UDC 620.179.162:621.383.51 DOI: https://doi.org/10.37434/tdnk2026.02.02

INFRARED TERMOGRAPHY OF SOLAR CELLS WITH A THERMOGENERATING LAYER BASED ON VARIZONE SEMICONDUCTORS

V.O. Storozhenko, O.V. Miahkyi, R.P. Orel, S.M. Meshkov

RTC «Thermocontrol» of Kharkiv National University of Radio Electronics. 14 Nauky Ave., 61166, Kharkiv, Ukraine.
E-mail: roman.orel@nure.ua

This study investigates the potential application of infrared thermography for integrity testing of modern solar cells with an additional thermogenerating layer based on varizone semiconductors (in particular, Si-Ge solid solutions). A comprehensive thermoelectric model of a multilayer structure has been developed and analysed, combining classical thermophysical equations with thermoelectric models of charge geion and transport in a varizone structure. Unlike standard approaches, the model accounts for the fact that the formation of a temperature signal from a defect is caused not only by a local change in thermophysical characteristics but also by a deterioration in heat dissipation due to the suppression (discontinuation) of charge carrier generation in the damaged zone. A classification of the main technological and operational defects is proposed, among which foreign inclusions (SiO_2 or Si impurities), thinning of the generating layer, and local thermal breakdown are identified. Through numerical modeling (using finite difference and finite element methods), quantitative parameters of the detectable signal in the form of a temperature contrast on the object's surface were established. It was shown that the magnitude of the temperature signal significantly depends on the type of defect: from fractions of a degree for local inclusions to tens of degrees in the case of thermal breakdown. The results show that the sensitivity of modern thermal imaging systems is sufficient for the reliable identification of the considered types of structural defects. It is noted that existing methods for suppressing interference can be applied to reduce the impact of interference on defect detection. Thus, the effectiveness of thermal inspection for the defect detection of solar panels with a thermogenerating layer is demonstrated. 12 Ref., 4 Fig.

Keywords: infrared thermography, solar panels, thermoelectric model, varizone semiconductors, generation defects

Introduction. Infrared termography (a passive method of thermal non-destructive testing) is widely used for detecting defects in solar cells (or panels) [1, 2]. The method is based on the use of a thermal imager to detect «hot spots», i.e., cracks, short circuits, faulty diodes, etc.

Recently, advanced solar panels have been developed that utilize additional thermogenerating layers based on varizone semiconductors made of samarium sulfide, zinc oxide, and n-type A2B6 group semiconductors, as well as in films of a varizone-type continuous silicon-germanium solid solution Si_xGe_{1-x} [3, 4]. This significantly increases efficiency, however, as the complexity of the generating element increases, so does the likelihood of defects–structural disruptions that reduce or completely disrupt power generation.

Defects can arise during production, as well as during the installation and operation of photovoltaic power plants, affecting the service life or limiting the performance of the panels; most of these defects are process-related. That is, defects caused by poor design and improper use of the panels. They may also be mechanical damages caused by external influences. The integrity of individual panel layers may also be compromised, caused either by internal stresses within the cell or by the inhomogeneous distribution of impurities in the silicon material during the manufacturing process. If a defect is present in a section of the photovoltaic panel, solar energy will not be converted into electrical energy.

In addition, defects may also arise in the additional thermoelectric layer, caused by the dispersion of Si and SiO_2 impurities in the Si_xGe_{1-x} solid solution, or by a change in layer thickness resulting from uneven solid solution precipitation [5, 6]. In such damaged areas, a temperature increase will occur, which can be detected using the thermography method, since, compared to intact panels, the temperature difference can reach tens of degrees Celsius, which can lead to thermal destruction, a «thermal» breakdown, and device failure.

Problem statement. The purpose of this work is to assess the possibilities of using infrared (thermal) flaw detection to detect the most characteristic defects in solar cells based on a multilayer varizone structure by constructing and analyzing its thermoelectric model.

Creation of the thermoelectric model. Here, a thermoelectric model is understood as a combination of a classical thermophysical model [7, 8] with a thermoelectric model describing the generation and propagation of charges in a varizone structure (Fig. 1) [2, 3].

The necessity of such a combination is explained by the fact that, in this case, the formation of a temperature contrast (a signal from the defect) on the surface of the specimen is caused not only by a local disturbance of the material's thermophysical properties but also by a deterioration in heat dissipation due to the suppression of charge carrier generation at the defect site.

