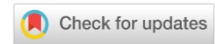


INFORMATION TECHNOLOGY, COMPUTER SCIENCE AND MANAGEMENT ИНФОРМАТИКА, ВЫЧИСЛИТЕЛЬНАЯ ТЕХНИКА И УПРАВЛЕНИЕ



UDC 681.51:004.81:536.2

Original Empirical Research

<https://doi.org/10.23947/2687-1653-2026-26-2-2661>

Hardware Implementation of Fuzzy Logic Based on Thermal Memory Elements for Fault-Tolerant Control in Mechanical Engineering

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Abstract

Introduction. The automation of high-temperature processes (for example, laser welding) requires fault-tolerant real-time control systems. Traditional microprocessors exhibit critical software latencies, while promising in-memory computing platforms (MRAM, RRAM) are subject to thermal instability and state drift in hot zones. There is a significant scientific gap in the development of controllers capable of utilizing heat transfer physics as a computational medium, thereby converting thermal interference into a useful logic signal. This study is aimed at the computer modeling of heat flows in thermal memory elements (TME) to justify the hardware implementation of fuzzy logic inference. The research addresses the tasks of the topological formation of AND/OR logic gates and the analysis of the impact of dielectric insulation on the weight parameter adjustment.

Materials and Methods. The investigation of thermal processes in memory cells (a 2–5 μm aluminum film on a silicon substrate) was conducted by the finite element method in the Transient Thermal module of ANSYS Workbench. The cells were fabricated via vacuum electron-beam evaporation: aluminum tracks 75 μm wide and 4 mm long were formed on the silicon substrate. The structures were subjected to rectangular current pulses with a current density amplitude of $(2–2.5) \cdot 10^{10}$ A/m² and a duration of 1–2 ms; the local heating of the structures reached up to 30°C. To implement AND and OR logic gates, the interelement distances were topologically varied to 0.1 mm and 0.5 mm, respectively. Furthermore, SiO₂ dielectric pockets with a depth of 30 μm were introduced into the design for directional heat flow control.

Results. Based on the developed computer models in ANSYS Workbench, a comprehensive study of non-stationary thermal fields in TME structures was conducted. It is proven that the integration of SiO₂ dielectric insulation effectively controls the direction and power of the heat flow, eliminating parasitic energy dissipation. The modeling physically substantiates the feasibility of hardware formation of a fuzzy inference rule base directly within the crystal topology. It is established that varying the interelement distances is the key factor in logic setting: a distance of 0.1 mm between the input and output elements provides the realization of the OR logic operation, whereas a 0.5 mm distance corresponds to the AND operation.

Discussion. The data obtained confirm that thermal field superposition enables delay-free fuzzy logic operations. The logic gate models developed exhibit response times (1–2 ms) that are an order of magnitude lower than those of standard PLC (20–50 ms). In contrast to phase-change memory (PCM), the proposed method demonstrates robustness against external temperature noise through the algorithmic correction of logic thresholds. The primary limitation of this study is the thermal inertia of the silicon substrate, which accounts for a 5–7% discrepancy between the ANSYS simulation results and in-situ experiments.

Conclusion. The findings validate the feasibility of hardware-based topological design for a fuzzy inference rule base and the practical implementation of in-memory computing. This opens up promising prospects for integrating peripheral artificial intelligence (Edge AI) directly into the hot zones of industrial equipment.

Keywords: thermal memory, fuzzy logic, hardware fuzzy inference, fuzzification, in-memory computing, silicon structures

Acknowledgments. The authors would like to thank Professor S.G. Kalenkov, Dr.Sci. (Physics-Mathematics), and Professor A.N. Beskopylny, Dr.Sci. (Engineering), for stimulating discussions. We also appreciate the Journal editorial team and the reviewer for their professional assessment and valuable recommendations for improving the article.

Funding Information. This research was supported by the Russian Science Foundation, grant No. 25-79-10123.

For Citation. Volodina OV, Skvortsov AA, Rybakova MR, Koryachko MV. Hardware Implementation of Fuzzy Logic Based on Thermal Memory Elements for Fault-Tolerant Control in Mechanical Engineering. *Advanced Engineering Research (Rostov-on-Don)*. 2026;26(2):2661. <https://doi.org/10.23947/2687-1653-2026-26-2-2661>

Оригинальное эмпирическое исследование

Аппаратная реализация нечеткой логики на базе элементов тепловой памяти для отказоустойчивого управления в машиностроении

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Аннотация

Введение. Автоматизация высокотемпературных процессов (например, лазерной сварки) требует отказоустойчивых систем управления в реальном времени. Традиционные микропроцессоры имеют критические программные задержки, а перспективные платформы вычислений в памяти (MRAM, RRAM) подвержены термической нестабильности и дрейфу состояний в горячих зонах. Существует научный пробел в знаниях о разработке контроллеров, использующих физику теплопереноса в качестве вычислительной среды, превращая тепловую помеху в логический сигнал. Цель данной работы — компьютерное моделирование тепловых потоков в элементах тепловой памяти (ЭТП) для обоснования аппаратной реализации нечеткого вывода. В исследовании решаются задачи топологического формирования вентилей AND/OR и анализа влияния диэлектрической изоляции на настройку весовых параметров.

