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RESEARCH ARTICLE

Identification of knowledge sources for micro- and nanoelectronics technologies

Andrey A. Sharapov [1, 2, @], Evgeny S. Gornev [1]

[1] *Molecular Electronics Research Institute, Moscow, Zelenograd, 124460 Russia*
[2] *Moscow Institute of Physics and Technology, Moscow oblast, Dolgoprudny, 141701 Russia*
[@] *Corresponding author, e-mail: andrey.sharapov@phystech.edu*

Abstract
Objectives. Over the past few decades, multiple knowledge management models have been developed by many research groups studying the innovation process in companies. However, these knowledge and information management models are rather general, and do not consider the dynamics and variability of technology development. This implies involving specific organizations in different types of knowledge generation activities. The paper aims to reveal the importance of a knowledge management system in micro- and nanoelectronics technologies as well as identify and systematize the sources of knowledge in the scientific and technical field.
Methods. In this paper, the method for analyzing the relationship between key business indicators of the companies is applied. The results are then represented in a causal loop diagram. The stakeholder analysis method is also used here.
Results. Three relevant trends in developing the knowledge management system for knowledge-intensive enterprises involved in micro- and nanoelectronics technologies are identified with respect to the social, commercial, and scientific and technical aspects in research organizations. The key sources of knowledge on micro- and nanoelectronics technologies include universities, institutions of the Russian Academy of Sciences, industry-specific institutions, customers, manufacturers, and consumers. Also, the authors consider digital twins to be a promising source of knowledge on micro- and nanoelectronics technologies.
Conclusions. The analysis of the technology life cycle curve using the example of micro- and nanoelectronics allows correlating single stages of this life cycle with specific activities during which new knowledge is generated. These activities include fundamental and applied research, requirements management, implementation in manufacturing, and operation analysis. For microelectronics, they correspond to the areas of emergence, peak of inflated expectations, trough of disillusionment, slope of enlightenment, and plateau of productivity on the technology life cycle curve.

Keywords: knowledge, knowledge management, nanoindustry, digital twin

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НАУЧНАЯ СТАТЬЯ

Определение источников знаний о технологиях микро- и наноэлектроники

А.А. Шарапов [1, 2, @], Е.С. Горнев [1]

[1] *АО «Научно-исследовательский институт молекулярной электроники», Москва, Зеленоград, 124460 Россия*
[2] *Московский физико-технический институт (национальный исследовательский университет), Московская область, Долгопрудный, 141701 Россия*
[@] *Автор для переписки, e-mail: andrey.sharapov@phystech.edu*

Резюме
Цели. В течение последних десятилетий разработано множество моделей управления знаниями. Однако использование данных моделей для создания информационной системы в интересах исследовательских предприятий микроэлектроники не представляется возможным, поскольку они не учитывают динамику и характер развития технологий, а также специфику деятельности организаций в разных видах работ по генерации знаний. Цель работы – выявить направления актуальности разработки системы управления знаниями о технологиях микро- и наноэлектроники, определить и систематизировать источники знаний в данной научно-технической области.
Методы. Использованы метод анализа взаимосвязи бизнес-показателей компаний с последующей визуализацией в виде циклической диаграммы причин, метод анализа заинтересованных сторон.
Результаты. Сформулированы три направления актуальности разработки системы управления знаниями в наукоемкой области технологий микро- и наноэлектроники – с точки зрения социальных, коммерческих и научно-технических эффектов в соответствующих организациях. К ключевым источникам знаний о технологиях микро- и наноэлектроники отнесены университеты, институты РАН, отраслевые институты, заказчики, производства и потребители. Обоснована важность рассмотрения цифровых двойников электронных компонент как перспективного источника знаний в данной области.
Выводы. Анализ кривой жизненного цикла технологии на примере области микро- и наноэлектроники позволяет соотнести отдельные этапы данного жизненного цикла с конкретными видами работ, в ходе выполнения которых происходит выработка новых знаний. В качестве видов работ выделены фундаментальные и прикладные исследования, изучение требований, реализация на производстве и анализ эксплуатации. Для отрасли микроэлектроники на кривой жизненного цикла технологий они соответствуют участкам появления, пика ожиданий, избавления от иллюзий, преодоления недостатков и плато продуктивности.

