Список использованных источников

1. Bauer G.H., Würfel P. Quantum Solar Energy Conversion and Application to Organic Solar Cells / G.H. Bauer, P. Würfel // Organic Photovoltaics / C.J. Brabec, V. Dyakonov, J. Parisi, N.S. Sariciftci (eds). — Berlin, Heidelberg : Springer, 2003. — Vol. 60 : Springer Series in Materials Science. — P. 85–108. — DOI: 10.1007/978-3-662-05187-0_4.

2. Zhang X., Zheng D., Xing S., Wang H., Huang J., Yu J. Precisely control the morphology and crystallization of temperature-dependent aggregation bulk heterojunction by using co-solvent system for optimized light intensity distribution and its effect on thick active layer polymer solar cells // Solar Energy. — 2017. — Vol. 147. — P. 106–112.

3. Brabec C.J., Shaheen S.E., Fromherz T., Padinger F., Hummelen J.C., Dhanabalan A., Janssen R.A.J., Sariciftci N.S. Organic photovoltaic devices produced from conjugated polymer/methanofullerene bulk heterojunctions // Synthetic Metals. — 2001. — Vol. 121, Issues 1–3. — P. 1517–1520.

4. Moulé A.J., Bonekamp J.B., Meerholz K. The effect of active layer thickness and composition on the performance of bulk-heterojunction solar cells // J. Appl. Phys. — 2006. — Vol. 100. — P. 094503.

Igbokwe E.E., Asiegbu A.D., Nnanna L.A. The optimization of P3HT:PCBM thin film thickness for organic solar cells // Journal of Chemical Society of Nigeria. — 2023. — Vol. 48, No. 6.

5. Zhao D.W., Tan S.T., Ke L., Liu P., Kyaw A.K.K., Sun X.W., Lo G.Q., Kwong D.L. Optimization of an inverted organic solar cell // Solar Energy Materials and Solar Cells. — 2010. — Vol. 94, Issue 6. — P. 985–991.

6. Brown P.J., Thomas D.S., Köhler A., Wilson J.S., Kim J.-S., Ramsdale C.M., Sirringhaus H., Friend R.H. Effect of interchain interactions on the absorption and emission of poly(3-hexylthiophene) // Phys. Rev. B. — 2003. — Vol. 67. — P. 064203.

7. Ramani R., Alam S. A comparative study on the influence of alkyl thiols on the structural transformations in P3HT/PCBM and P3OT/PCBM blends // Polymer. — 2013. — Vol. 54, Issue 25. — P. 6785–6792.

UDC 53.09

SIMULATION AND COMPARATIVE ANALYSIS OF HIGH-EFFICIENCY HIT SOLAR CELLS BASED ON P-TYPE AND N-TYPE CRYSTALLINE SILICON SUBSTRATES

Aimaganbetov K.P., Institute of Physics and Technology, Satbayev University, Almaty, Kazakhstan

Kishkenebayev M.P., Institute of Energy and Mechanical Engineering, Satbayev University, Almaty, Kazakhstan

Tokmoldin N.S., Institute of Physics and Astronomy, University of Potsdam, Potsdam, Germany

Yerezhep D.E., Institute of Energy and Mechanical Engineering, Satbayev University, Almaty, Kazakhstan

Abstract

This paper presents numerical simulation and comparative analysis of solar cells with a heterojunction on thin amorphous silicon (HIT) based on crystalline silicon substrates with p- and n-type conductivity. The study focuses on the influence of substrate thickness, dopant concentration, interface quality, and layer architecture on the key photovoltaic parameters: open-circuit voltage (Voc), short-circuit current density (Jsc), fill factor (FF), and power conversion efficiency (η). Simulations were performed using the AFORS-HET software, which accounts for carrier transport and recombination processes. The results demonstrate that n-type silicon-based devices exhibit higher Voc and FF values, reduced sensitivity to light-induced (LID) and potential-induced degradation (PID), and deliver 1.5–2% higher efficiency compared to p-type devices under identical conditions. Optimization of the substrate thickness (100–200 μm) and doping concentration (10^{15}–10^{16} cm^{-3}) enables achieving conversion efficiencies above 25%. Literature reports further confirm the potential of n-type silicon, where record efficiencies exceeding 26% have already been achieved. Therefore, the implementation of n-type silicon in HIT architectures represents the most promising pathway for the development of high-efficiency and stable photovoltaic devices.