Материалы и методы. Исследование тепловых процессов в ячейках памяти (алюминиевая плёнка, 2–5 мкм, на кремниевой подложке) были проведены методом конечных элементов в модуле Transient Thermal платформы ANSYS Workbench. Ячейки изготовлены методом вакуумного электронно-лучевого испарения: алюминиевые дорожки шириной 75 мкм и длиной 4 мм формировались на подложке кремния. Воздействие осуществлялось прямоугольными токовыми импульсами с амплитудой тока $(2–2,5) \cdot 10^{10}$ А/м² и длительностью 1–2 мс, локальный нагрев структур доходил до 30 °С. Для реализации логических вентилей AND и OR менялись межэлементные расстояния — 0,1 и 0,5 мм соответственно — топологическим способом. Для направленного управления тепловыми потоками в конструкцию были введены диэлектрические карманы из SiO₂ глубиной 30 мкм.

Результаты исследования. На основе разработанных компьютерных моделей в среде ANSYS Workbench проведено комплексное исследование нестационарных тепловых полей в структурах ЭТП. Доказано, что внедрение диэлектрической изоляции из SiO₂ позволяет эффективно управлять направлением и мощностью теплового потока, исключая паразитное рассеивание энергии. В ходе моделирования физически обоснована возможность аппаратного формирования базы правил нечеткого вывода непосредственно в топологии кристалла. Установлено, что варьирование межэлементных расстояний является ключевым фактором настройки логики: дистанция в 0,1 мм между входными и выходными элементами обеспечивает реализацию логической операции OR, а дистанция 0,5 мм — операции AND.

Обсуждение. Полученные данные подтверждают, что использование пространственного наложения тепловых полей позволяет реализовать нечеткие операции без программных задержек. Время реакции разработанных моделей логических вентилей (1–2 мс) на порядок превосходит показатели стандартных программируемых логических контроллеров (ПЛК) — 20–50 мс. В отличие от памяти на фазовых переходах предложенный метод демонстрирует

устойчивость к внешним температурным помехам за счет алгоритмической коррекции логических порогов. Основным ограничением работы является тепловая инерционность кремниевой подложки, которая обуславливает расхождение между результатами моделирования в ANSYS и натурными экспериментами на уровне 5–7 %.

Заключение. Полученные результаты подтверждают возможность аппаратного задания топологии базы правил нечеткого вывода и реализацию вычислений в памяти (in-memory computing). Это открывает перспективы для внедрения периферийного искусственного интеллекта (Edge AI) непосредственно в горячие зоны промышленного оборудования.

Ключевые слова: тепловая память, нечеткая логика, аппаратный логический вывод, фазификация, вычисления в памяти, кремниевые структуры

Благодарности. Авторы выражают признательность доктору физико-математических наук, профессору Каленкову С.Г. и доктору технических наук, профессору Бескопыльному А.Н. за стимулирующие дискуссии. Также благодарим редакционную команду журнала и рецензента за компетентную экспертизу и ценные рекомендации по улучшению статьи.

Финансирование. Исследование выполнено в рамках гранта Российского научного фонда РФ № 25-79-10123.

Для цитирования. Володина О.В., Скворцов А.А., Рыбакова М.Р., Корячко М.В. Аппаратная реализация нечеткой логики на базе элементов тепловой памяти для отказоустойчивого управления в машиностроении. *Advanced Engineering Research (Rostov-on-Don)*. 2026;26(2):2661. <https://doi.org/10.23947/2687-1653-2026-26-2-2661>

Introduction. The current stage of development of global mechanical engineering, which is characterized by the transition to the concepts of Industry 4.0 and 5.0, places high demands on the reliability of automation systems [1]. Technological processes, such as high-precision casting, laser and electron beam welding, as well as multistage heat treatment, operate under the impact of extreme factors: high-intensity electromagnetic fields, vibration loads, and ultra-high temperature gradients. Under extreme temperature conditions and electromagnetic interference, traditional von Neumann microprocessor architecture exhibits a critical reduction in efficiency [2, 3]. Up to 80% of the PLC computational time and energy is consumed by data transmission over vulnerable buses, causing response delays of 20–50 ms. Standard microprocessors require cumbersome protection and shielding systems against electromagnetic interference. Moreover, the implementation of intelligent control algorithms, in particular fuzzy logic, in software is associated with critical delays that arise due to the multiple conversion of signals in the “analog-to-digital converter (ADC) — processor — digital-to-analog converter (DAC)” chain and the sequential execution of the microcontroller software code. High-speed production system control algorithms must operate without latency [4], necessitating the use of parallel hardware processors where logical inference is independent of the CPU clock rate. The transition to alternative in-memory computing (IMC) platforms will enable signal processing directly in the physical environment (in situ).

