based on polyethylene terephthalate (PET) or ethylene tetrafluoroethylene copolymer (ETFE). Multilayer PET-based sheets, as well as fiberglass laminates and honeycomb panels are used as the back protective substrate. These structures use polymeric encapsulating materials in a highly elastic state, the same type as in industrial glass-to-glass PVMs or glass-to-protective back sheet structures. Semi-flexible lightweight PVMs based on heterojunction silicon photovoltaic converters (HJT solar cells) have a number of disadvantages: low shock and hail resistance, destruction of busbar jumpers during thermal cycling, the appearance of delamination and increased corrosion of HJT solar cells when exposed to high temperatures and high humidity [1–3].

The climatic and mechanical reliability of PVMs of any design is largely determined by the materials used and their mutual compatibility. The introduction of fiberglass reinforcing materials into the encapsulant can significantly improve the impact resistance of glassless modules [4–7]. This is achieved by immersing a matrix of connected solar cells in a durable, lightweight and optically transparent composite material. Composite PVMs can be made by pouring curable epoxy compounds into interconnected solar cells using Resin Transfer Molding technology. However, a more effective approach involves the production of a glass-filled prepreg encapsulant, which can be used to laminate PVMs in an industrial membrane vacuum laminator. Prepreg contains a hot-melt binder, which, when heated, takes the required shape and vulcanizes, actually turning into a solid aggregate state.

The purpose of this study is to develop a method for encapsulating solar cells into a transparent, impact-resistant composite material and assess the climatic resistance of the resulting samples. To solve the problem, it was proposed to use a polymer thermosetting material of epoxy-acrylic chemical nature. The main feature of the material under development is that it is based on a chemical cross-linkable system capable of processing within technological parameters close to those used in mass production of PVMs (using polyolefin-based film laminations). A separate objective of this study was to compare PVMs made with the new composite technology in terms of reliability with semi-flexible lightweight PVMs of traditional design using front and back protective sheets based on PET and laminating polyolefin films of the POE type.

2. Materials and Methods

2.1. Initial components

The study used silicon heterostructure (*n*-type, HJT technology) five-bar solar cells of M2+ format (157.35×157.35 mm) produced by Hevel. Metallization of the contact mesh was carried out by screen printing using an electrically conductive adhesive. The PV cells were connected to each other on an industrial stringer at the production site of the Hevel Company.

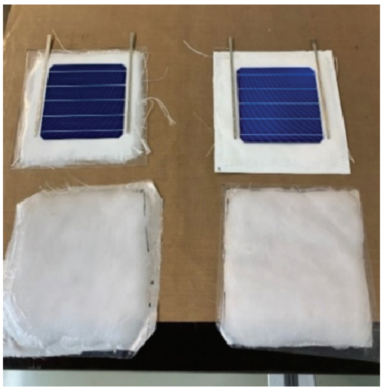
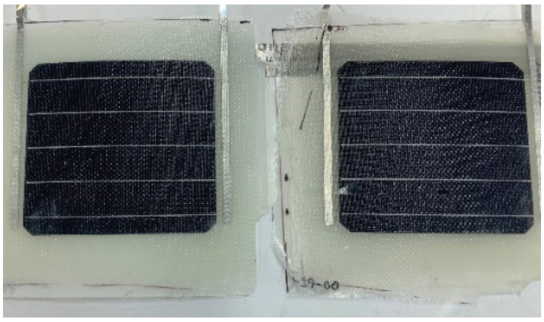
The commercial product, the thermosetting powder composition FREOCRYL Powder Coating PY1005BR999C, manufactured by Freilacke, was used as a polymer binder. This composition was chosen due to the fact that after curing it forms a transparent coating and has a processing temperature that is close to the temperature used in typical PVM lamination technology (about 140–160 °C). The powder composition is a polymer composition of epoxy-acrylic nature; its exact composition is not disclosed by the manufacturer, however, general technological aspects of production are given in [8]. An important difference between the cured polymer is its high glass transition temperature (more than 60 °C), which causes a high rigidity value (the cured polymer is close to plexiglass in mechanical characteristics). The latter circumstance favorably distinguishes the proposed approach from the common lamination technology using film encapsulants, which have a very low glass transition temperature (usually below –40 °C) and are in a highly elastic state under PVM operating temperatures.

Commercial plain weave glass fabric with a density of 80 $g \cdot m^{-2}$ based on EC6-34tex fiber was used as a reinforcing material. Photovoltaic rear protective sheets based on fluorinated polyethylene terephthalate and front ETFE films with corona treatment with a thickness of 50–150 microns were used.