Keywords: HIT solar cells; crystalline silicon; p-type; n-type; simulation; AFORS-HET.

Introduction

The efficiency of silicon solar cells largely depends on the materials, device design, and fabrication process. Crystalline silicon (c-Si), which can be either p-type or n-type, serves as the foundation of most solar cells. Despite the technological maturity of silicon-based photovoltaics, research efforts continue to focus on improving efficiency.

Heterojunction solar cells with an intrinsic thin amorphous silicon layer (HIT) are among the most promising technologies for improving the conversion of solar energy into electricity [1]. Laboratory efficiencies above 25% have been achieved [2], making them competitive with conventional p–n junction cells. A key factor in HIT performance is the choice of silicon substrate. While p-type silicon remains widely used due to its availability and mature processing, it suffers from light-induced degradation (LID) and potential-induced degradation (PID), which reduce long-term stability. By contrast, n-type silicon offers higher resistance to LID and PID, as well as better thermal stability and higher potential efficiency. This makes a comparative study of p- and n-type HIT devices critical for optimizing next-generation photovoltaic modules.

Recent studies have highlighted the importance of wafer thickness, doping profiles, layer architecture, and contact materials in achieving both efficiency and cost-effectiveness. Sai et al. [3] demonstrated that ultrathin wafers (30–50 μm) with light-trapping schemes retain strong absorption and high short-circuit currents, with Voc exceeding 0.76 V and stable fill factors (0.85–0.87). Maximum calculated efficiencies of 28.4% were reached at ~100 μm thickness, while fabricated cells on 59 μm wafers achieved 21.0%, comparable to 244 μm wafers. Numerical simulations [4] further showed that optimal a-Si:H thickness (12–18 nm) and doping concentrations (10^{19} cm⁻³ for a-Si:H, 10^{17} cm⁻³ for c-Si) yield efficiencies of 22–24%. The choice of transparent conductive oxide, especially indium tin oxide (ITO), was confirmed as critical due to its high conductivity and transparencyAdditional numerical modeling data were presented in [5], where the optimal thickness of the a-Si:H layer was found to be 10–20 nm and that of the c-Si substrate 100–200 μm, enabling high light absorption and reduced recombination losses. The calculated efficiency reached 25–28% with doping concentrations in the range of 10^{18}–10^{20} cm^{-3}, the use of low-temperature processes, and proper contact selection. The open-circuit voltage (Voc) reached 0.7–0.75 V, the current density was as high as 40–50 mA/cm^2, and the bulk recombination rate was reduced to 10^{-7} cm^3/s due to effective passivation.

Numerous studies have compared the performance of p-type and n-type silicon solar cells, focusing on efficiency, stability, and manufacturing challenges. Analyses [1, 6] show that n-type devices consistently achieve higher efficiencies and superior long-term stability, owing to lower surface recombination, reduced sensitivity to light-induced (LID) and potential-induced degradation (PID), and greater resilience to impurity contamination.

A techno-economic reassessment [1] indicated that ultrathin wafers (≈50 μm), combined with advanced designs, could reduce capital costs by up to 48%, module costs by 28%, and LCOE by 24% compared to standard wafers, supporting global climate targets. However, mechanical fragility of thin wafers remains a key challenge, requiring innovations such as contactless handling and reinforced interconnection schemes.

Overall, HIT technology strengthens these advantages, making n-type silicon particularly promising for the development of high-efficiency, stable photovoltaic devices.

Experimental and simulation studies confirm the high potential of HIT technology on thin silicon substrates. The combined optimization of thickness, structure, and materials enables achieving high efficiency while significantly reducing material consumption and costs, making this technology highly promising for large-scale deployment.

In this paper, a detailed comparative analysis of p-type and n-type HIT solar cells is presented, focusing on their efficiency and performance under various conditions based on numerical simulation results.