One of the possible directions for implementing the IMC algorithm is the creation of multi-valued logic circuits [5], which provides the implementation of fuzzy logic in circuit design through changing the physical properties of the material, such as resistance or thermal conductivity. The most studied thermal method for implementing IMC is phase-transition memory (pulse code modulation, PCM) [6], whose operating algorithm is based on encoding information through a change in the aggregate state of chalcogenide glass as a result of an increase in temperature under heating. But it must be taken into account that the use of PCM in hot shops (for example, in the laser welding zone) faces the problem of spontaneous phase switching due to the high external thermal background, which makes them unsuitable for emergency protection systems.

Memristor structures (RRAM) [7], which are characterized by similar problems, are also considered as basic elements of hardware fuzzy logic of the second type. Memristor crossbars are subject to thermal drift of resistive states, which results in the accumulation of errors in the weight coefficients of fuzzy inference. A logical continuation of this approach is the field of thermotronics [8] (phononics [9]). Experiments have been conducted that demonstrate the operation of nanoscale thermal logic gates (NOT, AND, OR) with power consumption on the order of femtojoule [10]. The study of wave-based thermoplastic logic gates built using thermally tunable metamaterials has led to the conclusion that it is possible to create highly complex, combinable circuits embedded directly into the structural material [11]. However, these solutions are purely laboratory-scale: they operate at the nanoscale and require high-quality insulation from macroscopic thermal noise.

Thus, there is a clear gap in current scientific knowledge: existing solid-state solutions (PCM, RRAM) are sensitive to external thermal interference, and nanophononic devices are not scalable for industrial environments. A solution to this problem could be the development of macroscopic thermal memory elements (MTME) that utilize the superposition of thermal fluxes for computation, converting harmful equipment overheating into a useful signal.

Unlike classical electronics, thermal memory uses the dynamic heating range [12] as an analog value. The dynamic change in TME temperature directly reflects the membership functions of fuzzy sets. Thus, the thermal memory element does not simply become a storage device, but turns into an active computing environment that implements fuzzy logic algorithms of the second type.

Unlike classical algorithms, Type-2 Fuzzy Logic operates on membership functions that are themselves fuzzy sets. The degree of membership here is not a specific number, but a range (interval). Fuzzy logic algorithms can directly process linguistic variables and perform an intuitive decision-making process similar to that of humans [13], which allows them to be used in fault-tolerant control systems (FTCS) [14].

The objective of this work is to develop a method for hardware implementation of fuzzy inference based on thermal memory structures. The proposed method will combine the advantages of thermal stability, system noise immunity, and intelligent data processing to solve the problem of creating next-generation fault-tolerant control systems for modern mechanical engineering.

Materials and Methods. The thermal memory elements discussed in this paper are metal film-on-silicon substrate structures. Unlike standard digital memory cells, these elements store information in a thermal state. As an active computing medium, they integrate storage, processing, and fuzzy logic in a single cell, exhibiting strong sensitivity to input energy. Current pulses serve as input signals: heat distribution from local heating implements AND/OR operations. This enables the creation of transistor-free neuromorphic networks for response recognition with energy efficiency of up to 10^{-15} J/operation.

For this reason, the authors used structures consisting of metallization tracks deposited on a silicon wafer through electron beam evaporation (Fig. 1) as the thermal memory cell. A 450- μm -thick silicon wafer with a resistivity of $30 \Omega \cdot \text{cm}$ served as the substrate. Aluminum films with a thickness of $h = 3\text{--}5 \mu\text{m}$ served as the conductive layer. The metallization track width was $b = 75 \mu\text{m}$, and its length was $l = 4 \text{ mm}$. Probes (1–12) were used to record oscillograms during the passage of current pulses [12]. Single current pulses were generated using an original setup. The duration of a rectangular current pulse did not exceed $\tau = 1 \text{ ms}$, and the amplitude $j = 8 \cdot 10^{10} \text{ A/m}^2$. The ohmic resistance of the structure was in the range $R = 0.3\text{--}0.5 \Omega$.

Preliminary studies have shown that this system operates well up to a temperature of $T = 550 \text{ }^\circ\text{C}$. Further increases in thermal loads lead to the onset of degradation processes. These processes are associated with contact melting at the Al–Si interface ($T_e = 577 \text{ }^\circ\text{C}$) and electrodiffusion processes, resulting in irreversible changes in the structure of the metal track [15].