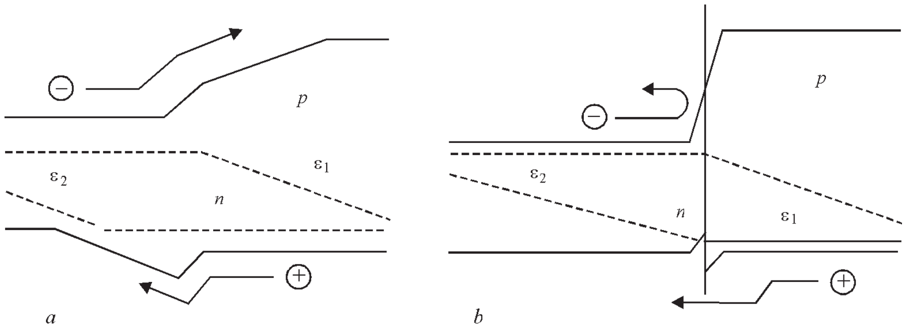

Fig. 1. Injection of charge carriers into a heterojunction under forward bias, taking into account the Fermi levels in the structure: *a* – in a smooth heterojunction in the presence of internal «pulling fields»; *b* – one-sided injection of holes in a sharp heterojunction

The total amount of energy in the specimen, which characterizes its temperature, is defined as the difference between the energy received from an external source and the energy expended on heat transfer to the environment and on the generation of thermo-EMF:

$$W_{ok}=W_q-(W_\alpha+W_\varepsilon),$$

where W_{ok} is the thermal energy of the specimen; W_q – energy supplied to the specimen from an external source; W_α – energy radiated by the body into the environment; W_ε – generation energy.

Accordingly, for a zone with a defect, generation will decrease or be absent altogether, and the value in parentheses will decrease, leading to a local increase in temperature in that region. This fact will manifest as a temperature contrast on the surface of the specimen, i.e., a signal from the defect.

The thermophysical part of the thermoelectric model (Fig. 2) graphically represents a multilayer plate with a local inhomogeneity (defect) in cylindrical coordinates [8, 9].

Its mathematical description is based on the non-stationary heat conduction equation [10]:

$$div(\lambda(\vec{r},T)\nabla T(\vec{r},t))+q(\vec{r},t)=c\rho\frac{\partial T(\vec{r},t)}{\partial t} \qquad (1)$$

where c – the specific heat capacity of the OK materials; $T(\vec{r},\,\tau)$ – the space-time function of temperature; λ – the thermal conductivity coefficient of the OK materials; q – heat flux density from an external source (heater); ρ – density of the specimen materials.

This equation is solved together with equations, which describe the heat energy consumption in a system with varizone semiconductors for EMF generation and charge transport [11]:

$$\varepsilon=-\frac{\sigma_n}{e_p}\oint\frac{\sigma_n}{\sigma_n+\sigma_p}\left(\frac{dE_g}{dx}\left(1-\frac{\theta_n}{\theta_p}\right)\frac{d\xi_{ng}}{dx}\right)dx, \qquad (2)$$

$$j_k=-\sigma_k\left(\frac{d}{dx}\tilde{\varphi}_k+\alpha_k\frac{d}{dx}T_k\right), \qquad (3)$$

where $\theta_k=\left(\frac{T_k-T_0}{T_0}\right)$ – the relative temperature difference of the k^{th} layer; E_g – the bandgap of the semiconductor; σ_k – electrical conductivity of the substance of the k^{th} element; φ_k – electrochemical potential of the substance of the k^{th} element; α_k – thermo-EMF coefficient; T_k – temperature of the k^{th} element; $\delta\xi=\xi_k-\xi_{k0}$ – the state function; $\xi_k=\xi_k\left(T_k,n_k\right)=T_k\ln\left(\frac{n_k}{N_k\left(T_k\right)}\right)$ – state function of the k^{th} layer, depending on temperature, concentration, and the number of free carriers; $\xi_{k0}=\xi_{k0}\left(T_0,n_{k0}\right)$ – state function of the boundary layer; n_{k0} and n_k – equilibrium and non-equilibrium concentrations of charge carriers; α_k – thermo-EMF coefficient.