Ключевые слова: знания, управление знаниями, наноиндустрия, цифровой двойник

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INTRODUCTION

Enhancing and applying total professional knowledge is an integral part of fundamental and applied research carried out by modern research organizations. According to [1], this knowledge may be considered as a part of an organization's intellectual capital and, consequently, as a management object. In [2, 3], some of the best-known models of knowledge management are given, such as the Choo decision-making model based on comprehension of information, the Hedlund model based on the knowledge transfer and transformation, the von Krogh and Roos model of individual and collective knowledge, and others. In general, they are all based on categorizing into the following two types of knowledge depending on the formalization state (the capability to be stored and transferred):

1) Formalized (explicit) knowledge, presented in a particular form: e.g., in the form of records using natural language and binary code, in the form of instructions in a programming language, etc. Explicit knowledge is systematized; it can be packaged in the form of a service (for example, online courses or professional development programs) or product (manuals, videos, notes, etc.) and transferred during the teaching process;
2) Unformalized (tacit) knowledge, usually stored in the minds of particular individuals including dynamically changing adaptive understanding, collective knowledge, and expertise in terms of "know-how." Such knowledge may be transferred through training and mentoring. This type of knowledge was proposed by Michael Polanyi in 1958 [4].

According to the Socialization, Externalization, Combination, and Internalization (SECI) model proposed by Ikujiro Nonaka in 1990[1], knowledge "moves" in a spiral cycle wherein tacit knowledge is "extracted" to become explicit knowledge while explicit knowledge is "re-internalized" into tacit knowledge. Thus, information passes through four stages: socialization, externalization, combination, and internalization; and it is in multiple transitions between formalized and unformalized states that new knowledge is generated.

These definitions are completely suitable for use in terms of knowledge management in micro- and nanoelectronics technologies. However, due to their generality, none of the described models could be directly applied to describe the process of enhancing intellectual capital in organizations of specific knowledge-intensive industries involved in multiple collaborations and project studies as well as performing a diversity of internal R&D activities. It would be advisable to start developing the model description of the knowledge management process by identifying their sources.

COMPONENTS OF THE KNOWLEDGE MANAGEMENT PROCESS IN TECHNOLOGICAL ORGANIZATIONS

Comparing the above models, principal components of the knowledge management process of organizations that are collection (acquisition), transfer (providing access and transmission), application, protection, and storage may be identified [5].

It should be noted, that these actions play a determining role in the operational efficiency of knowledge-intensive sectors, such as microelectronics, which combines nanoscale physics, solid-state electronics, quantum theory, chemistry, and other fields of science [6]. However, the study of Russian enterprises engaged in the development of micro- and nanoelectronics technologies has not revealed the existence of knowledge management systems having a complete set of key components. At the same time, several processes (e.g., accumulation of information in the form of project documentation) are being successfully implemented by certain departments for decades.

The systemic approach to knowledge management in micro- and nanoelectronics technologies would allow the following:

1) monitoring the research and technology development in microelectronics for correct positioning in the industry as well as for making decisions on participation in joint projects [7];
2) controlling the progress at the applied research stage so that not to miss changing trends;
3) accessing the maturity of new solutions with respect to opportunities for improvement of reliability and obtaining new functional properties.

THE RELEVANCE OF DEVELOPING A KNOWLEDGE MANAGEMENT SYSTEM IN MICROELECTRONICS

Creating, populating, and managing the knowledge base for micro- and nanoelectronics technologies may be relevant for R&D companies involved in this field from three perspectives: social, commercial, and scientific and technical. Thus, by sharing information, the scientific results generated by research departments may be more likely to find application in work of design departments. At the same time, the problems formulated by technical specialists that require scientific studies would become known to the research teams of companies due to the common information system. Thus, connecting the researchers and developers of microelectronic technologies communicatively would allow accelerating solution of common tasks of the entire enterprise; in particular, increasing the knowledge base. Moreover, the accumulated knowledge would allow analyzing commercially available products and technologies as well as scientific achievements in more detail, thus providing a more accurate picture of microelectronic technologies available in the Russian and world markets. Formally, these fields may be covered by the terms "innovation and technology exploration" or "scouting." Adjusting the objectives in product development and goals of theoretical and experimental research, one

[1] Management for Knowledge Creation, Tokyo: Nihon Keizai Shimbun-sha, 1990, (in Japanese).

