Analysis of the performance and economic parameters of different types of solar panels taking into account degradation processes

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Abstract. Analysis of the operational and economic parameters of various types of solar panels, taking into account their degradation. An inspection of literary sources of solar panels was carried out. The types of solar panels, their advantages and disadvantages are described in detail. An analysis of the degradation of solar panels was carried out. The calculation is made and graphs of degradation of solar panels are given. In the feasibility study, capital investment calculations were carried out for the introduction of two network stations with a capacity of 30 kW, with various types of solar panels. Scientific novelty lies in the analysis of the degradation of various types of solar panels.

1 Introduction

The process of degradation of the performance of photovoltaic modules (Potential Induced Degradation), hereinafter abbreviated as PID, is a significant deterioration of the properties of modules over time, reducing the efficiency of up to 95%, is the most undesirable phenomenon for any solar panels.

All modules without exception are subjected to the degradation process: mono- and polycrystalline; thin-film. In each case, however, it proceeds in a special way and with varying degrees of intensity. The process is especially undesirable from the point of view that the projects of any modular systems for processing solar energy into electrical energy, as well as large solar power plants, require uninterrupted operation for at least 25-30 years.

The effect of degradation under the action of light is characteristic of all first-generation solar cells; however, for second-generation solar cells based on a-Si:H, such a degradation mechanism seems to be the main one today. The first mention of the relationship between the degradation of this material and the light incident on it was published in [1]. The names of the authors gave the name to the effect, so today, referring to the degradation of SCs based on aSi:H under the action of light, they speak of the Stebler-Vronsky effect. The essence of the effect is that the dark conductivity and photoconductivity of a layer of thin-
film amorphous silicon obtained by deposition from a glow discharge plasma are significantly reduced if the sample is exposed to light for a long time.

It was found in [2] that the process of decrease in conductivity is reversible: upon prolonged annealing (>150°C), the conductivity of the sample could be restored almost completely. In the early stages of the development of the theory of the Stebler-Vronsky effect, it was suggested that weak Si-Si bonds were the cause of this phenomenon: the photoinduced charge carriers eventually recombined, the released energy turned out to be enough to destroy these weak bonds, the hydrogen atom passivated the bond of one of the atoms, but the bond of the second atom was broken. As a result, the number of defects increased, and the Fermi level shifted closer to the center of the band gap, and the conductivity of the material decreased [3]. In subsequent works [4, 5] it was shown that the main factors that determine the degradation caused by light, may be the disorder of the a-Si:H lattice, the behavior of complexes based on hydrogen, the behavior of impurities of other substances. In [6], the results of experiments with samples of very high purity are presented. Only at oxygen impurity concentrations above 1018 cm-3 was a weak correlation between the oxygen concentration and the degradation rate observed. Starting from this work, all subsequent researchers were mainly engaged in the study of the energy states of hydrogen and complexes based on it in amorphous silicon. Also, a significant number of articles were devoted to the study of the processes of defect formation. Only at oxygen impurity concentrations above 1018 cm-3 was a weak correlation between the oxygen concentration and the degradation rate observed. Starting from this work, all subsequent researchers were mainly engaged in the study of the energy states of hydrogen and complexes based on it in amorphous silicon. Also, a significant number of articles were devoted to the study of the processes of defect formation.

2 Results and discussion

The specificity of the degradation of solar cells based on CdTe is reduced to the following facts [7-12]:

- minimal differences in technology lead to serious differences in the characteristics of the samples: even in one industrial batch, you can find samples with a large spread in the parameters of the solar battery;
- the existence of exceptionally stable samples that are not subject to aging is noted, in addition, some samples even showed an increase in efficiency over time;
- the degradation rate of solar panels observed in the idle mode is higher than in the optimal load and short circuit modes;
- the rate of degradation increases with increasing temperature;
- with degradation, the defectiveness of the lattice increases.