It should be noted that the temperature T_k appears in equation (3) in two terms: directly in α_k (the gradient of temperature T) and implicitly in $\tilde{\varphi}_k\left(T\right)$. In the case of $T_k=\text{const}$, the term $\alpha_k=0$

The joint solution of equations (1), (2), and (3) was performed under mixed boundary conditions, which account for both heat transfer conditions at the interfaces and the generation and motion of charge carriers:

For $z=H$:

$$\frac{dE_g}{dx}=\frac{E_{gGe}-E_{gSi}}{H},$$

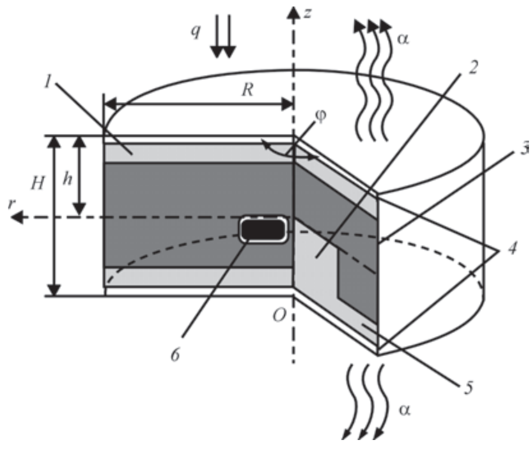

Fig. 2. Thermophysical part of the thermoelectric model of a panel with a graded-bandgap semiconductor: *1* – semiconductor 2, *2* – «thinning of the generating layer» defect, *3* – varizonal semiconductor (heterojunction), *4* – thermal contact, *5* – semiconductor 1, *6* – «foreign inclusion» defect

$$\lambda \frac{\partial T\left(\vec{r},t\right)}{\partial r} = \alpha\left(T\left(\vec{r},t\right) - T_{env}\right) - q\left(\vec{r},t\right).$$

For $z = 0$:

$$\frac{dE_g}{dx} = \frac{dE_g}{dz}, \quad -\lambda \frac{\partial T\left(\vec{r},t\right)}{\partial r} = -\alpha\left(T\left(\vec{r},t\right) - T_{env}\right).$$

For $z = h$:

$$\frac{dE_g}{dx} = 0,$$

$$-\lambda_1(\vec{r},T,t)\left(\frac{\partial T_1(\vec{r},t)}{\partial n}\right) = -\lambda_2(\vec{r},T,t)\left(\frac{\partial T_2(\vec{r},t)}{\partial n}\right),$$

where $T(\vec{r},\tau)$ – the space-time temperature function; λ – the thermal conductivity coefficient of the structural components; q – the heat flux density from an external source (heater); ρ – the density of the structural components; T_{env} – environment temperature.

Results of applying the thermoelectric model. The solution was obtained using the numerical (grid) finite difference method and the finite element method. Three most likely types of defects were considered (Fig. 1):

1. foreign inclusion caused by the dispersion of SiO_2 or Si;
2. thinning of the generating layer resulting from uneven condensation of the solid solution of a graded-bandgap semiconductor;
3. thermal breakdown, as an extreme case of thinning.

The purpose of the analysis was to estimate the magnitude of the useful signal from the defect, i.e., the temperature contrast (ΔT) on the monitored surface. A defect with a cross-sectional dimension $r_{def} = 5$ mm was chosen as an example. The shape of the temperature contrast over defects of the three types mentioned above was calculated and analysed. The results are shown in Fig. 3.

As can be seen from the graphs, for defects of the 1st and 2nd types, the gradient has a step-like shape well known in thermal non-destructive testing [8], whereas the 3rd type–thermal breakdown–leads to a temperature increase over a significant portion of the surface along *r*.

The effect of the defect's transverse dimension on the magnitude of the useful signal was also investigated (Fig. 4). As the results indicate, the magnitude of the useful signal varies for different defect types: it reaches a maximum value of tens of degrees for a breakdown, and approximately one degree for a local foreign inclusion.

Given that the sensitivity of the recording devices–thermal imagers–used in thermography is in the range of hundredths of a degree, it can be concluded that the application of the method under consideration to the task of detecting defects in panels with a thermogenerating layer is highly promising.

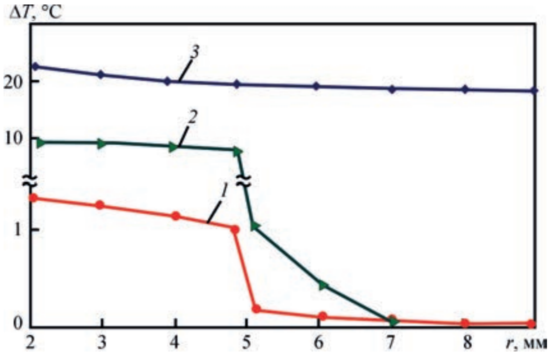

Fig. 3. Dependence of the temperature contrast above the defect on *r*: *1* – foreign inclusion defect (Si and SiO_2); *2* – thinning of the generating layer; *3* – «thermal breakdown» defect