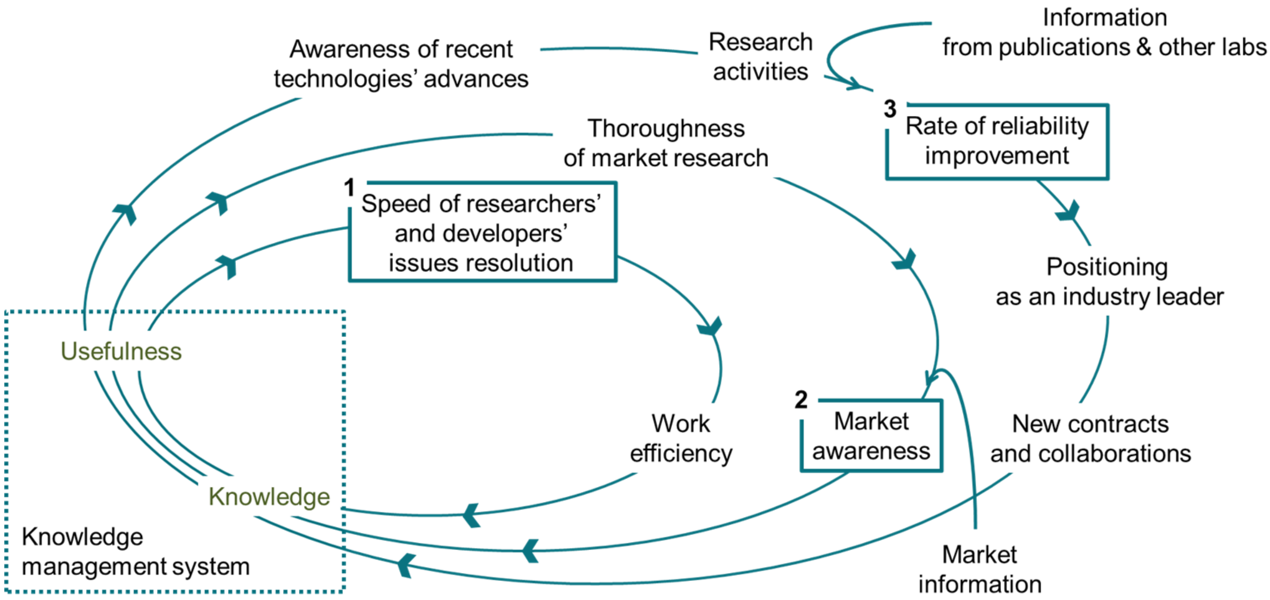

Fig. 1. Positive feedback loops with respect to business processes in the social, commercial, and scientific and technical aspects formed when implementing the corporate knowledge management system for microelectronics technologies

may eventually achieve the new results in high external demand. Solving development and manufacturing problems by performing additional research would result in better product reliability through improved microelectronics technology.

The relevant trends are shown in Fig. 1 schematically as three circuits of positive feedback, i.e., an increase in one indicator improves the next one, moving clockwise.

SYSTEMATIZING SOURCES OF KNOWLEDGE

Using the S-curve concept of the technology life cycle introduced by Gartner in 1995 (the Gartner Hype Cycle), it may be assumed that micro- and nanoelectronics as a set of manufacturing technologies have reached the plateau of productivity phase [8]. This means that the knowledge accumulated in these fields is sufficient for starting commercial microelectronic manufacturing. In addition, advances in related fields (materials science, optics, and nanophysics) may allow for new improvements in basic microelectronics technology, each undergoing the entire life cycle from emergence to widespread adoption.