In [13], the main measurements of the behavior of solar cells of the CdS–CdTe type are given, the algorithm of which is repeated in most works devoted to the problem under discussion. Two solar cell samples were exposed to temperatures of 60 and 120°C, respectively, while a series of measurements of the current-voltage characteristics were taken: immediately after production before exposure to temperature, after 1 hour in a hot cell, and after 723 hours in a hot cell. The measurement results are shown in Fig. 1.

Based on the measurements made, it is shown that the initial intersection of the dark and light characteristics, which disappears after annealing, is presumably the result of
metastable defects formed by copper. Similar measurements were carried out for a wider temperature range. Further, the results of processing experimental data are given, and the activation energies of the degradation process are calculated (Fig. 2.)

![Fig. 1. Current-voltage characteristics of solar cells based on CdTe-CdS, aged at different temperature conditions.](image1)

According to the results of measurements and calculations, the resulting activation energy, equal to 0.63 eV, is comparable to the activation energy of copper diffusion in CdTe (0.67 eV), on the basis of which a conclusion is made about the decisive role of copper diffusion in the degradation of a solar battery of this type.

The limiting lifetime of a solar cell is due to the degradation of the main barrier, however, there are a number of effects that disable the battery much earlier. The main source of degradation of solar cells based on a-Si:H is the Stebler–Vronsky effect, which, among other things, limits the maximum efficiency of batteries of this type. The degradation of solar cells based on CdTe - CdS is caused by the diffusion of copper from the top contact to the pn-junction, shunting the device. The exact mechanisms of this phenomenon are not yet known, including the behavior of some samples that demonstrate a very high resistance to degradation has not yet been explained.

![Fig. 2. The dependence of the percentage change in the efficiency of the solar battery as a function of time at different temperatures (left figure). The results of the calculation of the activation energy of the degradation process (right Figure).](image2)

It was shown in a number of works [14, 15] that the electron transport in polycrystalline films is mainly determined by potential barriers at intercrystallite boundaries. In this section, which is mainly devoted to the description of the possible degradation of polycrystalline SCs, the main attention is paid to the construction of a model that can assist developers in choosing the optimal technology, as well as in a priori assessment of the possible reliability of SCs at the design stage. It should be noted that quite a large amount of experimental material has been accumulated to date. However, existing models either
describe a rather narrow physical phenomenon or use a large number of semi-empirical parameters and functions that have no physical meaning. Therefore, this section is devoted to the creation of such a model and the corresponding calculations. Since the features of the electrical properties of CdTe films are determined by the influence of the crystallite interfaces, it is logical to assume that the features of degradation of solar cells based on this material are due to similar effects. The main effects associated with interfaces are: impurity segregation, charge carrier capture and recombination, interface charge, and charge-related potential variation. It is the change in the states at these boundaries and, as a consequence, the change in the height of the barriers that will mainly determine the change in the parameters of solar cells during their operation. In all polycrystalline materials, there is an effect of impurity segregation towards the crystallite interface, where atoms are trapped and become electrically neutral. This is reflected in the dependence of the electrical conductivity of the films on the degree of doping. Most of the impurity settles at the boundaries, while only a small part of the ligature introduced into the film goes to doping the crystallites. To describe such a system, models based on the consideration of intergranular barriers are most widely used. In these models, it was assumed that potential barriers are formed at the boundaries between crystallites, the height of which depends on the difference between the energies of the Fermi level at the boundary and in the bulk of the crystal. In this case, it was assumed that the Fermi level at the boundary lies lower than in the crystallite due to the presence of defect states, which serve as a diffusion sink for impurities during layer growth. Accordingly, these defect states serve as traps for the majority charge carriers. At the boundary, the carrier concentration is lower and, accordingly, there is a potential barrier whose height is equal to the difference between the Fermi levels at the boundary and in the bulk of the crystallite. The paper presents a model that assumes the homogeneity of the composition and structural properties of the material, in which, using typical average material parameters (trap concentrations and their position in the band gap, volume lifetimes, diffusion coefficients, etc.), and also taking into account the boundary conditions determined on the basis of from the geometry of the sample, it is possible to estimate the life cycle of the solar cell. The most important parameter for calculating the effect of the crystallite surface on the photoelectric properties of a semiconductor is the lifetime. When calculating the lifetime, we assume that the sample has finite dimensions and has the shape of a rectangular parallelepiped. When constructing the model, it was also assumed that all crystallites closely adjoin each other and have an arbitrary shape. However, for the calculation model, some hypothetical film with crystallites of the same size and equivalent spherical shape was used. The use of a hypothetical sphere made it possible to eliminate the problem of the uneven distribution of the field in the volume of the film and the charge along its boundaries. Therefore, it became possible to consider the film as homogeneous with parameters equal to some effective parameters depending on the parameters of the crystallites, for example, the lifetime. In polycrystalline samples, even within a single crystallite, the properties of the material vary greatly, and for the entire medium, only certain averaged properties can be used. Therefore, for semiconductor films on nonorienting substrates, one can speak of a certain characteristic dimension. For polycrystalline materials, this size is the average crystallite size. Within the framework of this model, the average crystallite size is the diameter of a model spherical crystallite.