Methodology

The modeling of heterostructure solar cells was carried out using the AFORS-HET software, which is specifically designed for the numerical simulation of thin-film and heterojunction photovoltaic devices. The program accounts for spatially resolved physical processes, including drift-diffusion transport, recombination, and built-in electric fields.

The basic structure of the solar cell under investigation is shown in Figure 1, and the corresponding layer parameters are summarized in Tables 1 and 2.

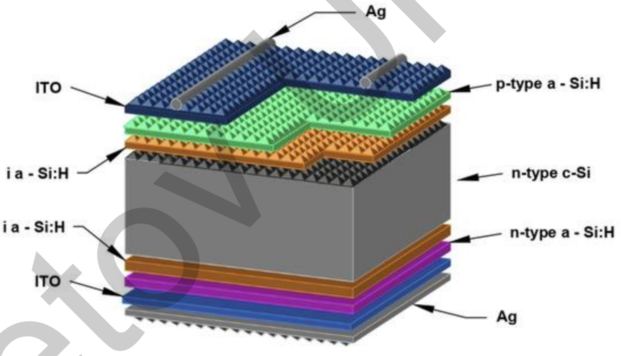

Figure 1. Schematic view of the HJT solar cell for n – type [7]

Table 1 – Substrate parameters

Parameter	p-type substrate	n-type substrate
Doping concentration	~$1×10^{15}$ cm^{-3}, $1×10^{16}$ cm^{-3}, $5×10^{16}$ cm^{-3} (boron)	~$1×10^{15}$ cm^{-3}, $1×10^{16}$ cm^{-3}, $5×10^{16}$ cm^{-3} (phosphorus)
Optimal thickness	100 – 150 – 200 μm	100 – 150 – 200 μm
Electron mobility	~450 $cm^2/V·s$	~1350 $cm^2/V·s$
Hole mobility	~150 $cm^2/V·s$	~450 $cm^2/V·s$

Table 2 – Layer parameters

Layer	Thickness (nm)	Doping type	Concentration (cm^{-3})
ITO	70–90	—	—
a-Si(p+/n+)	10	p+ / n+	~$1×10^{19}$
a-Si(i)	5–10	—	~$1×10^{15}$
c-Si(p/n)	100–250 μm	p или n	~$1×10^{16}$ / ~$5×10^{15}$
a-Si(i) (rear)	5–10	—	~$1×10^{15}$
a-Si(n+/p+) (rear)	10	n+ / p+	~$1×10^{19}$
Ag ((rear contact)	—	—	—

Simulation Results and Discussion

The simulation of solar cells based on different substrate types—p-type and n-type silicon—revealed (Figure 2) consistent differences in photovoltaic characteristics (Jsc, Voc, FF, and η) as a function of substrate thickness. For n-type silicon, a slightly higher short-circuit current density (Jsc) was observed compared to p-type at identical thicknesses, with the effect being most pronounced at around 200 µm. This improvement is attributed to the higher carrier mobility and reduced susceptibility to bulk recombination. The open-circuit voltage (Voc) also exhibited an advantage for n-type devices, consistently exceeding the values obtained for p-type, due to superior substrate properties and a lower recombination rate. A similar trend was observed for the fill factor (FF), which was higher in n-type devices, indicating reduced resistive losses and more favorable charge transport conditions. As a result, the combined influence of these factors leads to an increase in the power conversion efficiency (η) of n-type silicon solar cells by approximately 2% (absolute) compared to p-type cells of the same thickness, confirming the strong potential of n-type silicon for achieving high-efficiency photovoltaic devices.

The analysis of the graphs illustrating the effect of dopant concentration on the photovoltaic parameters of p-type and n-type solar cells (J_{sc}, V_{oc}, FF, and η) (Figure 3) showed that with increasing doping levels, the characteristics improve for both substrates; however, n-type devices consistently demonstrate higher values. The short-circuit current density (J_{sc}) increases with higher dopant concentrations due to improved transport properties and reduced material resistance, with the increase being more pronounced for n-type cells because of the higher electron mobility. The open-circuit voltage (V_{oc}) also rises with increasing doping concentration, although in the case of p-type the effect is weaker; moreover, at excessively high doping levels (around 5×10^{16} cm^{-3}), V_{oc} may decrease due to enhanced boundary recombination.