The chronological comparison proposed by the authors between the phases of the Gartner Hype Cycle and the sources of knowledge identified by classifying market counterparties in micro- and nanoelectronics technologies by activity area is shown in Fig. 2.

Knowledge accumulation occurs at all phases of the technology life cycle. In addition, after the successful completion of each stage, new organizations are involved in the activities in this field, thus becoming new sources of knowledge. For convenience, the following two types of activities resulting in generation of new knowledge may be specified:

1) research activities consisting of fundamental and applied ones;
2) engineering activities consisting of requirements management, manufacturing, and operation.

SOURCES OF KNOWLEDGE IN THE RESEARCH PHASE

The first phase implies **fundamental** research including the study of physical processes and identification of opportunities and acceptable limitations. In this phase, academic institutions and universities are the key players carrying out the main work of knowledge accumulation.

The principle of Coulomb blockade based on two tunnel junctions may exemplify a physical principle remaining in the fundamental research phase for decades. So far, this principle has not yet resulted in the appearance of the single-electron transistor and other alternative transistor structures as microelectronic devices.

The next phase includes **applied** research consisting of attempts to implement the physical principles studied thoroughly in previous phase in devices. As of 2021, this phase is presented by memristors and ferroelectric memory circuits [9, 10] as well as active and passive elements of photonic integrated circuits, fabricated using microelectronic