2.2. Methodology for preparing composite PVMs

Composite PVM samples were prepared in two steps (Table 1). The first stage is the production of prepreg – a sheet material consisting of fiberglass with a polymer binder fused to it. To make the prepreg, the glass fabric was placed on a heating table with a set temperature of about 100 °C, and then the polymer powder was manually applied, distributing it along the surface with a spatula, evenly pressing the melting polymer into the glass fabric and cleaning off the non-absorbable excess. Then the material was

Table 1. Sequence of manufacturing PVM samples

Stage 1. Preparation of samples (prepregs)	Stage 2. Lamination of the module with prepregs
	

pressed (rolling with a hand roller for 5–15 seconds). The prepreg prepared in this way contained a binder, the content of which was determined by the absorbency of the fiberglass fabric. The weight of the powder in a fiberglass-based prepreg with a density of 80 $g \cdot m^{-2}$ was (632 ± 109) $g \cdot m^{-2}$. The resulting prepreg had a thickness of (420 ± 55) microns.

At the second stage – lamination of the module blank – the prepreg was used as a laminate to bond the solar cell matrix to the front ETFE sheet and the rear PET protective sheet. The PVM samples were prepared using a laboratory membrane vacuum laminator at the following mode: temperature 160 °C, evacuation time 5 min, pressure build-up time 1 min, pressure 500 mbar, pressure application time 25 min. During the lamination process, the workpiece was positioned with its front side facing the heating plate of the laminator. After lamination, the PVM was cooled under load.

Reference semi-flexible lightweight PVMs of traditional design were manufactured from commercial 320 μm PET front and back sheets and 520 $g \cdot m^{-2}$ polyolefin polyolefin films. The PVM assembly was carried out on the same equipment using a technological regime that ensured cross-linking of POE laminates of at least 80 % (measured gel content using the xylene dissolution method).

2.3. Analytical methods and test conditions

A Nicolet 8700 FT-IR spectrometer and an Agilent Cary 5000 spectrophotometer were used to analyze the structure and properties of the encapsulating material.

The thermal properties of the materials were studied by differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) on a ZH-1000 synchronous analyzer (Shanghai Innuo Precision Instruments Co., Ltd.). The measurements were carried out in the temperature range from 30 to 200 °C, at a scanning speed of 10 $°C \cdot min^{-1}$ in an air atmosphere. Samples were weighed at 15–20 mg.

Climatic tests of the modules for reliability included the following tests according to the conditions of Russian Standard R 56980.2 (IEC 61215-2:2016) - 2020: damp heat test (section 4.10), thermal cycling (section 4.8), test for exposure to ultraviolet radiation with frontal exposure of the sample (section 4.7).

The test for resistance to hail impacts was carried out under standard conditions according to Russian Standard R 56980.2 (IEC 61215-2:2016) – 2020 section 4.14: hail diameter 25 mm, speed 22 $m \cdot s^{-1}$. During testing, two shots were fired - at the center and at the edge of each sample.

Electro- and photoluminescence images of the samples were obtained using LumiSolarCell and MBJ Solutions illumination stands, respectively.

The current-voltage characteristic (short circuit current I_{sc}, open circuit potential V_{oc}, power at maximum point P_{mpp} and FF duty cycle) was measured using a specialized I-V tester under standard conditions (1.5AM, 25 °C).

3. Results and Discussion

3.1 Characteristics of transparent composite material

Figure 2 shows the infrared spectrum of attenuated total internal reflection (ATR) of the binder polymer before and after curing. Table 2 shows the attribution data for the absorption bands observed in the spectrum [9–12]. Based on the data

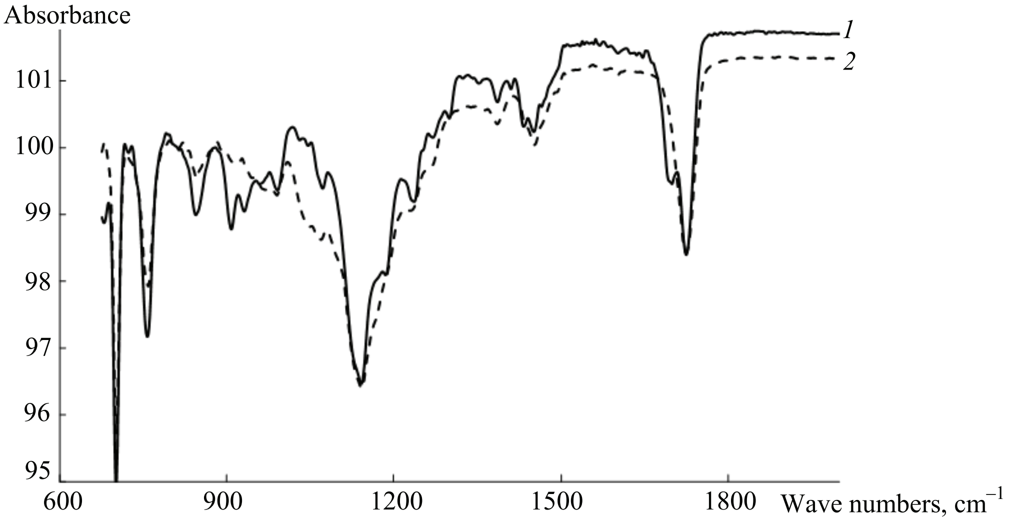


Fig. 2. ATR IR spectra of the binder polymer before (curve *1*) and after (curve *2*) curing