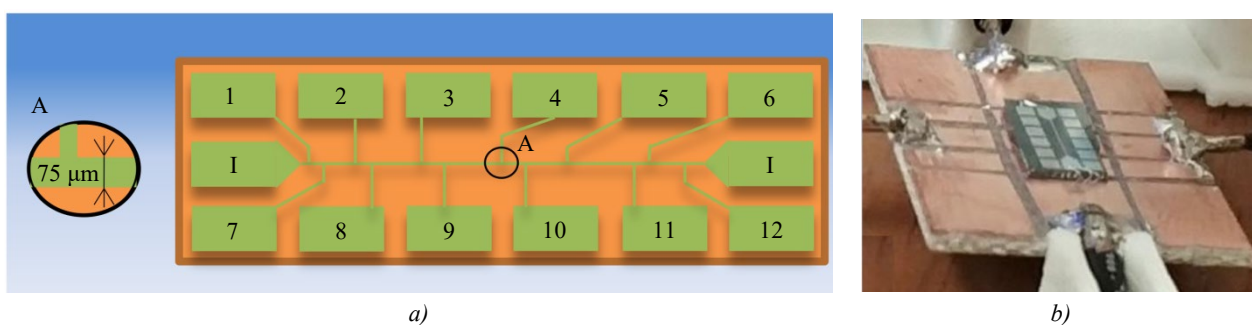


Fig. 1. Hardware implementation of a thermal memory cell:
a — schematic representation; b — experimental electrophysical setup

To conduct a computational experiment and evaluate the spatial distribution of thermal fields, the finite element method in the Transient Thermal module of the ANSYS Workbench platform was used. The numerical solution through constructing a thermal model based on the finite element method in the ANSYS engineering analysis system has proven to be an effective approach for calculating the temperature fields of various mechanical engineering objects [16].

The three-dimensional geometric model (Fig. 2) included a 2 mm thick single-crystal silicon substrate with conductive aluminum tracks (4 mm long, 75 μm wide, 3 μm thick) located on its surface, serving as TME. To specifically control the heat flow and eliminate mutual influence of the input elements, dielectric heat-insulating pockets made of silicon dioxide (SiO_2) 30 μm deep and 1 μm thick were integrated into the structure.

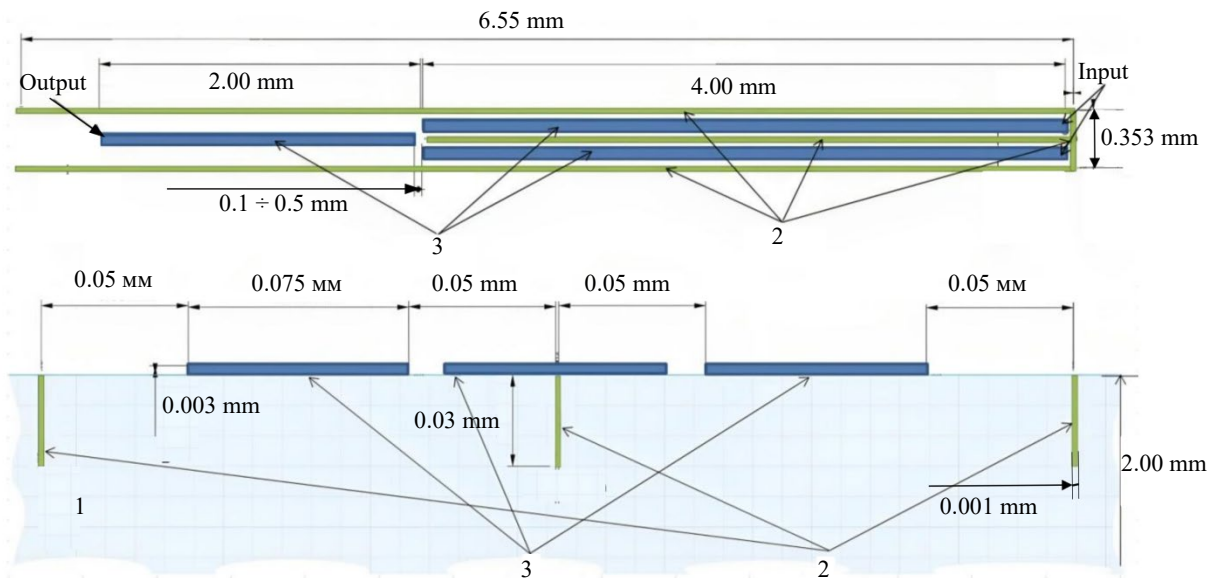


Fig. 2. Logic gate structure geometry: 1 — silicon wafer; 2 — insulating dielectric layers; 3 — metal tracks

When setting up the solver, the following thermodynamic properties of materials were specified:

1. Silicon (Si): density — 2330 kg/m³, thermal conductivity — 148 W/(m·°C), specific heat — 712 J/(kg·°C).
 2. Silicon dioxide (SiO₂): density — 2220 kg/m³, thermal conductivity — 1.5 W/m·°C, specific heat — 745 J/(kg·°C).
 3. Aluminum (Al): density — 2689 kg/m³, thermal conductivity — 237.5 W/m·°C, specific heat — 951 J/(kg·°C).
- The computational unstructured mesh was generated in the built-in ANSYS Meshing module (Fig. 3).



Fig. 3. Image of the constructed mesh on a model of a silicon wafer with a thermal memory element in a 100 μm wide dielectric pocket

Convective heat exchange with the environment was specified as the boundary conditions on the free surfaces of the silicon wafer, with a heat transfer coefficient of 5 W/(m²·°C). Thermal exposure was modeled by specifying the heat dissipation power distributed over the volume of the aluminum tracks. The logic of the gate operation was verified through evaluating the temperature at the output TME with varying thermal clearance distances (from 0.1 to 0.5 mm).

