РОЗДІЛ 1
ПЕРЕДУМОВИ ТА ОСОБЛИВОСТІ ВИКОРИСТАННЯ АКТИВНОГО УЛЬТРАЗВУКА

1.1. Ефекти впливу ультразвука на мікроелектронні структури та матеріали

[1–67, 67]:

In the literature, there are several models that describe the current–voltage $(I - V)$ characteristics of the solar cells (SCs). These models contain some parameters, which reflect the processes within the structures and are related to the main characteristics of the photovoltaic conversion. So single diode model with three parameters has been used to represent the SC static characteristic because of simplicity:

$$I = I_0 \left[\exp\left(-\frac{qV}{nkT}\right) - 1\right] - I_{ph}\,, \tag{1.1}$$

were

СПИСОК ВИКОРИСТАНИХ ДЖЕРЕЛ

1. Olikh, O.Ya. Relationship between the ideality factor and the iron concentration in silicon solar cells / O.Ya. Olikh // Superlattices Microstruct. — 2019. — Dec. — Vol. 136. — P. 106309.
2. Explanation of High Solar Cell Diode Factors by Nonuniform Contact Resistance / A. S. H. van der Heide, A. Schonecker, J. H. Bultman, W. C. Sinke // Progress in Photovoltaics: Research and Applications. — 2005. — Jan. — Vol. 13, no. 1. — Pp. 3–16.
3. Relationship Between the Diode Ideality Factor and the Carrier Recombination Resistance in Organic Solar Cells / L. Duan, H. Yi, C. Xu et al. // IEEE Journal of Photovoltaics. — 2018. — Nov. — Vol. 8, no. 6. — Pp. 1701–1709.
4. Electrical characterization of GaN Schottky barrier diode at cryogenic temperatures / Jiaxiang Chen, Min Zhu, Xing Lu, Xinbo Zou // Appl. Phys. Lett. — 2020. — Feb. — Vol. 116, no. 6. — P. 062102.
5. Dalapati, P. Analysis of the Temperature Dependence of Diode Ideality Factor in InGaN-Based UV-A Light-Emitting Diode / P. Dalapati, N.B. Manik, A.N. Basu // Semiconductors. — 2020. — Oct. — Vol. 54, no. 10. — Pp. 1284–1289.
6. Identifying Dominant Recombination Mechanisms in Perovskite Solar Cells by Measuring the Transient Ideality Factor / Phil Calado, Dan Burkitt, Jizhong Yao et al. // Phys. Rev. Applied. — 2019. — Apr. — Vol. 11. — P. 044005.
7. Machine learning and the physical sciences / Giuseppe Carleo, Ignacio Cirac, Kyle Cranmer et al. // Rev. Mod. Phys. — 2019. — Dec. — Vol. 91. — P. 045002.
8. Ju, Shenghong. Designing thermal functional materials by coupling thermal transport calculations and machine learning / Shenghong Ju, Shuntaro Shimizu, Junichiro Shiomi // J. Appl. Phys. — 2020. — Oct. — Vol. 128, no. 16. — P. 161102.
9. Rodrigues, Sandy. Machine learning PV system performance analyser / Sandy Rodrigues, Helena Geirinhas Ramos, Fernando Morgado-Dias // Prog. Photovoltaics Res. Appl. — 2018. — Aug. — Vol. 26, no. 8. — Pp. 675–687.