Table 2. Characteristic bands of the ATR IR spectra of the binder and cured composites (according to Fig. 2)

Prepreg	Cured polymer	Attribution
700	700	Flexural deformation of CH groups of monosubstituted aromatic compounds
757	757	Bending vibration of the CH group of the epoxy ring
760	760	Bending vibration of CH groups of epoxy ring
790	–	Stretching vibrations of Si–C bonds
846 907	–	Epoxy ring vibrations (glycidyl methacrylate)
966 990	966 990	Vibrations of Si–O–Si bonds
1030	–	Vibrations of Si–C bonds
1074 1147 1189 1247	1074 1147 1189 1247	Stretching vibrations of C–O bonds of butyl acrylate and glycidyl methacrylate
1238	1238	Bending vibrations of Si–C bonds
1302	1302	Glycidyl methacrylate side chain methyl groups (presumably)
1387	1387	Bending vibrations of C–H bonds
1410 1431	1431	Bending vibrations of groups of CH_2 groups
1452 1493 1600	1452 1493 1600	Aromatic group vibrations
1462	1462	Vibrations of C–H bonds of methylene groups of glycidyl methacrylate
1695 1728	1728	Stretching vibrations of carbonyl C=O, C–O, methacrylate groups of butyl and glycidyl methacrylate
2851 2937	–	Asymmetric and symmetric vibrations of CH_2 alkanes groups
3060 3026	3060 3026	C–H vibrations of aromatic groups

obtained, it can be concluded that the binder is a copolymer containing acrylic comonomers (butyl methacrylate, glycidyl methacrylate), styrene, and grafted silane groups. The intensities of the bands at 845 and 906 cm^{-1}, attributed to vibrations of the epoxy ring [11], differ markedly between the prepreg and the cured polymer. This suggests that curing occurred through the reaction of the crosslinker with the epoxy groups of glycidyl methacrylate. It was found that after curing, the polymer material lost solubility in boiling xylene, with the insoluble residue reaching 95 %. The changes in bonds with Si noted in Table 2 can presumably be attributed to changes in silane additives that act as adhesion promoters. A more detailed analysis of the comonomer composition of the base polymer, the content of functional additives, and the degree of conversion using chromatographic and spectroscopic methods will be presented in a separate study.

During the first heating cycle the DSC curve (Fig. 3) reveals a glass transition transition in the temperature range of 50–70 °C and a melting peak around 118 °C. The crosslinking chemical reaction is detected as a peak at 160 °C. Comparing the thermogram data with IR spectroscopy data, we can conclude that the transition corresponding to the glass transition is associated with the softening of the copolymer of glycidyl methacrylate with butyl methacrylate [14], and the melting observed at 118 °C referred to dodecanedioic acid, which was used as a cross-linker for this group of copolymers [8]. During the second and further cycles of cooling/heating of the sample, the noted melting process is not observed, however, a glass transition transition is detected in the region of 78 °C (Fig. 3, inset).

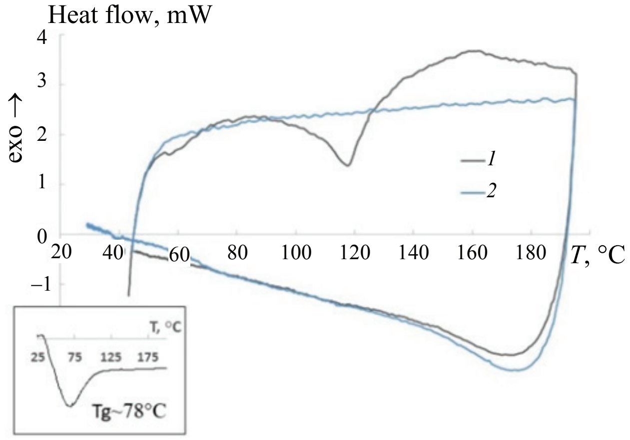


Fig. 3. DSC curve of a polymer binder (*1* – first pass, *2* – second pass); inset – DSC scanning section of the cured composite to determine Tg