To use this physical structure as a fuzzy logic calculator, a direct connection must be established between the thermophysical processes and the mathematical apparatus of fuzzy sets. To establish a hardware correspondence between a specific numerical value of the input variable (signal from the temperature sensor) and the value of the membership function of the corresponding term of the input linguistic variable (terms “logic 0”, “logic 1”, “critical overheating”), a procedure for finding the values of the membership functions of fuzzy sets (terms) based on clear initial data was carried out — the fuzzification process.

Fuzzification and Input Weight Generation. In the developed TME architecture, input electrical pulses from sensors are converted into local thermal fields directly within the aluminum track — silicon substrate structure. The key parameter at this stage is the input signal weight. While in classical software algorithms, the weight is defined by an abstract numerical coefficient, in the proposed hardware implementation, it has a specific physical meaning, characterizing the

intermediate state of the system between logical 0 and 1. The weight is determined by the amount of thermal energy released (heat flow power), which depends on the amplitude of the current pulse ($2 \cdot 10^{10} < I_m < 2.5 \cdot 10^{10}$ A/m²) and its duration (1–2 ms). The higher the values of these electrical parameters, the more intense the local Joule heating of the element. A physical increase in the temperature of the TME is equivalent to a mathematical increase in the degree of membership of the input variable to the fuzzy term “logic 1”. Thus, the temperature dynamics $T(t)$ of the TME acts as an analog carrier of information about membership in a fuzzy set.

Thus, once the membership degrees of several inputs are established, the system must perform fuzzy inference to generate the hardware output according to a rule base. Unlike microprocessors, where logical inference requires resource-intensive mathematical calculations, in the TME matrix, this procedure is implemented at the hardware level by adding heat fluxes in the volume of the silicon substrate. To level out the uncontrolled mutual influence of thermal memory elements and to set strict inference rules (formation of the rule base topology), dielectric pockets made of silicon oxide (SiO₂) are used (Fig. 2).

Dielectric pockets act as thermal barriers, strictly directing heat flows to the weight (output) element of the matrix for performing intersection or union operations.

Hardware Implementation of AND Intersection and OR Union Operations. To create fault-tolerant control systems implementing hardware fuzzy logic directly within the structure of a memory device, the authors investigated mechanisms for controlling the spatial distribution of thermal fields. Using SolidWorks software, 3D models were constructed demonstrating the topological hardware implementation of AND and OR logic operations based on thermal memory elements (TME).

OR Operation (MAX / Union). This is implemented with a minimum distance between elements (0.1 mm) (Figs. 4, 5). The thermal power of even one heated input under conditions of localized heat flow pockets is sufficient to switch the output element to the “logic 1” state (heating by ≈ 2 °C), which corresponds to the recording of a critical event on any of the channels.

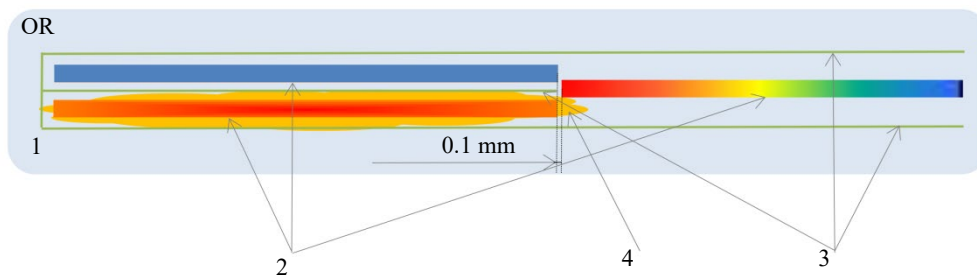


Fig. 4. OR gate hardware implementation (input–output distance: 0.1 mm): 1 — Si wafer; 2 — metal tracks; 3 — dielectric insulation; 4 — heat flow direction