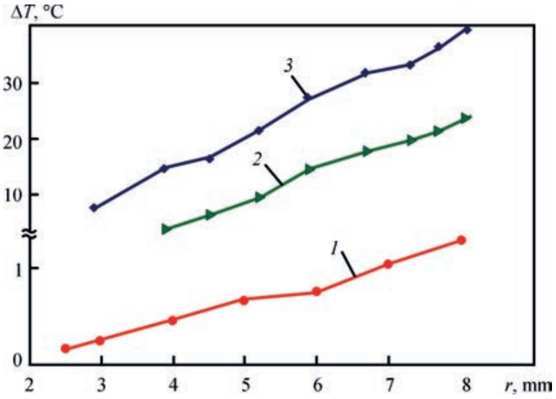

Fig. 4. Dependence of the temperature contrast above the defect on its transverse dimension for various types: *1* – foreign inclusion; *2* – thinning of the generating layer; *3* – «thermal breakdown»

Any limitations in sensitivity that may arise due to interference characteristic of thermal inspection can be overcome using known methods of interference suppression [12].

Conclusions

1. It has been shown that the use of infrared termography for defect detection in solar cells with a thermogenerating layer based on graded-bandgap semiconductors is fundamentally feasible, as it allows for the detection of various types of defects characteristic of this inspection object.

2. A thermoelectric model of the complex structure under consideration has been constructed and analysed, describing the mechanism for detecting a new type of defect–deterioration of heat dissipation due to disruptions in the generation and transport of charge carriers.

3. A quantitative estimate of the magnitude of the measured signal from various types of defects has been obtained, allowing for their subsequent classification during thermography.

References

1. Maldague, Xavier P.V. (2001) *Theory and practice of infrared technology for nondestructive testing*. New York: John Wiley & Sons, Inc.

2. Saidov, A., Leyderman, A.Y., Karshiev, A.B. (2019) Photothermovoltaic effect in a $Si_{1-x}Ge_x$ variband solid solution. *Applied Solar Energy*, 55(**1**), 12–17. DOI: https://doi.org/10.3103/S0003701X19010122
3. Saidov, A.S., Usmonov, S.N., Saparov, D.V. (2019) Structural studies of the epitaxial layer of a substitutional solid solution $(GaAs)_{1-x}(ZnSe)_x$ with nanocrystals. *Advances in Mater. Sci. and Engineering*, **2019**, 195, 3932195. DOI: https://doi.org/10.1155/2019/3932195
4. Saidov, A.S., Leyderman, A.Yu., Karshiev, A.B. (2016) The thermovoltaic effect in variband solid $Si_{1-x}Ge_x$ ($0 \le x \le 1$). *Technical Physics Letters*, 42(**7**), 725–728. DOI: https://doi.org/10.1134/S1063785016070270
5. Saidov, A.S., Leiderman, A.Yu. (2015) Electrophysical and optical properties of silicon produced by multiple remelting of metallurgical silicon by concentrated solar beams (Review). *Applied Solar Energy*, 51(**3**), 183–194. DOI: https://doi.org/10.3103/S0003701X1503010X
6. Saidov, A.S, Usmonov, S.N., Asatova, U.P. (2012) Growth of $Ge_{1-x}Sn_x$ solid solution films and study of their structural properties and some of their photoelectric properties. *Semiconductors*, **46,** 1088–1095. DOI: https://doi.org/10.1134/S1063782612080180
7. Saidov, A.S., Usmonov, S.N., Saidov, M.S. (2015) Liquid-phase epitaxy of the $(Si_2)_{1-x-y}(Ge_2)_x(GaAs)$ y substitutional solid solution ($0 \le x \le 0.91$, $0 \le y \le 0.94$) and their electrophysical properties. *Semiconductors*, 49(**4**), 547–550. DOI: https://doi.org/10.1134/S106378261504020X
8. Storozhenko, V., Myagkiy, A., Orel, R. (2016) Optimization of the procedure for thermal flaw detection in honeycomb structures by improving the accuracy of the interference function. *Eastern-European J. of Enterprise Technologies*, 5/5(**83**), 12–18. DOI: https://doi.org/10.15587/1729-4061.2016.79563
9. Aziz, A. (2009) A similarity solution for laminar thermal boundary layer over a flat plate with a convective surface boundary condition. *Commun. Nonlinear Sci. Numer. Simulat.*, **14**, 1064–1068. DOI: https://doi.org/10.1016/j.cnsns.2008.05.003
10. Pidkopai, V.M., Hanzha, A.M., Marchenko, N.A. (2014) Mathematical simulation and identification of actual heat losses caused by the damaged insulation of the pipelines of heating mains. *Visnyk NTU «KhPI»: Zbirnyk Naukovykh Prats. Seriша: Enerhetychni ta Teplotekhnichni Protsesy y Ustatkuvannia*, 12(**1055**), 83–89 [in Ukrainian]. https://repository.kpi.kharkov.ua/handle/KhPI-Press/8979
11. Miahkyi, O.V., Orel, R.P., Meshkov, S.M., Storozhenko, V.O. (2024) Ways to increase the EMF of semiconductor elements based on thermoelectric effects. *Radiotekhnika*, **216**, 103–107 [in Ukrainian]. DOI: https://doi.org/10.30837/rt.2024.1.216.10
12. Storozhenko, V.O., Miahkyi, O.V., Meshkov, S.M., Orel, R.P. (2025) Application of wavelet analysis and differential-integral graphical methods for thermogram processing in thermal nondestructive testing. *Technical Diagnostics and Nondestructive Testing*, **2**, 18–22. DOI: https://doi.org/10.37434/tdnk2025.02.03