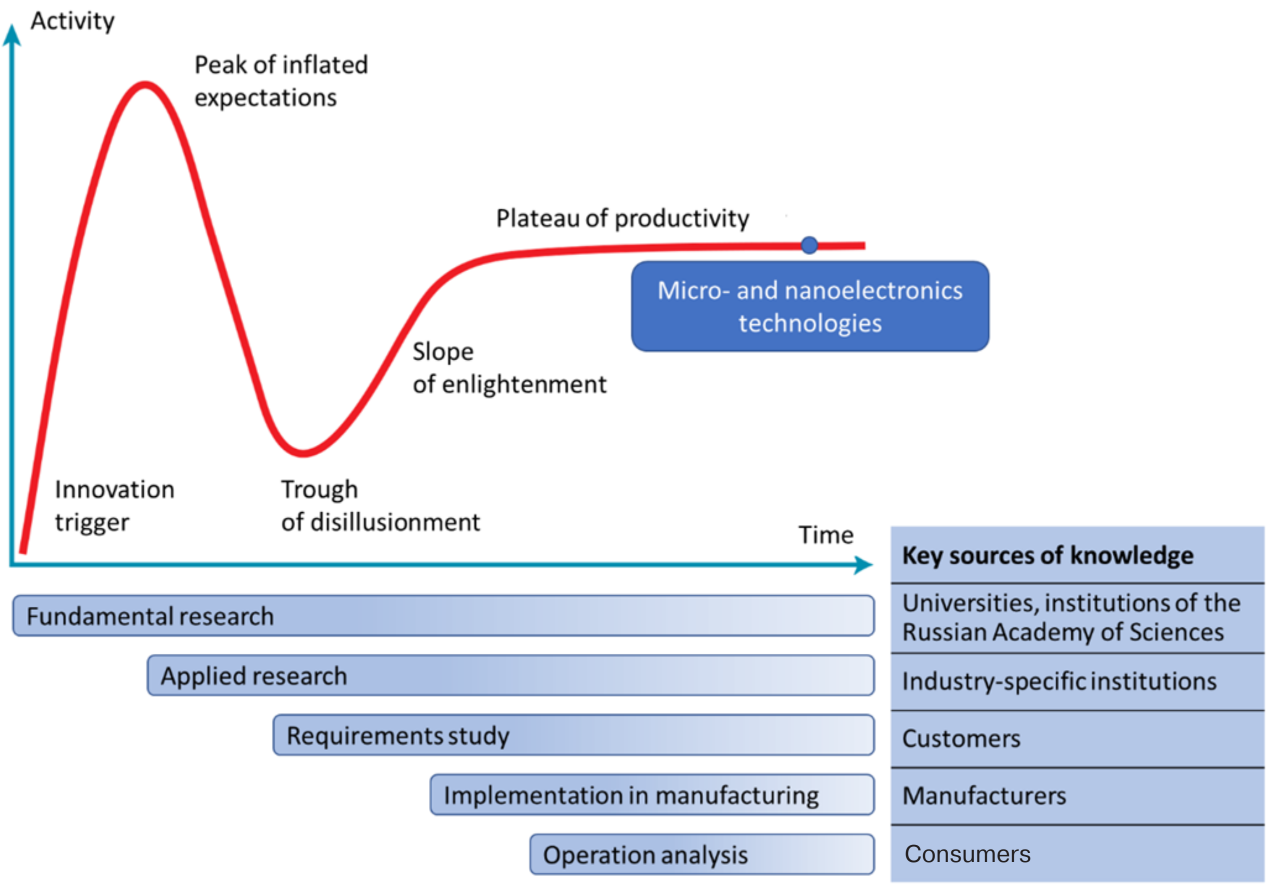

Fig. 2. The technology life cycle curve, phases of knowledge accumulation and sources of knowledge on microelectronics technologies

technologies [11]. Once the research becomes mature, it moves on to the stage of R&D activities resulting in creating prototypes.

In particular, the transition towards new materials [12] requires a large-scale set of tests to make sure that the introduced modifications did not lead to performance degradation of the final devices, primarily in terms of reliability [13, 14]. This is crucial for military application [15] and critical for unmanned space systems manufactured using micro- and nanoelectronics technologies [16].

SOURCES OF KNOWLEDGE IN THE CHIP DESIGN ENGINEERING PHASES

The miniaturization of already designed chips by implementing them in the form of microsystem units was among the main trends stimulating development of Russian microelectronics in the 1970s. The use of integrated circuits (ICs) for custom systems with predetermined functional and reliability requirements is the next step in that process. So far, microelectronics has remained the element base of informatics.

Contemporary methods for requirement-driven design of devices include the widespread use of automation. The use of fundamental parametric synthesis at the initial stage of development, allowing for selecting more effective design decisions using the principle of measuring environmental parameters [17], may add to the existing design algorithms. Awareness of such principles is the result of fundamental and applied research.

Another area of knowledge in microelectronics technologies is related to the changing **requirements to the development** of computing devices. The progress in some areas, such as neural network algorithms [18] and artificial intelligence, may give rise to special-purpose processors with the architecture optimized to solve a certain class of computational tasks with minimal instruction set due to the reduced information storage capabilities.

A key source of knowledge on technologies is related to their implementation in specific **manufacturing**. With the industry being developed, the problems of clean technology environment are being addressed—first, at the level of particles per area, then microparticles per volume, and now the task of airborne molecular contamination removal is of great importance. Significant progress has been made in solving the issue of early failures by introducing process tests and design enhancements [19].

Another source of knowledge relates to issues arising in the phase of the manufactured chips **operating**. Some aspects refer to possibilities of expanding the application boundaries and increasing functionality by software modification. In addition, chip failure cases are analyzed, in particular, breakdowns expressed as an irreversible change in the system induced by localized heating effects.

DIGITAL TWINS AS PROSPECTIVE SOURCES OF KNOWLEDGE

A relatively recent trend in science and technology is application of the model-based systems engineering (MBSE). This implies the integration of executable models as a single source of new information. The creation of the so-called digital twin may be the final objective for this type of systems engineering.

Digital twins may allow modeling semiconductor devices and finite electronic systems at both hardware and software levels [20]. Of particular importance may be considering environmental conditions having varying impacts on equipment and software, such as the effects of external electromagnetic fields and acoustic waves, penetration of high-energy particles, etc. [21]. Modeling of physical processes in integrated circuits and microsystems allows assessing the impact of various internal and external factors on temperature and electrical parameters determining the reliability and noise immunity of the component base.