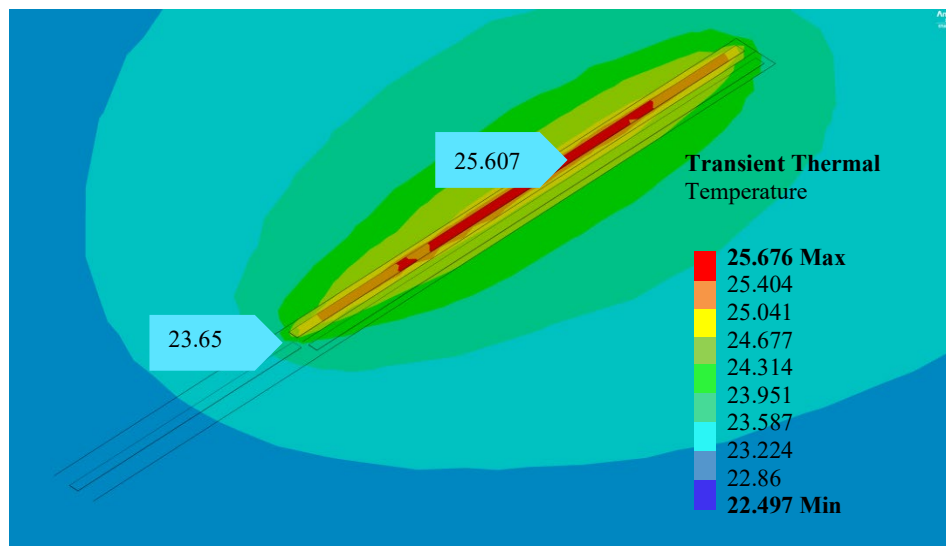


Fig. 5. Simulation model of OR logic gate: temperature field at a distance of 0.1 mm between input and output TME (heating of one input element)

AND (MIN / Intersection) Operation. This is implemented through increasing the distance to 0.5 mm (Figs. 6, 7). In this case, the output element reaches the response threshold only when both inputs are heated simultaneously, which physically emulates the intersection of conditions (e.g., “high temperature” and “long exposure time”).

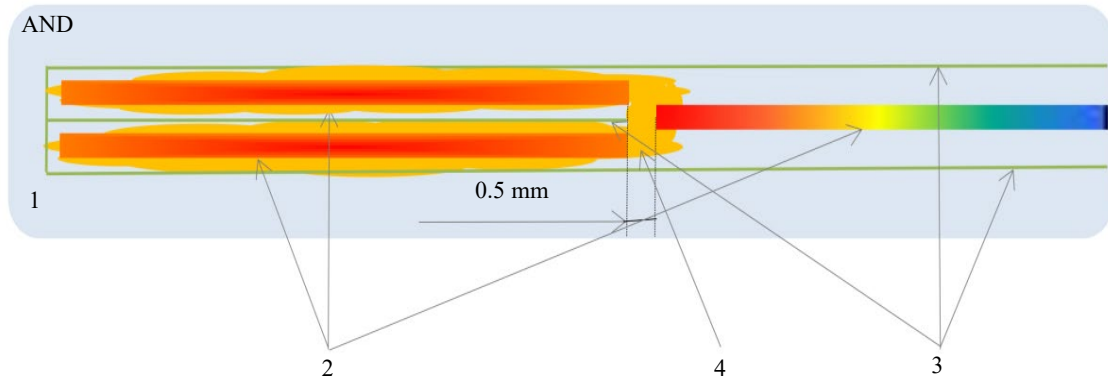


Fig. 6. Hardware implementation of AND operation, distance between input and output elements is 0.5 mm: 1 — silicon wafer; 2 — metal tracks; 3 — insulating dielectric layers; 4 — heat flow direction

Simulation modeling of the operation of logic gates was performed on the ANSYS Workbench platform (Figs. 5, 7) using the Transient Thermal module for non-stationary thermal calculations.

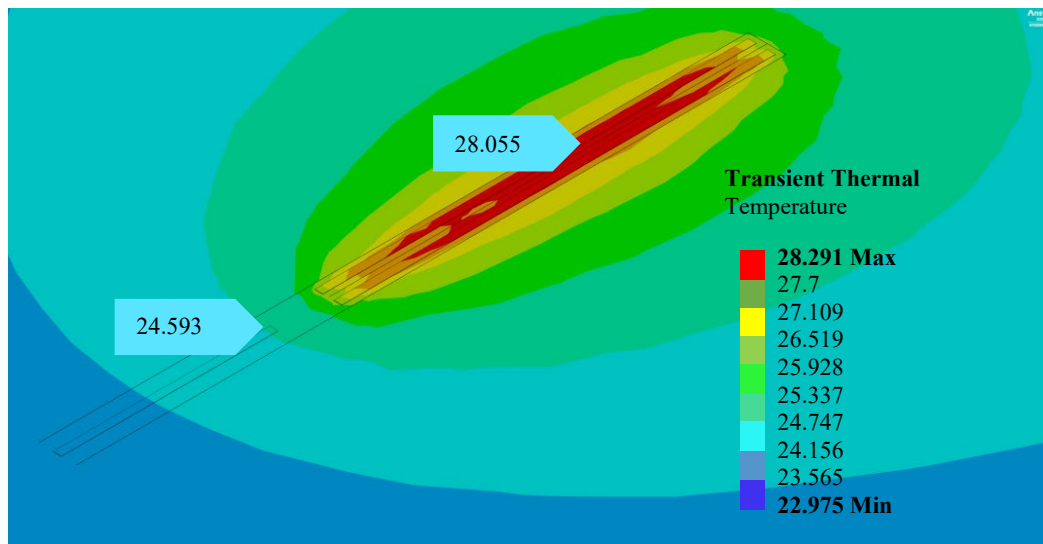


Fig. 7. Simulation model of AND logic gate: temperature field at a distance of 0.5 mm between input and output TME (simultaneous heating of two input elements)

The simulation results (Figs. 5, 7) fully confirmed the efficiency of using thermal insulation (SiO_2) and the selected geometric distances for adjusting the weight parameters of the hardware fuzzy inference.