10. Pathways for solar photovoltaics / Joel Jean, Patrick R. Brown, Robert L. Jaffe et al. // Energy Environ Sci. — 2015. — Jul. — Vol. 8, no. 4. — Pp. 1200–1219.
11. A review of photovoltaic performance of organic/inorganic solar cells for future renewable and sustainable energy technologies / J. Ajayan, D. Nirmal, P. Mohankumar et al. // Superlattices Microstruct. — 2020. — Jul. — Vol. 143. — P. 106549.
12. Schmidt, Jan. Effect of Dissociation of Iron–Boron Pairs in Crystalline Silicon on Solar Cell Properties / Jan Schmidt // Progress in Photovoltaics: Research and Applications. — 2005. — Jun. — Vol. 13, no. 4. — Pp. 325–331.
13. Iron related solar cell instability: Imaging analysis and impact on cell performance / M.C. Schubert, M. Padilla, B. Michl et al. // Sol. Energy Mater. Sol. Cells. — 2015. — Jul. — Vol. 138. — Pp. 96–101.
14. Geerligs, L. J. Dynamics of light-induced FeB pair dissociation in crystalline silicon / L. J. Geerligs, Daniel Macdonald // Appl. Phys. Lett. — 2004. — Nov. — Vol. 85, no. 22. — Pp. 5227–5229.
15. Zoth, G. A fast, preperetion-free method to detect iron in silicon / G. Zoth, W. Bergholz // J. Appl. Phys. — 1990. — Jun. — Vol. 67, no. 11. — Pp. 6764–6771.
16. The effect of oxide precipitates on minority carrier lifetime in p–type silicon / J. D. Murphy, K. Bothe, M. Olmo et al. // J. Appl. Phys. — 2011. — Sep. — Vol. 110, no. 5. — P. 053713.
17. Wijaranakula, W. The Reaction Kinetics of Iron–Boron Pair Formation and Dissociation in P–Type Silicon / W. Wijaranakula // J. Electrochem. Soc. — 1993. — Jan. — Vol. 140, no. 1. — Pp. 275–281.
18. Iron-boron pairing kinetics in illuminated p-type and in boron/phosphorus co-doped n-type silicon / Christian Möller, Til Bartel, Fabien Gibaja, Kevin Lauer // J. Appl. Phys. — 2014. — Jul. — Vol. 116, no. 2. — P. 024503.
19. Dissociation and Formation Kinetics of Iron–Boron Pairs in Silicon after Phosphorus Implantation Gettering / Nabil Khelifati, Hannu S. Laine, Ville Vähänissi et al. // Phys Status Solidi A. — 2019. — Sep. — Vol. 216, no. 17. — P. 1900253.

20. Ostapenko, Sergei S. Ultrasound Stimulated Defect Reactions in Semiconductors / Sergei S. Ostapenko, Nadejda E. Korsunskaya, Moissei K. Sheinkman // Defect Interaction and Clustering in Semiconductors. — Vol. 85 of Solid State Phenomena. — Trans Tech Publications Ltd, 2001. — 12. — Pp. 317–336.
21. Savkina, Rada K. Recent Progress in Semiconductor Properties Engineering by Ultrasonication / Rada K. Savkina // Recent Patents on Electrical & Electronic Engineering. — 2013. — Vol. 6, no. 3. — Pp. 157–172.
22. Acousto–defect interaction in irradiated and non–irradiated silicon n^{+}–p structure / O. Ya. Olikh, A. M. Gorb, R. G. Chupryna, O. V. Pristay-Fenenkov // J. Appl. Phys. — 2018. — Apr. — Vol. 123, no. 16. — P. 161573.
23. Davletova, A. Open-circuit voltage decay transient in dislocation-engineered Si p–n junction / A. Davletova, S. Zh. Karazhanov // Journal of Physics D: Applied Physics. — 2008. — Aug. — Vol. 41, no. 16. — P. 165107.
24. Olikh, Y. Mechanisms of Two-Stage Conductivity Relaxation in CdTe:Cl with Ultrasound / Y. Olikh, M. Tymochko, O. Olikh // J. Electron. Mater. — 2020. — Aug. — Vol. 49, no. 8. — P. 4524–453.
25. Olikh, Oleg. Reversible influence of ultrasound on $\gamma-$irradiated Mo/n-Si Schottky barrier structure / Oleg Olikh // Ultrasonics. — 2015. — Feb. — Vol. 56. — Pp. 545–550.
26. Olikh, O. Ya. Ultrasound influence on I–V–T characteristics of silicon Schottky barrier structure / O. Ya. Olikh, K. V. Voytenko, R. M. Burbelo // J. Appl. Phys. — 2015. — Jan. — Vol. 117, no. 4. — P. 044505.
27. Sukach, A.V. Ultrasonic treatment–induced modification of the electrical properties of InAs p–n junctions / A.V. Sukach, V.V. Teterkin // Tech. Phys. Lett. — 2009. — June. — Vol. 35, no. 6. — Pp. 514–517.
28. Influence of in situ ultrasound treatment during ion implantation on amorphization and junction formation in silicon / D. Krüger, B. Romanyuk, V. Melnik et al. // J. Vac. Sci. Technol. B. — 2002. — Jul. — Vol. 20, no. 4. — Pp. 1448–1451.
29. Modification of the Si amorphization process by in situ ultrasonic treatment during ion implantation / B. Romanyuk, V. Melnik, Ya. Olikh et al. // Semicond. Sci. Technol. — 2001. — May. — Vol. 16, no. 5. — Pp. 397–401.