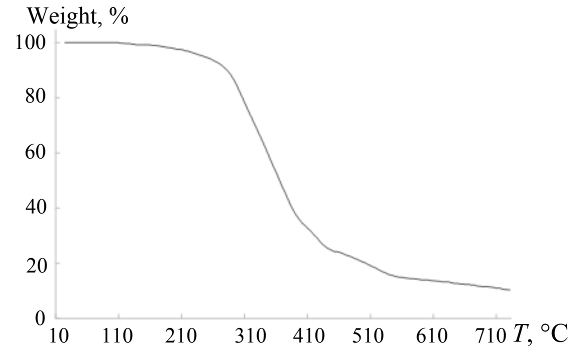


Fig. 4. TGA composite curve

An important feature of this polymer material is that it is based on a chemical cross-linkable system, the thermal behavior of which is close to the behavior of POE or EVA laminating films common in the solar industry. Thanks to this, the composite laminate is capable of processing within technological parameters close to those used in PVM mass production.

The cured composite material shows relatively high thermal stability (Fig. 4). According to thermogravimetry data, it was found that when heated to a temperature of 102 °C, the material lost no more than 0.1 % of its weight; a loss of 1.0 % of weight was observed only when reaching 162 °C, 10 % – at 280 °C, 50 % – at 364 °C. The process of thermal decomposition of the main polymer unit began at a temperature of about 243 °C. After complete burnout of organic residues, the weight of the remaining glass fiber occupied about 10 % of the original weight of the sample.

As can be seen from the light transmission spectra (Fig. 5), the composite prepared by the described method is characterized by a relatively high level of light transmission – the average value in the wave range 400–900 nm was 89.6 %.

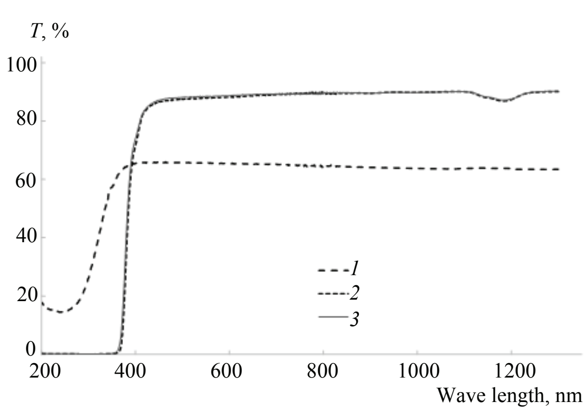


Fig. 5. Light transmittance of glass fabric (*1*), binder (*2*) and cured composite (*3*)

At a wavelength of 360 nm, transmission did not exceed 0.5 %. It is obvious that the polymer binder contains a substance that plays the role of a UV filter. It is significant that the transmission spectrum of the composite and the cured binder are identical, which indicates a good match of the refractive indices of the polymer and glass fabric.

3.2 Climatic testing of composite photovoltaic modules

It is known that silicon HJT solar cells exhibit increased degradation upon UV exposure [13]. UV-induced degradation of a heterostructural solar cell consists of a decrease in the lifetime of charge carriers, usually accompanied by a decrease in the V_{oc} and FF parameters, which is associated with the appearance of bulk defects in the a-Si:H structure and the interface between c-Si and a-Si:H. In practice, it is necessary to provide UV protection to HJT solar cells by introducing a UV absorbent component into the protective encapsulating layers. The behavior of a PVM sample with a UV exposure of at least 60 kW·h·m^{-2} corresponds to one year of operation in a temperate climate [16]. As can be seen from the results obtained (Fig. 6), the level of power degradation (P_{mpp}) of composite PVM samples after a frontal exposure of 60 kWh·m^{-2} slightly exceeded the degradation value of the reference sample prepared by lamination using a commercial POE polyolefin film containing a UV adsorber. Another PVM reference sample laminated to POE film without UV blocker showed noticeably higher (30 %) power degradation. The main contribution to the degradation of composite PVM under UV exposure after exposure to 60 kWh·m^{-2} was associated with a decrease in the I_{sc} parameter. For a reference sample laminated with a commercial POE film without a UV blocker, significant degradation in the I_{sc}, V_{oc} and FF parameters was observed. It is noteworthy that for the reference sample laminated to a commercial lamination film with a UV blocker, degradation was more pronounced for the FF parameter than for the I_{sc} parameter compared to the data for the composite PVM. This circumstance may be associated with different UV adsorbers used by different manufacturers of protective materials [15]. As a UV adsorber, additives based on benzophenones or benzotriazoles were used in combination with antioxidants and HALS stabilizers, and provided cutoff of the UV spectrum. The electroluminescence (EL) image of the composite sample showed no noticeable darkening (Fig. 7).