It should be expected that as the size of individual crystallites decreases, the state of the sample will be increasingly affected by their surface. In this case, surface instability can lead to instability of material properties. Fig. 3 and 4 show the calculated dependences of the effective lifetime and effective diffusion length of a polycrystalline semiconductor film on the average crystallite size in it.
As can be seen from the graphs, a decrease in the average crystallite size leads to a decrease in the effective lifetime and, accordingly, in the effective diffusion length. This result is understandable, since in this case surface recombination plays a decisive role in the effective lifetime. The results obtained are in good agreement with the experimental and theoretical studies performed earlier at the Department of Semiconductor Electronics of the NRU MPEI [16-20], as well as literature data [21].

**Fig. 3.** Dependences of the effective lifetime on the average crystallite size at different surface recombination rates (τn=10−9 s, Dn = 12.5 cm2/s) [22].

![Dependences of the effective lifetime on the average crystallite size at different surface recombination rates](image)

**Fig. 4.** Dependences of the effective diffusion length on the average crystallite size at different surface recombination rates (τn=10−9 s, Dn = 12.5 cm2/s) [23].

![Dependences of the effective diffusion length on the average crystallite size at different surface recombination rates](image)

### Table 1. Average monthly insolation on a horizontal surface (kW/m2/day) [24].

<table>
<thead>
<tr>
<th>Latitude 48.3</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
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Data taken from the NASA website. Average production of 1 m2 of solar panels per month.

\[ P = E \times \eta \]
Fig. 5. Average daily output of a 25-year panel where \( E \) is the average monthly daily total amount of solar energy entering the horizontal surface; \( \eta \) - solar panel efficiency [24].

If solar panels are used for a sufficiently long time, then, taking into account degradation, the most stable panels will come out of amorphous silicon, and after 12 years of operation their output will be at the level of single-crystal panels, and after 25 years it will almost be equal to single-crystal ones. Fig.6 shows the power of solar panels during the day.

Fig. 6. Production of solar panels during the day.

The output of monocrystalline and polycrystalline solar cells is highly dependent on lighting, so they have low output in the morning and evening compared to amorphous silicon panels.

3 Conclusion

All modules without exception are subjected to the degradation process: mono- and polycrystalline; thin-film. In each case, however, it proceeds in a special way and with varying degrees of intensity.

The degradation of solar modules was analyzed, which shows that amorphous silicon panels degrade their properties more slowly than others.

The daily schedule of solar panels was also analyzed, which shows that modules from amorphous silicon have a much higher efficiency at low illumination. However, at maximum illumination, monocrystalline panels generate the most electricity.

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