30. Kalem, S. Effect of Light Exposure and Ultrasound on the Formation of Porous Silicon / S. Kalem, O. Yavuzcetin, C. Altineller // Journal of Porous Materials. — 2000. — Jan. — Vol. 7, no. 1. — Pp. 381–383.
31. Ultrasonic–assisted mist chemical vapor deposition of II–oxide and related oxide compounds / Shizuo Fujita, Kentaro Kaneko, Takumi Ikenoue et al. // Phys. Status Solidi C. — 2014. — Jul. — Vol. 11, no. 7–8. — Pp. 1225–1228.
32. Impact of Iron Precipitation on Phosphorus-Implanted Silicon Solar Cells / Hannu S. Laine, Ville Vähänissi, Ashley E. Morishige et al. // IEEE Journal of Photovoltaics. — 2016. — Sep. — Vol. 6, no. 5. — Pp. 1094–1102.
33. Impact of phosphorus gettering parameters and initial iron level on silicon solar cell properties / Ville Vähänissi, Antti Haarahiltunen, Heli Talvitie et al. // Progress in Photovoltaics: Research and Applications. — 2013. — Aug. — Vol. 21, no. 5. — Pp. 1127–1135.
34. Evolution of iron-containing defects during processing of Si solar cells / Teimuraz Mchedlidze, Christian Möller, Kevin Lauer, Jörg Weber // J. Appl. Phys. — 2014. — Dec. — Vol. 116, no. 24. — P. 245701.
35. Ostapenko, S. S. Ultrasound stimulated dissociation of Fe–B pairs in silicon / S. S. Ostapenko, R. E. Bell // J. Appl. Phys. — 1995. — May. — Vol. 77, no. 10. — Pp. 5458–5460.
36. Increasing short minority carrier diffusion lengths in solar–grade polycrystalline silicon by ultrasound treatment / S. S. Ostapenko, L. Jastrzebski, J. Lagowski, B. Sopori // Appl. Phys. Lett. — 1994. — Sep. — Vol. 65, no. 12. — Pp. 1555–1557.
37. Ostapenko, S. S. Change of minority carrier diffusion length in polycrystalline silicon by ultrasound treatment / S. S. Ostapenko, L. Jastrzebski, B. Sopori // Semicond. Sci. Technol. — 1995. — Nov. — Vol. 10, no. 11. — Pp. 1494–1500.
38. Rajkanan, K. Absorption coefficient of silicon for solar cell calculations / K. Rajkanan, R. Singh, J. Shewchun // Solid-State Electron. — 1979. — Sep. — Vol. 22, no. 9. — Pp. 793–795.
39. Green, Martin A. Optical properties of intrinsic silicon at 300 K / Martin A. Green, Mark J. Keevers // Progress in Photovoltaics: Research and Applications. — 1995. — Vol. 3, no. 3. — Pp. 189–192.