When testing for exposure to high temperature and high humidity (temperature 85 °C, humidity 85 %), increased PVM power degradation was detected, this exceeded 5 % when reaching 600 hours of experiment (Fig. 8). Degradation was accompanied by the appearance of darkening in EL images. In this case, the greatest contribution to the magnitude of power degradation was made by a decrease in the FF fill factor. Photoluminescence (PL) images of test samples with power degradation of more than 10 % had a uniform color (in contrast to the EL images of the corresponding solar cells).

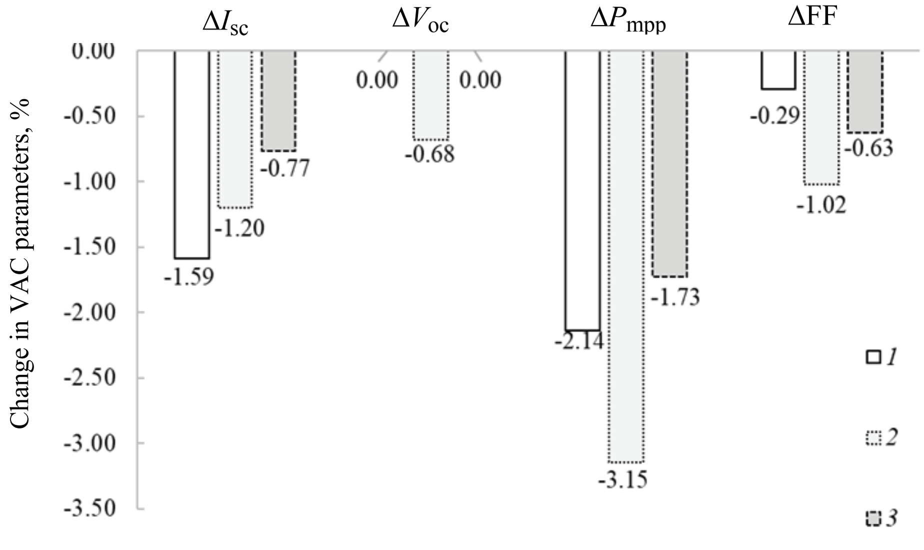
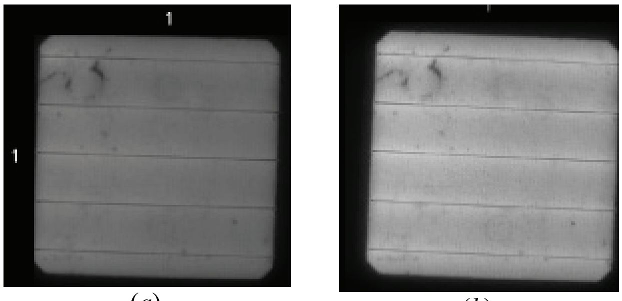


Fig. 6. The degradation value of the current-voltage characteristics (I_{sc}, V_{oc}, P_{mpp} and FF) for a composite PVM after UV exposure of 60 kW·h·m^{-2} (*1*), a reference PVM with a POE laminating film without a UV blocker (*2*) and a reference PVM with a laminating film with a UV blocker (*3*)



(*a*) (*b*)

Fig. 7. Electroluminescence image of a composite PVM sample before (*a*) and after (*b*) 60 kW·h·m^{-2} UV irradiation of the front side of the PVM

This allows us to conclude that the reduction in power occurred due to corrosion of the current collection system: in the layers of transparent conductive oxide ITO or on the elements of the contact mesh. Increasing the resistance of HJT solar cells to high temperatures and high humidity was a solvable problem and was achievable by using methods for cleaning the solar cell surface from contaminants, modifying the composition of metallizing materials, and also forming additional dielectric protective coatings [17, 18].

To carry out thermal cycling tests, PVMs with dimensions of 2×3 solar cell were manufactured (Fig. 9). The minimodules underwent 200 cycles of transitions between –40 °C – +85 °C with a final power degradation of 0.3 %, which was noticeably better than the results obtained when testing semi-flexible lightweight PVMs of traditional design using polyolefin encapsulating films [3]. Thus, the samples demonstrated high resistance to temperature changes, which was due to the fact that the rigid and glassy composite was capable of forming a frame resistant to thermomechanical effects, which increased the durability of busbars in solar cell chains.