ІНФРАЧЕРВОНА ДЕФЕКТОСКОПІЯ СОНЯЧНИХ БАТАРЕЙ З ТЕРМОГЕНЕРУЮЧИМ ШАРОМ НА БАЗІ ВАРІЗОННИХ НАПІВПРОВІДНИКІВ

В.О. Стороженко, О.В. Мягкий, Р.П. Орел, С.М. Мешков

НТЦ «Термоконтроль» Харківського національного університету радіоелектроніки. 61166, м. Харків, пр. Науки, 14.
E-mail: roman.orel@nure.ua

У роботі досліджено можливості застосування методу інфрачервоної дефектоскопії для контролю цілісності сучасних сонячних батарей з додатковим термогенеруючим шаром на основі варізонних напівпровідників (зокрема, твердих розчинів Si-Ge). Розроблено та проаналізовано комплексну теплоелектричну модель багатошарової структури, що поєднує класичні теплофізичні рівняння з термоелектричними моделями генерації та перенесення зарядів у варізонному середовищі. На відміну від стандартних підходів, у моделі враховано, що формування температурного сигналу від дефекту зумовлене не лише локальною зміною теплофізичних характеристик, а й погіршенням тепловідведення через припинення генерації носіїв заряду в зоні пошкодження. Запропоновано класифікацію основних технологічних та експлуатаційних дефектів, серед яких виділено сторонні включення (домішки SiO_2 або Si), потоншення генеруючого шару та локальний тепловий пробій. Шляхом чисельного моделювання (методами скінченних різниць і скінченних елементів) встановлено кількісні параметри корисного сигналу у вигляді температурного перепаду на поверхні об’єкта. Показано, що величина температурного сигналу істотно залежить від типу дефекту: від частки градуса для локальних включень до десятків градусів у разі теплового пробою. Встановлено, що чутливість сучасних тепловізійних систем є достатньою для надійної ідентифікації розглянутих типів порушень структури. Зазначено, що для зниження впливу перешкод на виявлення дефектів можуть застосовуватися існуючі методи їх придушення. Таким чином, показано ефективність застосування теплового контролю для дефектоскопії сонячних панелей з термогенеруючим шаром. Бібліогр. 12, рис. 4.

Ключові слова: інфрачервона дефектоскопія, сонячні панелі, теплоелектрична модель, варізонні напівпровідники, дефекти генерації

ORCID

V.O. Storozhenko – https://orcid.org/0000-0002-7609-2955, O.V. Miahkyi – https://orcid.org/0000-0002-0442-5570, R.P. Orel – https://orcid.org/0000-0002-3592-2393, S.M. Meshkov – https://orcid.org/0000-0003-3464-8318

КОНФЛІКТ ІНТЕРЕСІВ

Автори заявляють про відсутність конфлікту інтересів

АВТОР ДЛЯ ЛИСТУВАННЯ

R.P. Orel

RTC «Thermocontrol» of Kharkiv National University of Radio Electronics. 14 Nauky Ave., 61166, Kharkiv, Ukraine.

E-mail: roman.orel@nure.ua

РЕКОМЕНДОВАНЕ ЦИТУВАННЯ

V.O. Storozhenko, O.V. Miahkyi, R.P. Orel, S.M. Meshkov (2026) Infrared termography of solar cells with a thermogenerating layer based on varizone semiconductors. *Technical Diagnostics and Non-Destructive Testing*, **02**, 13–16.
DOI: https://doi.org/10.37434/tdnk2026.02.02

ГОЛОВНА СТОРІНКА ЖУРНАЛУ

https://patonpublishinghouse.com/ukr/journals/tdnk

Отримано 20.04.2026

Отримано у переглянутому вигляді 28.05.2026

Підписано до друку 10.06.2026

Оприлюднено 30.06.2026