40. Silicon solar cells with antireflecting and protective coatings based on diamond-like carbon and silicon carbide films / N.I. Klyui, V.P. Kostylyov, A.G. Rozhin et al. // Opto-Electr. Rev. — 2000. — Vol. 8, no. 4. — Pp. 402–405.
41. Stokes, E. D. Diffusion lengths in solar cells from short-circuit current measurements / E. D. Stokes, T. L. Chu // Appl. Phys. Lett. — 1977. — Apr. — Vol. 30, no. 8. — Pp. 425–426.
42. Accurate measurement of the formation rate of iron–boron pairs in silicon / J. Tan, D. Macdonald, F. Rougieux, A. Cuevas // Semicond Sci. Technol. — 2011. — Mar. — Vol. 26, no. 5. — P. 055019.
43. Fast and Slow Stages of Lifetime Degradation by Boron–Oxygen Centers in Crystalline Silicon / Jan Schmidt, Karsten Bothe, Vladimir V. Voronkov, Robert Falster // physica status solidi (b). — 2020. — Jan. — Vol. 257, no. 1. — P. 1900167.
44. Iron detection in the part per quadrillion range in silicon using surface photovoltage and photodissociation of iron-boron pairs / J. Lagowski, P. Edelman, A. M. Kontkiewicz et al. // Appl. Phys. Lett. — 1993. — Nov. — Vol. 63, no. 22. — Pp. 3043–3045.
45. Aziz, Michael J. Stress effects on defects and dopant diffusion in Si / Michael J. Aziz // Mater. Sci. Semicond. Process. — 2001. — Oct. — Vol. 4, no. 5. — Pp. 397–403.
46. Weber, E.R. Transition metals in silicon / E.R. Weber // Appl. Phys. A. — 1983. — Jan. — Vol. 30, no. 1. — Pp. 1–22.
47. Pressure and stress effects on the diffusion of B and Sb in Si and Si-Ge alloys / Michael J. Aziz, Yuechao Zhao, Hans-J. Gossmann et al. // Phys. Rev. B. — 2006. — Feb. — Vol. 73. — P. 054101.
48. Influence of dislocation strain fields on the diffusion of interstitial iron impurities in silicon / Benedikt Ziebarth, Matous Mrovec, Christian Elsässer, Peter Gumbsch // Phys. Rev. B. — 2015. — Sep. — Vol. 92. — P. 115309.
49. Mirzade, Fikret. Elastic wave propagation in a solid layer with laser-induced point defects / Fikret Mirzade // J. Appl. Phys. — 2011. — Sep. — Vol. 110, no. 6. — P. 064906.
50. Mirzade, F. Kh. A model for the propagation of strain solitary waves in solids

with relaxing atomic defects / F. Kh. Mirzade // J. Appl. Phys. — 2008. — Feb. — Vol. 103, no. 4. — P. 044904.

