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MODERN STATISTICAL METHODS ENHANCED BY MACHINE LEARNING FOR ANALYZING COMPLEX AND LOW-NOISE DATA IN NANOTECHNOLOGY

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Nanotechnology has garnered significant interest across diverse disciplines, evolving into a multidisciplinary field with numerous research initiatives in recent years. It is anticipated to influence all aspects of our economy and everyday life soon. Alongside progress in physics, chemistry, biology, and other science-driven technologies, statistical methods have also contributed to nanotechnology's rapid growth, particularly in data gathering, effect estimation, hypothesis validation, and quality assurance [1].

With the development of nanotechnology, the demand for reliable and stable nanodevices, from sensors to transistors and quantum dots, is growing. However, the behavior of nanostructures is difficult to analyze deterministically due to strong fluctuations, quantum effects, and instability at the atomic level. Therefore, modern statistical methods are becoming key tools for assessing the reliability and

reproducibility of results. The reliability of a device is its ability to maintain its parameters and functions for a given time under certain conditions. At the nanoscale, this includes: tunnel current stability; resistance to electromigration; degradation of conductive channels; and variations in barrier height. The same graphene-based transistor can exhibit a spread in saturation current of up to 20% between different chips manufactured on the same substrate [2].

The paper considers modern statistical analysis methods used in assessing the reliability of nanotechnological devices, with an emphasis on the integration of machine learning (ML) algorithms that provide highly accurate detection of deviations and forecasting the service life of nanosystems. Regression, clustering, and Bayesian approaches are used to analyze experimental data with a low signal level. The novelty of the work lies in the application of adaptive Bayesian modeling and predictive analytics based on neural networks in the framework of testing the reliability of nanostructures.

The key parameter is the survival function of the device:

$$R(t) = P(T > t) = 1 - F(t), \tag{1}$$

where $R(t)$ is the reliability function; t is time; $P(T)$ is the probability of failure; T is a random variable describing the time to failure; $F(t)$ is the probability distribution function of failure.

The Weibull distribution is often used for failure analysis [3]:

$$F(t) = 1 - e^{-(t/\lambda)^k}, \tag{2}$$

where λ is the scale parameter, k is the shape parameter. The parameters are estimated using the Bayesian method.

Prediction of the failure time based on the initial device parameters is carried out using linear regression models:

$$T = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \varepsilon, \tag{3}$$

Clustering methods such as k-means allow grouping devices by degradation level. Euclidean metric and dimensionality reduction algorithms (PCA, t-SNE) are used [4].

Bayesian networks allow taking into account a priori knowledge about the device. The network structure is trained using data, and probabilities are updated using the Bayes formula [5].

The general scheme for studying the reliability of nanodevices using statistical processing of experimental data is shown in Fig. 1. A Weibull model for HfO_2-based memristors is constructed. To refine the model, an adaptive Bayesian approach is used, allowing for real-time updating of the reliability assessment during operation.

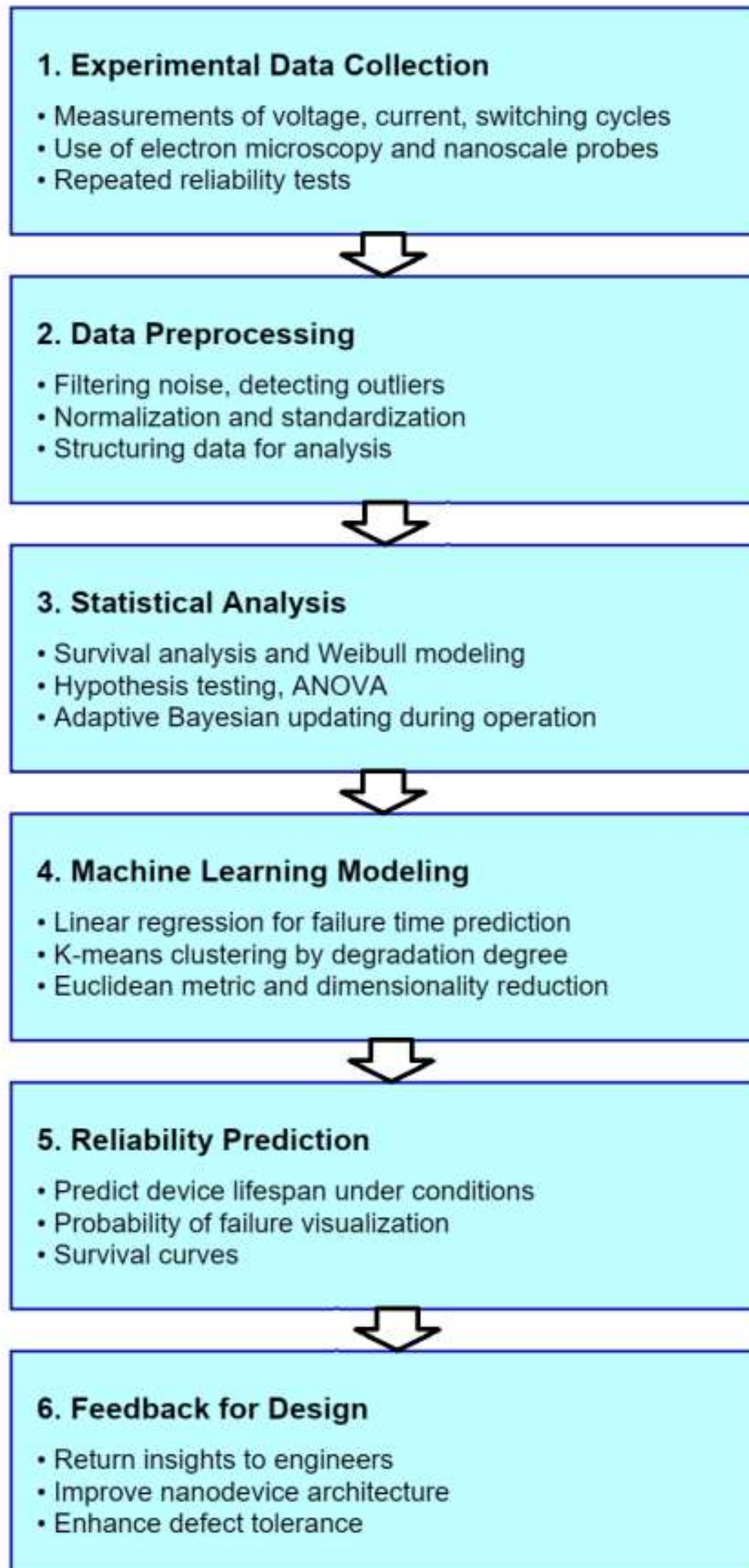

Figure 1. Scheme of Evaluation of the Reliability of Nanodevices.

Therefore, the integration of statistical models with machine learning algorithms enables efficient processing of low-noise and heterogeneous data typical of nanotechnology. This opens the way to the creation of intelligent systems for predictive diagnostics and adaptive testing of devices at the nanoscale.

References

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