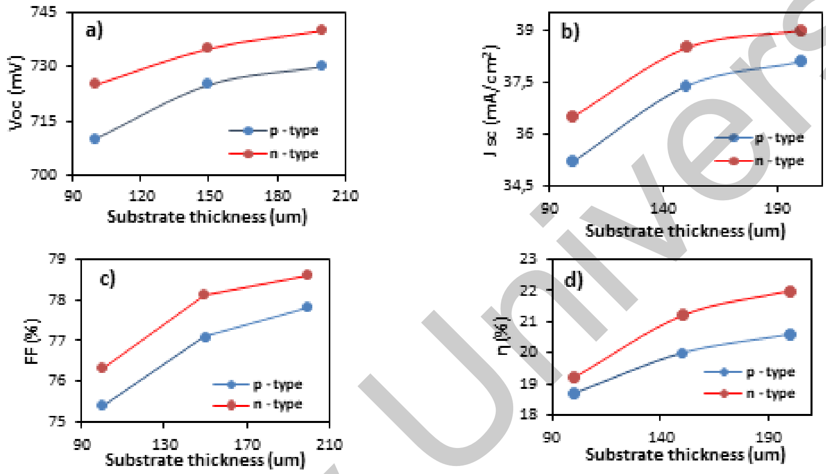

Figure 2. Simulation of solar cells with different substrate types — p-type and n-type silicon: (a) Voc, (b) Jsc, (c) FF, and (d) η as a function of substrate thickness.

The fill factor (FF) improves as dopant concentration increases, owing to reduced ohmic losses and enhanced conductivity, with n-type devices again showing superiority across all doping levels. Overall, the power conversion efficiency (η) increases with dopant concentration for both substrate types [13–15], but n-type achieves higher values. This advantage is attributed to the higher electron mobility, which reduces the probability of recombination, and the greater tolerance of n-type structures to interface defects at the a-Si/c-Si junction. By contrast, holes in p-type silicon have lower mobility, which increases the likelihood of recombination at the interface, leading to somewhat lower η values.

The density of states at the a-Si:H/c-Si interface plays a critical role in HIT cell efficiency. The optimal thickness of the intrinsic amorphous silicon layer (a-Si(i)) depends on substrate conductivity: 5–10 nm for n-type and about 5 nm for p-type, as thicker layers hinder hole transport. Excessive a-Si(i) thickness increases carrier transport barriers, especially for p-type substrates. The thickness of the emitter layer (a-Si(p^+) or a-Si(n^+)) also strongly affects device performance: it determines short-wavelength (300–400 nm) light absorption and carrier extraction efficiency. However, excessive emitter thickness can enhance recombination losses at the a-Si/c-Si interface [9–15].

Table 3 – Comparative overview of experimental and numerical data on the efficiency of HIT structures

Study work	Substrate type	η (%)	V_{oc} (mV)	J_{sc} (mA/cm²)	FF (%)
Yoshikawa et al., [DOI: 10.1038/nenergy.2017.3]	n-type	26.6	750	42.1	83.3
Masuko Keiichiro, et al. [DOI: 10.1109/JPHOTOV.2014.2352151]	n-type	25.6	740	41.8	83.0
Eiji Kobayashi et al., [DOI: 10.1063/1.4922196]	n-type	22.5	735	38.5	79.0
H. S. Kim et al., [DOI: 10.1016/j.solmat.2018.05.015]	p- type	17.9	639	-	74.6
C.Y. Wei et al., [DOI: 10.3390/ma6115440]	p- type	20.83	-	39.3	-
M. A. Green et al., [DOI: 10.1002/pip.3102]	n-type	27.2	760	43.5	84.0