Compared to system-level models, the digital twin of a semiconductor component reflects the system behavior not only at a particular stage but throughout the entire life cycle. This includes the following stages:

1) concept description, statement of work;
2) architecture design;
3) IC logic development;
4) IC topology development;
5) verification;
6) photomask approval;
7) photomask manufacturing;
8) validation;
9) route map development;
10) fabrication;
11) packaging;
12) benchmarking;
13) testing;
14) certification;
15) series manufacturing;
16) operation.

Implementation of the digital twin involves concurrent data collection and analysis for all stages and participants in the process of a particular semiconductor device manufacturing, ranging from the design centers through the manufacturing site to the user. In fact, a management system for data appearing in developing and process designing as well as for the processes of appearance and transformation of this data is required. The integrated system would allow managing the design project, accounting for the limited time, cost, resources, and quality metrics of the final products [22], as well as thoroughly monitoring, if required, particular operating components up to the formation of structures within IC using micro- and nanoelectronics technologies.

It may be concluded that digital twins of electronic systems as a single channel of new information would be an additional source of knowledge on the micro- and nanoelectronics technologies. However, there is no existing information on complete digital twins at present, so this source is missed in our chart of knowledge sources in micro- and nanoelectronics technologies.

CONCLUSIONS

It should be emphasized in conclusion that existing knowledge management models may be successfully used only within separate knowledge-intensive enterprises. The systematization carried out in the paper may be useful due to the noticeable difference in types of activities in microelectronics performed by different organizations (yet, closely cooperating for solving common scientific and technical problems). The proposed definition of players involved in microelectronics is the information tool prototype allowing project teams to identify the range of promising partners in accordance with the stages of technology development along the life cycle curve. Some details may be added to this chart, e.g., the specific research fields or organization names.

Processing the information streams from the revealed sources of knowledge on micro- and nanoelectronics technologies will allow constructing an effective knowledge base structure for the enterprise as well as the related means of access, use, and management of the stored information. In addition, this will allow for an approach to processing of open-source information for automatic update of knowledge base to be defined.

Authors' contribution. All authors equally contributed to the research work.

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About the authors

Andrey A. Sharapov, Research Scientist, Molecular Electronics Research Institute (6/1, ul. Akademika Valieva, Zelenograd, Moscow, 124460 Russia); Postgraduate Student, Phystech School of Electronics, Photonics and Molecular Physics, and Master Student, Higher School of Systems Engineering, Moscow Institute of Physics and Technology (9, Institutskii per., Dolgoprudny, Moscow oblast, 141701 Russia). E-mail: andrey.sharapov@phystech.edu. ResearcherID ABC-7256-2021, https://orcid.org/0000-0001-9945-3875

Evgeny S. Gornev, Corresponding Member of the Russian Academy of Sciences, Dr. Sci. (Eng.), Professor, Deputy Head of the Priority Technological Area for Electronic Technologies, Molecular Electronics Research Institute (6/1, ul. Akademika Valieva, Zelenograd, Moscow, 124460 Russia). E-mail: egornev@niime.ru. Scopus Author ID 6507763230.

Об авторах

Шарапов Андрей Анатольевич, научный сотрудник АО «Научно-исследовательский институт молекулярной электроники» (124460, Россия, Москва, Зеленоград, ул. Академика Валиева, д. 6/1); аспирант Физтех-школы электроники, фотоники и молекулярной физики и магистрант кафедры системного инжиниринга Высшей школы системного инжиниринга ФГАОУ ВО «Московский физико-технический институт (национальный исследовательский университет)» (141701, Московская обл., г. Долгопрудный, Институтский пер., д. 9). E-mail: andrey.sharapov@phystech.edu. ResearcherID ABC-7256-2021, https://orcid.org/0000-0001-9945-3875

Горнев Евгений Сергеевич, член-корреспондент РАН, д.т.н., профессор, заместитель руководителя приоритетного технологического направления по электронным технологиям, АО «Научно-исследовательский институт молекулярной электроники» (124460, Россия, Москва, Зеленоград, ул. Академика Валиева, д. 6/1). E-mail: egornev@niime.ru. Scopus Author ID 6507763230.

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