51. Peleshchak, R.M. Formation of Periodic Structures under the Influence of an Acousti Wave in Semiconductors with a Two-Component Defect Subsystem / R.M. Peleshchak, O.V. Kuzyk, O.O. Dan'kiv // Ukr. J. Phys. — 2016. — Aug. — Vol. 61, no. 8. — Pp. 741–746.
52. Pavlovich, V. N. Enhanced Diffusion of Impurities and Defects in Crystals in Conditions of Ultrasonic and Radiative Excitation of the Crystal Lattice / V. N. Pavlovich // Phys. Status Solidi B. — 1993. — Nov. — Vol. 180, no. 1. — Pp. 97–105.
53. Krevchik, V. D. Influence of ultrasound on ionic diffusion process in semiconductors / V. D. Krevchik, R. A. Muminov, A. Ya. Yafasov // Phys. Status Solidi A. — 1981. — Feb. — Vol. 63, no. 2. — Pp. K159–K162.
54. Yost, W. T. Acoustic-radiation stress in solids. II. Experiment / W. T. Yost, John H. Cantrell // Phys. Rev. B. — 1984. — Sep. — Vol. 30. — Pp. 3221–3227.
55. Chen, Ming-Jer. Effect of uniaxial strain on anisotropic diffusion in silicon / Ming-Jer Chen, Yi-Ming Sheu // Appl. Phys. Lett. — 2006. — Oct. — Vol. 89, no. 16. — P. 161908.
56. Philip, Jacob. Temperature variation of some combinations of third–order elastic constants of silicon between 300 and 3 °K / Jacob Philip, M. A. Breazeale // J. Appl. Phys. — 1981. — May. — Vol. 52, no. 5. — Pp. 3383–3387.
57. Механизм изменения подвижности носителей заряда при ультразвуковой обработке полупроводниковых твердых растворов / П.И. Баранский, А.Е. Беляев, С.М. Комиренко, Н.В. Шевченко // ФТТ. — 1990. — Jul. — Т. 32, № 7. — С. 2159–2161.
58. Korotchenkov, O.A. Long-wavelength acoustic-mode-enhanced electron emission from Se and Te donors in silicon / O.A. Korotchenkov, H.G. Grimmeiss // Phys. Rev. B. — 1995. — Nov. — Vol. 52, no. 20. — Pp. 14598–14606.
59. Olikh, O. Ya. Ultrasound-Stimulated Increase in the Electron Diffusion Length in p–Si Crystals / O. Ya. Olikh, I. V. Ostrovskii // Phys. Solid State. — 2002. — Jul. — Vol. 44, no. 7. — Pp. 1249–1253.
60. Simulation and characterization of planar high-efficiency back contact silicon

solar cells / A.V. Sachenko, V.P. Kostylyov, R.M. Korkishko et al. // Semiconductor Physics, Quantum Electronics & Optoelectronics. — 2021. — Vol. 24, no. 3. — Pp. 319–327.

61. Modeling of the key characteristics of high-efficiency silicon solar cells with planar surfaces / Anatoliy Sachenko, Vitaliy Kostylyov, Viktor Vlasiuk et al. // 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC). — 2021. — Pp. 0590–0595.
62. Analysis of the recombination mechanisms in silicon solar cells with the record 26.6% photoconversion efficiency / Anatoliy Sachenko, Vitaliy Kostylyov, Viktor Vlasiuk et al. // 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC). — 2021. — Pp. 0532–0539.
63. Characterization and Optimization of Highly Efficient Silicon-Based Textured Solar Cells: Theory and Experiment / A.V. Sachenko, V. P. Kostylyov, V. M. Vlasiuk et al. // 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC). — 2021. — Pp. 0544–0550.
64. Olikh, O. Deep-learning approach to the iron concentration evaluation in silicon solar cell / O. Olikh, O. Lozitsky, O. Zavhorodnii // 9 European conference on renewable energy systems. Proceedings. Istanbul, Turkey. / Ed. by Erol Kurt. — Istanbul: 2021. — P. 22.
65. Estimation of Iron Concenration in Silicon Solar Cell by Kinetics of Light-Induced Change in Short-Circuit Current / O. Olikh, V. Kostylyov, V. Vlasiuk, R. Korkishko // II International Advanced Study Conference Condensed Matter and Low Temperature Physics CM&LTP 2021. Book of Abstracts. Kharkiv, Ukraine. — Kharkiv: 2021. — P. 191.
66. Acoustically Induced Acceleration of Iron Migration in Silicon Solar Cells / O. Olikh, V. Kostylyov, V. Vlasiuk, R. Korkishko // Ultrasonics 2021, 5th International Caparica Conference on Ultrasonic based Applications: from analysis to synthesis. Proceedings Book. Caparica, Portugal. — Caparica: 2021. — P. 109.
67. Iron-impurities-activated kinetics of the light-induced processes in silicon solar cells / V. Vlasiuk, R. Korkishko, V. Kostylyov, O. Olikh // International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME). — Mauritius: 2021. — Pp. 27–31.