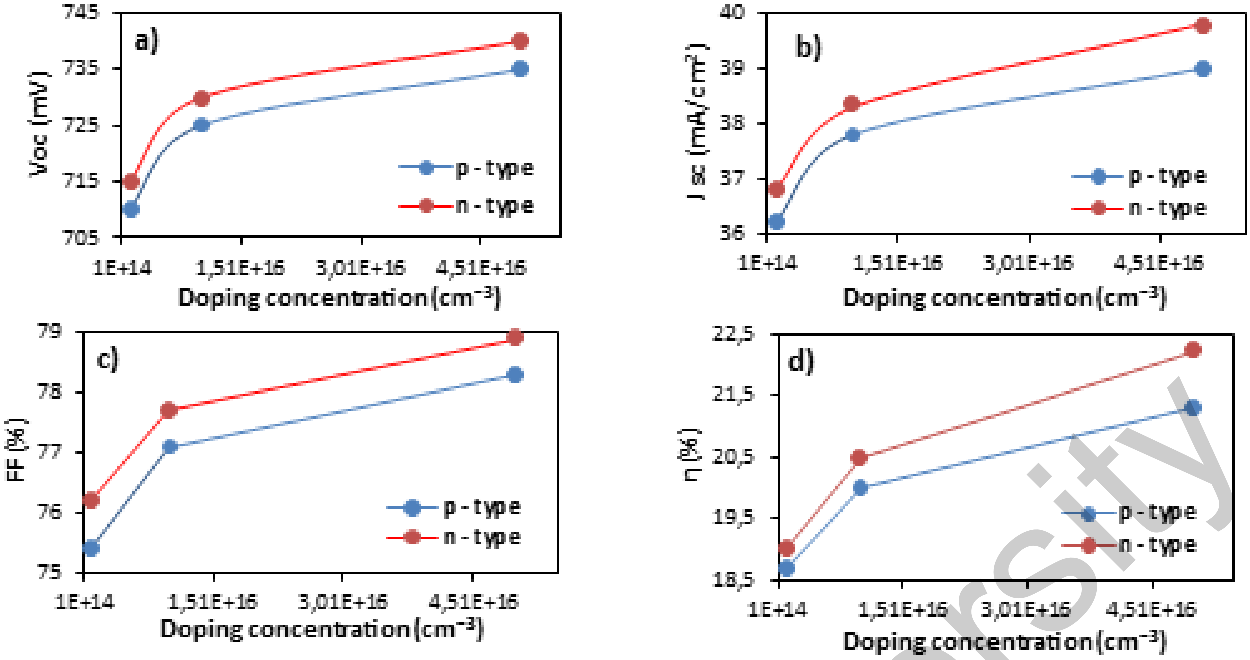

Figure 3. Simulation results with variation of (a) Voc, (b) Jsc, (c) FF, and (d) η as a function of substrate doping concentration for p-type and n-type silicon.

Studies confirm that HIT structures based on n-type silicon substrates demonstrate higher values of key photovoltaic parameters, including open-circuit voltage (Voc) and fill factor (FF). For instance, in the works of Yoshikawa et al. and Masuko et al., Voc values up to 750 mV and FF values up to 83% were achieved for n-type substrates, significantly exceeding the performance of devices based on p-type substrates. For p-type devices, interface passivation quality remains a critical factor, since the efficiency of such structures is strongly dependent on recombination losses at the interfaces. Modern engineering approaches, such as interdigitated back contact (IBC) designs and passivated contacts, open new prospects for further improvement of both the efficiency and stability of HIT structures. These technologies help reduce performance degradation at elevated temperatures and ensure more stable operation under real-world conditions, as confirmed by the studies of H. S. Kim et al..

Conclusion

In this work, a study and comparative analysis of solar cells based on the HIT (Heterojunction with Intrinsic Thin-layer) structure fabricated on crystalline silicon substrates of both p-type and n-type conductivity were carried out. Simulations performed using the AFORS-HET environment made it possible to investigate the influence of substrate type, doping concentration, thickness, and other factors on the key photovoltaic parameters: Voc, Jsc, FF, and η. The analysis was further supported by literature data, as well as laboratory and commercial achievements in the field of high-efficiency solar cells. The results highlight the strong potential of n-type silicon substrates for the fabrication of high-efficiency and reliable solar cells, particularly within the framework of heterojunction technologies such as HIT. Thus, although both p-type and n-type silicon possess their own unique advantages and limitations, n-type silicon has become the focus of recent advancements due to its higher efficiency and superior long-term stability.