The results of the damp heat and thermal cycling tests of PVMs of PET/POE/POE/PET design are shown in Table 3. The comparison of the results of these tests with the results obtained for composite PVMs (Figs. 6–8) shows that the composite structure is inferior traditional in moisture resistance, but noticeably superior in thermal cycling. The lower resistance of HJT solar cell composite encapsulation

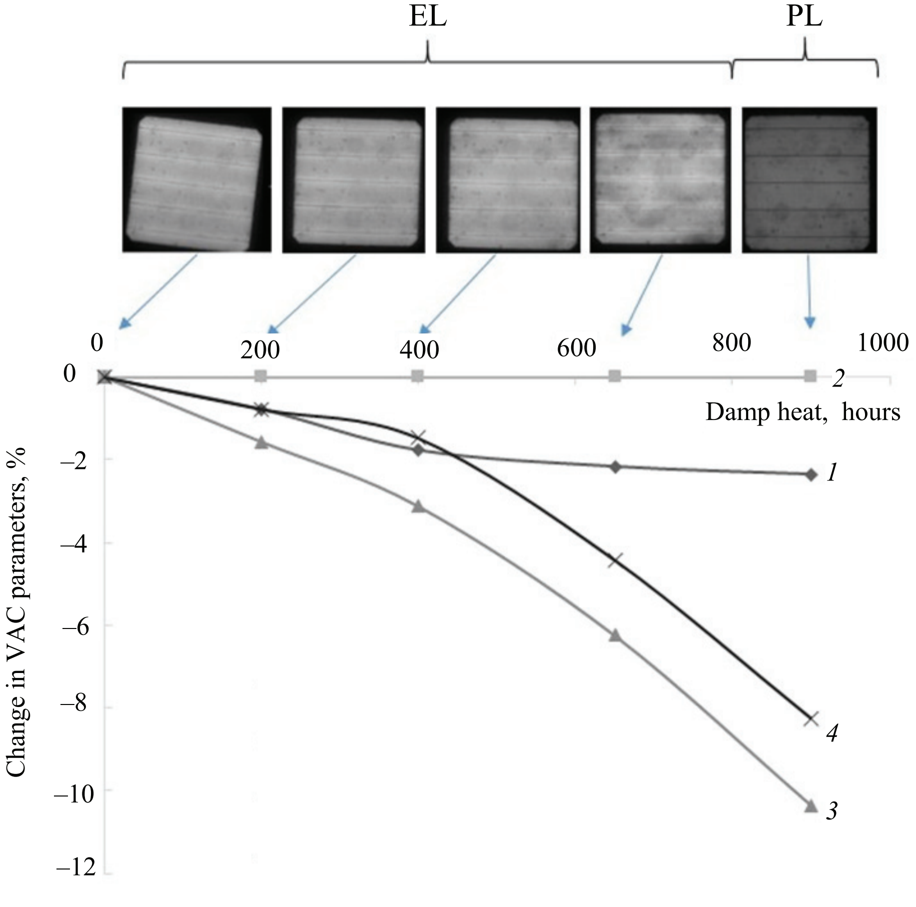


Fig. 8. Changing the values of the current-voltage characteristic parameters (I_{sc} (*1*), V_{oc} (*2*), P_{mpp} (*3*) and FF (*4*)) during damp heat test f a composite PVM, as well as EL and PL images of the corresponding samples

to moisture penetration is associated with the higher vapor transmission coefficient of acrylic polymers compared to polyolefin ones [19]. In addition, it is necessary to take into account the likely degradation of the polymer base during hydrolysis with the release of corrosive by-products of the reaction.