Research Results. In the course of the study, the concept of hardware implementation of fuzzy logical inference based on thermal memory elements (TME) was theoretically substantiated. It has been established that the use of a planar metallization system on a silicon substrate allows bypassing the hardware limitations of the classical von Neumann architecture through transferring the fuzzification and defuzzification processes directly into the physical environment of the semiconductor.

Computer simulation results in ANSYS Workbench have confirmed that the proposed spatial organization of thermal field superposition within the material enables successful implementation of basic fuzzy logic operations. It is found that the ability to define the fuzzy rule base topology enables precise spatial arrangement of the TME matrix and the use of insulating dielectric pockets made of silicon oxide (SiO_2). Optimal linear dimensions between the input TME and the output weight TME are specified: a distance of 0.1 mm between elements guarantees the execution of the combination operation (logic OR), and an increase in the thermal gap to 0.5 mm establishes rules for the intersection operation (logic AND), switching the output element only under combined thermal effect.

The simulation results prove that the hardware implementation of fuzzy logic based on the electronic control platform allows overcoming the limitations of standard microprocessor systems in the tasks of automating fast-moving processes.

The response time of the developed logic gate models is 1–2 ms, compared to the typical 20–50 ms processing cycle for fuzzy algorithms in standard PLC. The use of macroscopic heat transfer as a useful signal distinguishes the proposed TME from PCM (phase-change memory) technologies, which are subject to spontaneous switching under external thermal conditions. Unlike memristor structures (RRAM), TME are more resistant to temperature drift in hot zones due to the use of a unique floating-zero algorithm.

Discussion. The results of the study have practical significance in the fault-tolerant process control (PC) for automated laser (or electron beam) welding of thin-walled structures. This PC is characterized by high-speed thermophysical reactions (millisecond range) and the presence of electromagnetic interference from power inverters, making the use of conventional microprocessors for fuzzy control impossible without special protection techniques.

A severe violation of this PC is the formation of weld defects (burn-through, evaporation of alloying elements, or critical thermal stresses). To prevent defects, it is required to simultaneously monitor two parameters: the temperature of the welding pool (determined by a non-contact pyrometer) and the time it is maintained at this temperature (or laser pump current).

Fault-tolerant control of this PC can be built on the basis of a hardware implementation of a logic AND gate, which is a three-element structure of thermal memory: two input TME (input A is the temperature factor, input B is the time or power factor) and one output (weight) element that generates a command for correction or emergency shutdown of the process (Fig. 8).