Funding

This research was funded by the Kazakhstan Ministry of Higher Education and Science Grant Project No. AP27508001.

References

1. Blakers A. W., Richards B. S., Bett A. J., Cuevas A., Battaglia C., Hameiri Z. The role of thin silicon wafers in photovoltaics — A technoeconomic reassessment // Energy & Environmental Science. – 2019. – Vol. 12, № 4. – P. 1295–1304. – DOI: 10.1039/c9ee02452b.
2. Descoeudres A., Feldmann F., De Wolf S., Jeangros Q., Ballif C. Silicon heterojunction solar cells: Recent advances, current challenges and future prospects // Advanced Materials. – 2016. – Vol. 28, № 47. – P. 10365–10387. – DOI: 10.1002/adma.201602354.
3. Sai H., Matsubara K., Kanamori Y., Kondo M., Okamoto H. Impact of silicon wafer thickness on photovoltaic performance of crystalline silicon heterojunction solar cells // Japanese Journal of Applied Physics. – 2018. – Vol. 57, № 8. – P. 08RB10. – DOI: 10.7567/JJAP.57.08RB10.
4. Betts T. R., Boyd D. I. W. Optimization of a-Si:H/c-Si Heterojunction Solar Cells by Numerical Simulation // Proc. of the 35th European PV Solar Energy Conference. – 2018.

5. Wang L., Zhang Y., Wang Y. Simulation of high efficiency heterojunction solar cells using AFORS-HET // Journal of Physics: Conference Series. – 2011. – Vol. 276, № 1. – P. 012177. – DOI: 10.1088/1742-6596/276/1/012177.

6. Kato K., et al. Comparative analysis of p-type and n-type silicon heterojunction solar cells // Nature Energy. – 2020. – Vol. 5. – P. 123–129. – DOI: 10.1038/s41560-020-0555-6.

7. Aimaganbetov K., Yerezhep D., Kishkenebayev M., Chuchvaga N., Almas N., Tokmoldin S., Tokmoldin N. Characterization of a heterojunction silicon solar cell by means of impedance spectroscopy // Micromachines. – 2024. – Vol. 15, № 2. – P. 184. – DOI: 10.3390/mi15020184.

ӘОЖ 910.1

ГЕОГРАФИЯНЫ ОҚЫТУДАҒЫ АКТ ЕНГІЗУДІҢ ПСИХОЛОГИЯЛЫҚ ЖӘНЕ ПЕДАГОГИКАЛЫҚ ЕРЕКШЕЛІКТЕРІ

Акпамбетова К.М., академик Е.А. Бөкетов атындағы Қарағанды университеті, Қарағанды, Қазақстан

Буланбаева Д.М., «Казгидромет» РМК Қарағанды және Ұлытау облыстары бойынша филиалы Қарағанды қ., Қазақстан

Ақпараттық-коммуникациялық технологиялар (АКТ) білім беру саласына енген сәттен бастап, олар тек оқу үдерісін түрлендіріп қоймай, сонымен қатар оқушылардың психологиялық жай-күйіне тікелей әсер ете бастады. География пәні контекстінде бұл өзгерістер ерекше сезіледі, себебі күрделі табиғи-географиялық процестерді визуализациялау мен нақты қабылдауға АКТ үлкен мүмкіндік береді. Алайда кез келген технологияның тиімділігі – оны кімге, қалай, қанша көлемде қолдануға байланысты. Сондықтан да психологиялық тұрғыдан АКТ-ның оқушыларға ықпалына байыппен қарау қажет.

Жүргізілген зерттеулер оқушылардың АКТ-мен жұмыс істеу барысында мотивациясы едәуір артатынын көрсетті. Мысалы, мультимедиялық презентациялар немесе виртуалды экскурсиялар география сабақтарын тек визуалды тартымды етіп қоймай, оқушыны материалдың ішіне «енгізіп» жібереді. Бұл әсіресе эмоционалдық қабылдауы жоғары оқушыларда тез байқалады: олар тақырыпқа көбірек сұрақ қойып, қосымша ақпарат іздеуге ұмтылады. Бұл өздігінен туындайтын мотивациялық серпіліс оқушының ішкі танымдық белсенділігін күшейтеді. Нәтижесінде сабақ барысында белсенді әрекетке көшу жүзеге асады, ал бұл оқушылардың пәнге деген тұрақты қызығушылығын қалыптастырудың тиімді жолы екені зерттеулермен дәлелденген [1].