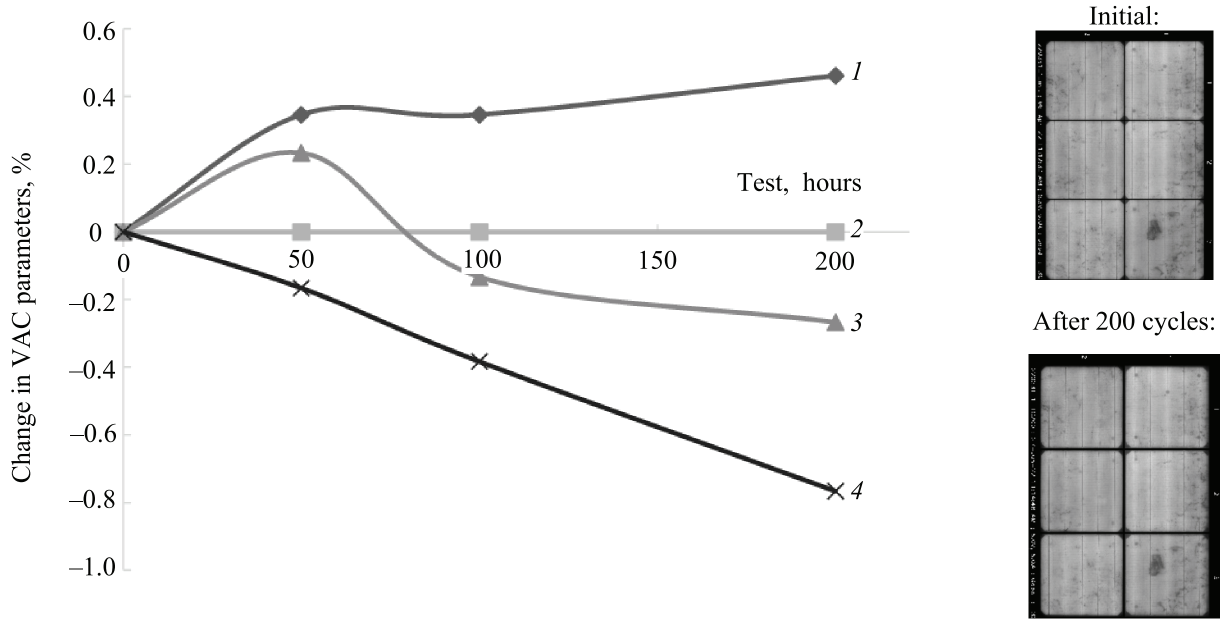


Fig. 9. Relative change in values I_{sc} (*1*), V_{oc} (*2*), P_{mpp} (*3*) and FF (*4*) when testing composite PVMs for thermal cycling and EL images of samples before and after testing (right)

Table 3. Results of damp heat and thermal cycling tests of PVMs of PET/POE/POE/PET design (reference modules)

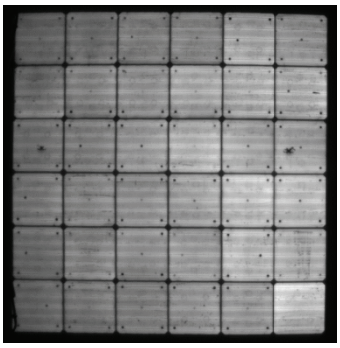
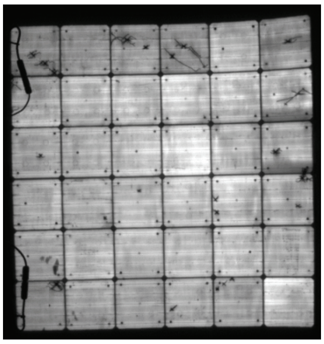
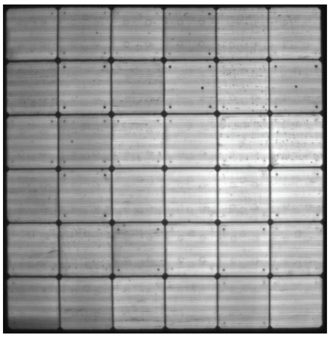
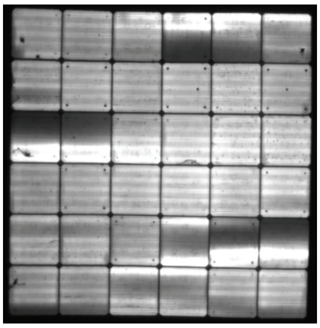
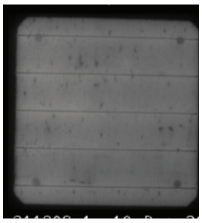
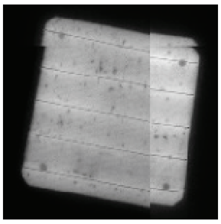
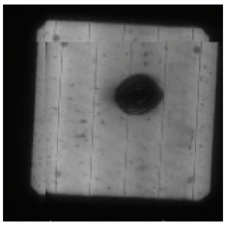
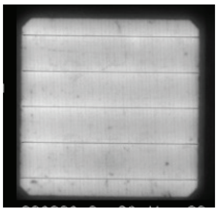
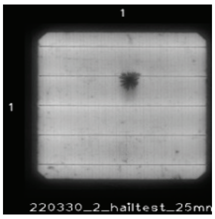
Test	Results		
	Initial EL	EL after testing	P_{mpp} degradation after test
Exposure to high temperature and high humidity 1000 hours			–1,0 %
	Initial EL	EL after testing	P_{mpp} degradation after test
Thermal cycling 200 cycles			–10.5 %

Table 4. Hail resistance test results (EL images)

Sample	Initial	After being hit by hail	
		Method of fixing PVM on a substrate	
		No gap from the rear	Gap from the rear
PVM composite construction			
Solar cell lamination in PET/POE/POE/PET structure			

For hail resistance tests (Table 4), two conditions for attaching samples were considered: 1) PVM fixed on the back side with double-sided tape to a rigid base, and 2) PVM fixed only at the edges in the absence of tight contact of the central part of the sample with the rigid base. It was found that if the back side of the PVM is tightly fixed to a rigid substrate, hail shots do not lead to any damage (Table 4). In case of loose contact with the base, damage remained in the central places of the module, i.e. in places where there is slight bulging of the module from the substrate. Thus, the effect of hail resistance of the modules occurs in conditions when the back side of the solar cell is completely supported by a sufficiently rigid base, which eliminates critical deflection of the fragile photovoltaic plate. The lack of a rigid base only on the back side of the solar cell is the main reason that semi-flexible lightweight PVMs of traditional design are not able to pass the hail test even when tightly fixed to a rigid base, since the back side of the solar cell is located on a viscoelastic, pliable base (polyolefin film) [2] . Thus, traditionally designed semi-flexible lightweight PVMs can be recommended more for deployable and portable solar generation systems with reduced impact requirements.