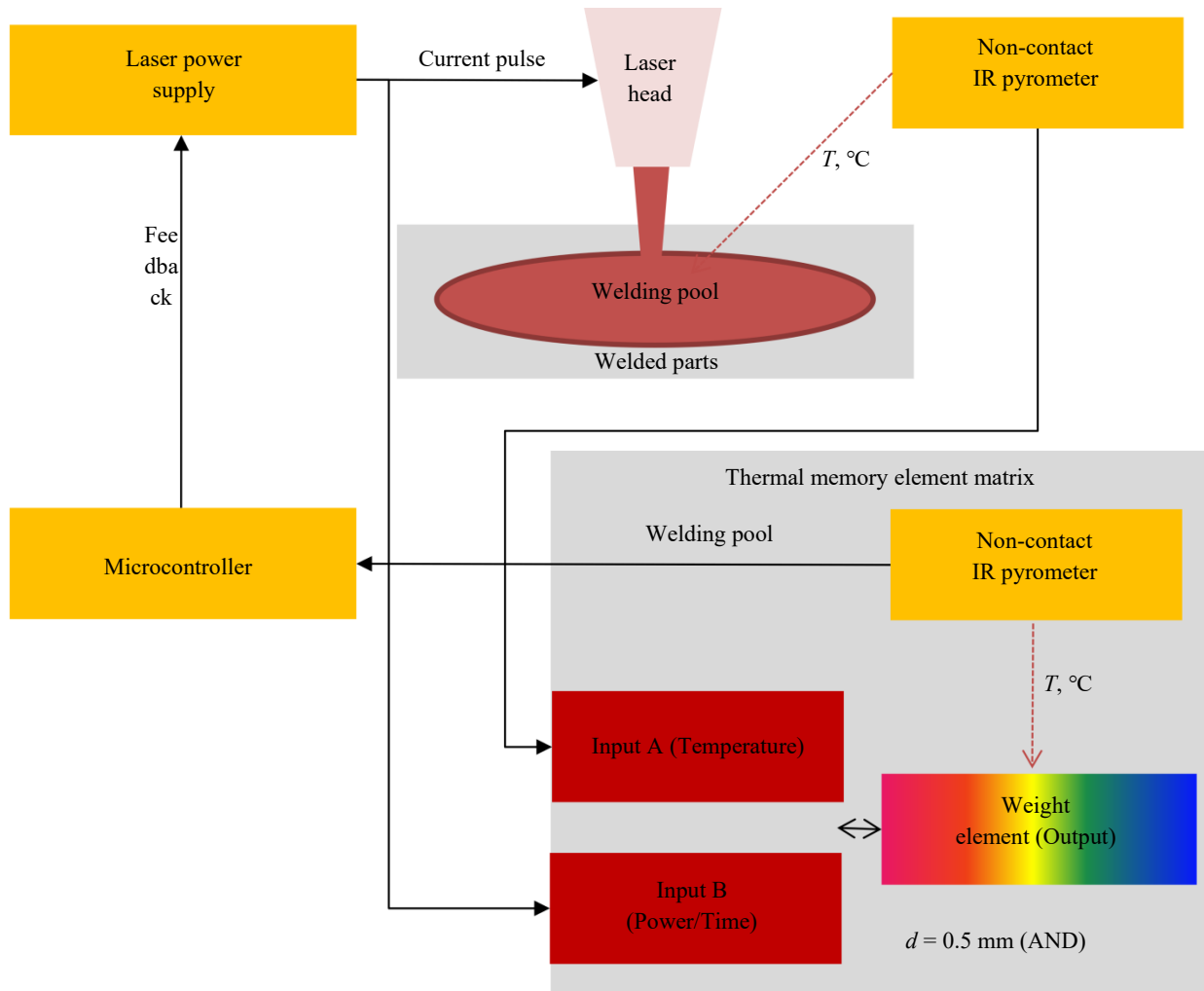


Fig. 8. Schematic diagram for integrating fault-tolerant computer based on TME into laser welding process

The high response rate is due to the fact that logical inference takes place directly in the physical medium, without intermediate analog-to-digital conversion. The implemented AND gate (based on a three-element structure) physically sums the laser power and welding pool temperature factors, allowing the system thermal state to be interpreted as a linguistic variable.

Integrating an active computing environment into a laser welding PC solve the following problems:

- prevent irreversible process failures (weld microstructure degradation, thermal drift, or burn-through);
- adjust energy supply within 1–2 ms;
- TME matrix enables the implementation of an Edge Computing paradigm directly in the hot zone of the process.

This relieves the load on industrial data networks and eliminates latency in critical decision-making.

Hardware implementation of fuzzy logic on TME solves the problems of high-temperature diagnostics in hot workshops (for example, foundries), where standard semiconductor controllers inevitably fail or are forcibly turned off by built-in overheating protection systems [17].

The basic limitation of the TME operation is the thermal inertia of the silicon substrate, which causes a discrepancy between the results of ANSYS simulations and field experiments at a level of 5–7%. It should also be noted that the proposed method is focused on high-speed threshold logic (protection against defects) and does not replace high-precision numerical control systems.

Conclusion. A hardware implementation method for fuzzy inference using thermal memory elements (TME) in industrial automation systems is proposed and validated in the study.

1. A method for organizing information storage and a floating-zero algorithm have been developed, providing adaptive correction of logic thresholds. This allows for the stabilization of logic cell operation under non-stationary temperature conditions typical of industrial environments.

2. The feasibility of topological formation of a fuzzy inference rule base was validated through simulation. It was found that varying the interelement distance in a silicon structure (0.1 mm for the OR operation, and 0.5 mm for the AND operation) allowed logical operations to be emulated directly through the distribution of thermal fields.

3. The efficiency of using TME as peripheral computing links in extreme impact zones is substantiated. It is shown that the use of the proposed structures reduces the system response time to a thermal event to 1–2 ms, which is sufficient to prevent burn-throughs and defects during laser welding.

Prospects for further research suggest the following. Based on the successful hardware implementation of basic logic gates (AND/OR), further research should be pursued in the following areas.

1. Scaling the computing architecture: moving from single logic gates to topological synthesis of multidimensional TME matrices. This will enable hardware implementation of complex fuzzy inference rule bases operating with three or more input linguistic variables for multicriteria process control. According to modern research, multicriteria optimization, taking into account conflicting criteria (for example, finding the optimal temperature), is in demand for improving product quality and the efficiency of complex chemical reactions. Hardware implementation will allow such multicriteria calculations to be transferred directly to the physical environment of the equipment.

2. Optimizing system performance: since simulations have revealed a 5–7% error due to the thermal inertia of the silicon substrate, a promising area is exploring alternative dielectric materials and topologies (for example, localized substrate thinning). This will minimize parasitic heat dissipation and reduce controller response time to the submillisecond range.

3. Hardware-in-the-Loop (HIL) simulation: testing in which a physical prototype of a fault-tolerant computer based on an electronic process platform will be integrated into the control loop of a digital twin of real process equipment. This will enable the robustness of the proposed architecture (Edge AI) to be assessed under conditions of real-world high-frequency electromagnetic interference generated by power welding inverters.

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Conflict of Interest Statement: the authors declare no conflict of interest.

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Все авторы прочитали и одобрили окончательный вариант рукописи.

Received / Поступила в редакцию 10.03.2026

Reviewed / Поступила после рецензирования 17.04.2026

Accepted / Принята к публикации 07.05.2026