Сонымен қатар, АКТ оқушыға өзіне деген сенімділігін арттыруға да елеулі үлес қосады. Мысалы, PowerPoint сияқты қарапайым визуал құралдар мен Google Earth сынды күрделі интерактивті платформаларда жұмыс істей отырып, оқушы өз бетінше ақпарат іздей алады, деректерді салыстыра алады. Бұл процестің өзі оқушыға бақылау сезімін береді – яғни олар тек тыңдаушы емес, белсенді зерттеуші. Бұл сенімділік деңгейінің артуы – әсіресе ұялшақ немесе сабақты баяу меңгеретін оқушылар үшін маңызды артықшылық. Осы тұрғыда С.Т. Мұхамбетжанова мен М.Т. Мелдебекова педагогтардың ақпараттық құзыреттілігін жүйелі әрі үздіксіз дамыту қажеттігін баса көрсетеді. Ғалымдардың пікірінше, мұғалімнің АКТ құралдарын меңгеру деңгейі оқушылардың цифрлық ортада еркін жұмыс істеуіне және өздігінен білім алу қабілетінің дамуына тікелей әсер етеді деген тұжырымға келеді. Осыған байланысты педагогтардың үздіксіз кәсіби даму бағдарламалары мен тәжірибелік оқыту формалары арқылы АКТ бойынша құзыреттерін жүйелі жетілдіру қажеттігі айқын көрінеді [2].

География пәнінің ерекшелігі – күрделі және кеңістіктік ұғымдарды түсінуді талап етеді. Сондықтан зейін, қабылдау және есте сақтау секілді танымдық функциялардың белсенді болуы – табысты оқу кепілі. Шетелдік зерттеулерде 3D-карталар мен геоақпараттық жүйелерді (ГАЖ) пайдалану кеңістіктік қабылдауды жақсартып, оқушылардың танымдық белсенділігін арттыратыны көрсетілген [4]. Мысалы, табиғи апаттар тақырыбын оқытуда NASA World Wind платформасы арқылы жер сілкінісі карталарын динамикалық түрде көрсету – оқушының процесті нақты әрі ұзақ мерзімге есте сақтауына жағдай жасайды. Бақылау нәтижелері де осыны растайды.

Мультимедиялық презентациялармен және интерактивті тренажерлармен жұмыс істеген сабақтарда оқушылар жиі сұрақ қойып, сынып ішінде пікір алмасуға көбірек қатыса бастайды. Бұл әсіресе орта буын (5–7 сынып) оқушыларына тән. Олар үшін визуал мен дыбыстың үндесуі маңызды, ал осы екеуін үйлестіретін – АКТ құралдары [3].

Сонымен қатар, оқушының эмоционалдық жағдайына да АКТ оң әсер ете алады. Әсіресе виртуалды экскурсиялар оқушыны сабақты уайымсыз, жеңіл қабылдауға жетелейді, жағымды эмоциялық қатынас орнатып, күйзеліс деңгейін төмендетеді. Бірнеше мектепте жүргізілген бақылаулар нәтижесінде, АКТ қолданған сабақтарда оқушыларда күйзеліс деңгейі төмендегені байқалды. Себебі материал көрнекі әрі интуитивті түрде беріледі, және қателік жасау қорқынышы азаяды. Бұл – жай ғана цифрлық құрал емес, оқушыны ынталандыратын, сенімділік беретін тәсіл.

АКТ құралдарының психологиялық және педагогикалық әсерлерін салыстыра отырып бағалау, олардың оқушы тұлғасына ықпалын жан-жақты түсінуге мүмкіндік береді. Төменде осы әсерлердің салыстырмалы кестесі берілген (1-кесте).