4. Conclusion

The study proposes to use a polymer thermosetting material of epoxy-acrylic chemical nature for the preparation of a composite laminating material on a fiberglass substrate. The prospects for using the resulting composite material for the lamination of high-performance silicon HJT solar cells and the production of lightweight impact-resistant PVMs have been studied. The general concept for the production of composite modules has been defined and PVM prototypes have been manufactured for reliability testing. Prototypes of composite PVMs with five-bar adhesive solar cells perform well in thermal cycling, UV exposure and hail resistance tests. However, testing of prototype composite modules revealed increased degradation during the damp heat test, which is associated with corrosion when water penetrates between the composite material and the ITO layer or contact mesh. The results obtained open up new prospects for expanding the scope of practical applications of heterostructure technology of silicon solar cells.

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6. Conflict of interests

The authors declare no conflict of interest.

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Information about the authors / Информация об авторах

Ivan Yu. Dmitriev, Cand. Sc. (Phys. and Math.), Lead Process Technologist, R&D Center of Thin Film Technologies in Energetics (R&D Center TFTE), Saint Petersburg, Russian Federation; ORCID 0000-0003-0605-9006; e-mail: I.Dmitriev@hevelsolar.com

Artem V. Kochergin, Postgraduate Student, Saint Petersburg Electrotechnical University "LETI", Saint Petersburg, Russian Federation; ORCID0009-0005-6670-8508; e-mail: A.Kochergin@hevelsolar.com

Дмитриев Иван Юрьевич, кандидат физико-математических наук, ведущий технолог, Научно-технический центр тонкопленочных технологий в энергетике (НТЦ ТПТ), Санкт-Петербург, Российская Федерация; ORCID 0000-0003-0605-9006; e-mail: I.Dmitriev@hevelsolar.com

Кочергин Артем Владимирович, аспирант, Санкт-Петербургский государственный электротехнический университет «ЛЭТИ», Санкт-Петербург, Российская Федерация; ORCID 0009-0005-6670-8508; e-mail: A.Kochergin@hevelsolar.com

Sergey A. Yakovlev, Cand. Sc. (Phys. and Math.), Lead Process Technologist, R&D Center TFTE, Saint Petersburg, Russian Federation; ORCID0009-0009-3963-8355; e-mail: S.Yakovlev@hevelsolar.com

Vladimir S. Levitskii, Cand. Sc. (Eng.), Lead Measurements Specialist, R&D Center TFTE, Saint Petersburg, Russian Federation; ORCID 0000-0002-7877-1329; e-mail: V.Levitskiy@hevelsolar.com

Alexey S. Abramov, Cand. Sc. (Phys. and Math.), Head of Solar Energy Department, R&D Center TFTE, Saint Petersburg, Russian Federation; ORCID 0000-0003-4310-4478; e-mail: a.abramov@hevelsolar.com

Eugenii I. Terukov, D. Sc (Eng.), Professor, Deputy Director for Science, R&D Center TFTE, Saint Petersburg, Russian Federation; ORCID 0000-0002-4818-4924; e-mail: e.terukov@hevelsolar.com

Яковлев Сергей Александрович, кандидат физико-математических наук, ведущий технолог, НТЦ ТПТ, Санкт-Петербург, Российская Федерация; ORCID 0009-0009-3963-8355; e-mail: S.Yakovlev@hevelsolar.com

Левицкий Владимир Сергеевич, кандидат технических наук, ведущий специалист по измерениям, НТЦ ТПТ, Санкт-Петербург, Российская Федерация; ORCID 0000-0002-7877-1329; e-mail: V.Levitskiy@hevelsolar.com

Абрамов Алексей Станиславович, кандидат физико-математических наук, руководитель отдела солнечной энергетики, НТЦ ТПТ, Санкт-Петербург, Российская Федерация; ORCID 0000-0003-4310-4478; e-mail: a.abramov@hevelsolar.com

Теруков Евгений Иванович, доктор технических наук, профессор, заместитель генерального директора по научной работе, НТЦ ТПТ, Санкт-Петербург, Российская Федерация; ORCID 0000-0002-4818-4924; e-mail: e.terukov@hevelsolar.com

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